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HYDROGEOCHEMICAL PROCESSES INFLUENCING GROUNDWATER QUALITY WITHIN THE LOWER PRA BASIN, GHANA

THIS THESIS IS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF DOCTOR OF PHILOSOPHY DEGREE

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DECLARATION

This is to certify that this Thesis is entirely my original work and does not contain any material previously published or written by another person(s) except where due reference has been duly made in the text. This Thesis has also not been previously submitted to any other University for the purpose of the award of a Doctor of Philosophy Degree. However, portions of this Thesis have been turned into scientific journal papers and published in international journals.

The study was undertaken under the strict supervision of Dr. Ebenezer Kofi Hayford, a Retired Senior Lecturer, at the Department of Earth Science, University of Ghana and Dr. Isaac Owusu Afriyie Hodgson, a Chief Research Scientist with the Council for Scientific and Industrial Research-Water Research Institute (CSIR-WRI), Accra. All the invaluable efforts made by my capable supervisors are hereby acknowledged.

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ABSTRACT

Hydrogeochemical and social impact studies were carried out within the Lower Pra Basin where groundwater serves as a source of potable water supply to majority of the communities. The main objective of the study was to investigate the hydrogeochemical processes and the anthropogenic impact that influence groundwater as well as the perception of inhabitants about the impact of their socio-economic activities on the quality of groundwater and subsequently make recommendations towards proper management and development of groundwater resources within the basin. The methodology involved quarterly sampling of selected surface and groundwater sources between January 2011 and October 2012 for major ions, minor ions, stable isotopes of deuterium (^{2}H) and oxygen-18 (^{18}O) and trace metals analyses as well as administration of questionnaires designed to collect information on the socio-economic impact on the water resources within the basin. In all, a chemical data-base on three hundred and ninety seven (397) point sources was generated and three hundred (300) questionnaires were administered. The hydrochemical results show that, the major processes responsible for chemical evolution of groundwater include: silicate $(SiO_4)^{4-}$ weathering, ion-exchange reactions, sea aerosol spray, the leaching of biotite, chlorite and actinolite. The groundwater is mildly acidic to neutral (pH 3.5 – 7.3) due principally to natural biogeochemical processes. Groundwater acidity studies show that, notwithstanding the moderately low pH, the groundwater still has the potential to neutralize acids due largely to the presence of silicates/aluminosilicates. Results of the Total Dissolved Solids (TDS) show that 98.6 % of groundwater is fresh (TDS < 500 mg/L). The relative abundance of cations and anions is in the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$ respectively. Stable isotopes results show that, the groundwater emanated primarily from meteoric origin with evaporation playing an insignificant role on the infiltrating water. However, with reference to the *Local Meteoric Water Line (LMWL)* for the Accra Plains by Akiti (1986), the results suggest evidence of isotopic enrichment by evaporation on the surface or in the unsaturated zone before recharge into the groundwater system. Hydrochemical facies delineated two main water types, the Ca-Mg-HCO_3 and Na-HCO_3 water types, with Ca-Mg-Cl and Na-Cl as minor water types. Using Q-mode Hierarchical Cluster Analyses (HCA), surface and groundwater within the basin have been characterized into four (4) water groups and five (5) subgroups. Water quality data for subgroups show that, Groups 1 and 2 waters both represent a transition zone between Ca-Mg-HCO_3/Na-HCO_3 and Na-Cl/ Ca-Mg-Cl /Na-SO_4 water types and therefore, can be regarded as transition zones between groundwaters which evolved from Ca-Mg-HCO_3 water type into Na-HCO_3, Ca-Mg-Cl, and Na-Cl water types along its flow-path. Hydrochemical data also suggest that, groundwater within the basin is primarily undergoing recharge processes involving freshwater mixing with geochemically different ionic signatures than processes involving saline-freshwater mixing. PCA using Varimax with Kaiser Normalization for component matrix has delineated three main processes; i.e. natural geochemical and biochemical processes (water-soil-rock interactions), incongruent dissolution of silicates/aluminosilicates, and pollution of the water resources principally from agricultural inputs. The trace metal results show that, groundwater in some communities within the basin is contaminated, due to natural and anthropogenic sources with Al (19.2 % of boreholes), Se (18.4 % of boreholes), Cd (18.0 % of boreholes), As (11.6 % of boreholes), Pb (39.6 % of boreholes), Mn (5.6 % of boreholes), Hg (42.0 % of boreholes) and Fe (21.6 % of boreholes) concentrations exceeding the WHO (2004) guideline limits for drinking water. Results from the social impact survey shows that, majority (93.0 %) of the inhabitants depend on groundwater. The survey also shows that, 58.0 % of the inhabitants use groundwater for their drinking water needs due largely to quality reasons. With respect to the cost of abstracting groundwater, 68.0 % of the inhabitants are of the view that, the cost is appreciably low. Results further shows that, 13.3 % of

groundwater within the basin may become contaminated through solid waste disposal, while, 2.0 % of groundwater may become contaminated through human waste excreta. Regarding contamination of groundwater through farming and mining activities, surface waters which are most often used in these activities are endangered since 81.0 % of farmers spray their farms with agrochemicals and all mining activities especially “galamsey”are located close to surface water course.

DEDICATION

TO GOD BE THE GLORY

DEDICATED

TO

MY WIFE, BRIDGET AKOSUA TAY (Mrs)

AND

CHILDREN, MIRABEL YAYRA TAY, JERRY JEFFERSON SELASI TAY AND DONALD SENYO TAY

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ACi	Groundwater Acidification
ANC	Acid Neutralizing Capacity
AMD	Acid Mine Drainage
AAS	Atomic Absorption Spectrophotoscopy
ATSD	Agency for Toxic Substances & Disease Registry
CAI	Chloro alkaline Indices
CEDECOM	Central Region Development Commission
CWSA	Community Water and Sanitation Agency
CSIR-WRI	Council for Scientific and Industrial Research- Water Research Institute
DRASTIC	Depth, Recharge, Aquifer, Soil, Topographic Slope, Impact of Vadose Zone and Conductivity of Aquifer
DANIDA	Danish International Development Assistance
EU	European Union
ERP	Economic Recovery Programme
EDTA	Ethylenediamenetetraceticacid
GMWL	Global Meteoric Water Line
HCA	Hierarchical Cluster Analyses
IAEA	International Atomic Energy Agency
IWRM	Integrated Water Resources Management
KVIP	Kumasi Ventilated Improved Pit
LMWL	Local Meteoric Water Line
MDG’s	Millenium Development Goals

MoFEP	Ministry of Finance & Economic Planning
NANC	Net Acid Neutralizing Capacity
NDPC	National Development Planning Commission
PhD	Doctor of Philosophy
PCA	Principal Component Analysis
SAP	Structural Adjustment Programme
SPSS	Statistical Package for Social Sciences
SI	Saturation Indicies
TOR	Terms of Reference
USEPA	United States Environmental Protection Agency
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
WRC	Water Resources Commission
WHO	World Health Organization

CHAPTER ONE

1.0 INTRODUCTION

Globally, groundwater plays a very significant role in sustaining human life as it is estimated that approximately one third (⅓) of the world's population exploit groundwater for drinking purposes (UNEP, 1999). Majority of the populations in Africa including Ghana, who depend on groundwater for domestic purposes, live in rural and peri-urban communities where poverty predominates. Lack of access to quality groundwater in these communities in Africa therefore, not only infringes on their basic human rights but also impact negatively on human life as, the availability of good quality water is an essential feature for preventing diseases and improving the quality of life (Oluduro and Aderiye, 2007). Since the last decade, African governments have continuously made conscious efforts to provide their people with quality water from groundwater sources. This is due to the fact that, groundwater is not only viable but the most cost-effective source of potable water for scattered and isolated communities as well (Duah, 2007).

The United Nations Water Statistics have showed that, the total volume of water on earth is approximately 1.4 billion km^3 with freshwater accounting for about 2.5 % of the total volume (Morris *et al.*, 2003). Of the world's total freshwater, approximately 30 % is stocked as groundwater with approximately 97 % of all freshwater being potentially available for use by human (Morris *et al.*, 2003). However, groundwater quality is increasingly deteriorating due to natural geochemical and biochemical processes within aquifers as well as anthropogenic activities and in some cases, over-exploitation due to limited water resources. For instance in India, over- reliance on groundwater has resulted to sixty-six (66) million of the population in twenty-two (22) states at risk due to high levels of fluoride in groundwater, while, approximately ten (10) million of the population in six (6) states are at risk due to arsenic poisoning in groundwater (Ghosh, 2007). This shows that, endemic fluorosis and arsenosis are amongst the most alarming public health issues in India (Susheela, *et al.,* 1993; Suheela, 1999; Choubisa, 2001). As stated earlier, besides natural processes as controlling factors on groundwater quality, over the last decades, the effect of pollution such as nitrates and phosphates from inorganic fertilizers as well as acid rain have also impacted groundwater chemistry (Appelo and Postma, 1999). Owing to the long residence time of groundwater in the subsurface environment, the impact of pollution may become apparent after several years (Appelo and Postma, 1999). It is thus, clear that, an explicit understanding of the processes occurring in aquifers is paramount in order to predict the effects of present day anthropogenic activities on such time scales for sustainability. Hydrogeochemical processes in groundwater are mostly controlled by the physical and chemical interactions that occur between the groundwater and the aquifer materials and are responsible for the seasonal, spatial and temporal variations of groundwater quality and chemistry (Rajmohan and Elango, 2004).

The quality and chemistry of groundwater reveals the mineralogic composition of the rocks with which the water is in contact (Hounslow, 1995). As water slowly moves through the subsurface its composition gradually changes (Hounslow, 1995). This reflects the increasing saturation of some ions or the end products of various rock-water interactions (Hounslow, 1995). Many of these reactions define the geochemical environment, including such parameters as pH, pe and the ionic strength, which subsequently, determine the adsorptive properties of the subsurface as well as the types of microbial processes that may occur (Hounslow, 1995). These reactions may consequently; affect the availability and mobility of many trace elements (Hounslow, 1995).

Thus, knowledge of the processes that control natural water composition is mandatory for rational management of water quality. During the past decade, interest in geochemistry of groundwater has increased as evidenced by several hydrogeochemical studies which are increasingly, becoming a firm part of regional hydrogeological studies. Hydrochemical studies primarily, aims at determining the origin of chemical composition of groundwater and the relationship between water-rock interactions, particularly as they relate to groundwater movement (Hounslow, 1995). The major ion chemistry of groundwater is an essential tool for determining solute sources as well as describing water evolution as a result of water–rock interaction resulting to the dissolution of carbonate minerals, silicate weathering and ion-exchange processes (Herczeg *et al.*, 1991; Hiscock, 1993; Kimblin, 1995; Elliot *et al.,* 1999; Edmunds and Smedley, 2000; Jeelani and Shah, 2006). The geochemistry of groundwater is multifaceted due to the infiltration of water through complex geological formations and anthropogenic impact on flow systems (Hounslow, 1995).

Earlier studies on the categorization of groundwater facies and chemical evolutionary history made use of graphical presentations of major ion composition of groundwater (Piper, 1944; Stiff, 1951; Schoeller, 1962; Hem, 1989). These schemes were helpful in visually describing variations in major-ion chemistry of groundwater and categorizing water compositions into identifiable groups (Freeze and Cherry, 1979), which are generally of comparable genetic history. Assessment of aquifer vulnerability to determine the impact of Depth, Recharge, Aquifer, Soil, Topographic slope, Impact of vadose zone and Conductivity of aquifer on groundwater quality as proposed in DRASTIC by Aller *et al*., (1987) has become known as the most accepted and widely used procedure for assessing the "intrinsic" vulnerability of aquifers (Hui Qian *et al.*, 2012).

In Ghana, there are several problems associated with rural and urban water delivery. The present state of performance of the water sector in Ghana is deep-seated in the economic restructuring which begun in the 1980s under the Economic Recovery Program (ERP), the Structural Adjustment Program (SAP: 1983- 1993) and the Program of Action for the First Medium Term

Development Plan of Ghana (1997-2000), Vision 2020 (NDPC, 1998). It became crucial to initiate restructuring of the drinking water supply sector following the International Drinking Water Decade in order to increase coverage of communities with safe drinking water (Black and White, 2004). Subsequently, a new policy was established to ensure that water supply to rural communities was demand-driven and community-managed. Accordingly, the government of Ghana as part of the Water Sector Rehabilitation Project, between 1996 and 1998, spent an average of US$1.95 million per annum while, donor contribution increased to US$34.2 million in 1998 (Gyau-Boakye *et al.*, 2003).

In Ghana most urban communities depend on treated tap water from river basins within its catchment. Where, peri-urban communities are close to the periphery of the urban catchments, these communities also tap into the urban water delivery system. It has become increasingly clear especially in developing countries (where there is limited access to potable water resulting in women and children in both urban (**Plate 1-1**) and rural (**Plate 1-2**) areas spending long hours in queues waiting for their turn to buy water for use in their homes) in recent times, that sustainable socio-economic development of a country is tied to the management of surface and groundwater resources. The uses of water include; domestic, industry, irrigation, fishing and tourism. The agricultural sector contributes significantly to the economy. However, this enterprise is rain- fed and with the irregularity of rainfall patterns in recent times due to global climate change, reliance on rainfall for agriculture cannot support sustainable socio-economic development of the nation. There is therefore, a growing need to develop and manage groundwater resources in support of sustainable human life and socio-economic development of Ghana.

Groundwater within the Lower Pra Basin is a key source of water supply for most communities in the Central and Western Regions due to the fact that surface water resources which hitherto, served as drinking water sources have become contaminated as a result of anthropogenic activities (predominantly, farming and mining activities). For instance, the Birim River valley, one of the main tributaries of the Pra, is the country's most important diamond-producing area.

Plate 1-1: Women and children in urban Accra waiting for their turn to buy water for use in their homes (Source: Switch workshop report).

Plate 1-2: Children waiting for their turn to fetch water from a borehole at Somnyamekordur community in the Central Region.

Therefore, the need to evaluate the natural geochemical and biochemical processes as well as anthropogenic activities that influence the suitability of groundwater for drinking cannot be over emphasised.

Previous studies on water resources within the study area include; the first phase of the Water and Sanitation Sector Programme Support (WSSPS) project which was initiated by the Danish International Development Assistance (DANIDA) between 2004 and 2008. A second phase was initiated per an agreement which was signed in December 2009 between the European Union (EU), the Ministry of Finance and Economic Planning and the CSIR-Water Research Institute (Anon, 2010). The project commenced in March 2010 and involved a component for continued support for the introduction of Integrated Water Resources Management (IWRM) by the Water Resources Commission (WRC) (Anon, 2010). However, it was realized that further assistance was necessary for the WRC and its collaborating partners to enable progress towards realization of the call for the preparation of a comprehensive national IWRM and water efficiency plans (Anon, 2010). The European Union therefore, assisted financially by dedicating financial resources through the European Development Fund (EDF) to support the project with specific focus on the decentralized IWRM activities to initiate preparation of basin level and national IWRM plans (Anon, 2010). The objective of the national IWRM plan was to facilitate effective utilization, development and management of water resources in Ghana for socio-economic development of the country.

The surface water quality assessment of South-western, Coastal and Volta Rivers System in addition to the groundwater resources assessment and water balance scheme of the Pra and Tano River Basins were follow-ups to confirm the results achieved by the DANIDA-supported projects (Anon, 2010). The primary objective of the project was to conduct sampling and laboratory analysis of the surface water quality parameters at forty (40) sampling stations, using internationally recognized manuals and ISO standards (Anon, 2010). The results were to be compared with the Ghana Raw Water Quality Guidelines and Criteria published by the Water Resources Commission in 2003. The aim of the groundwater component of the DANIDA-supported projects was to: (1) identify existing borehole, (2) rehabilitate them and (3) install divers for the monitoring of the groundwater level fluctuations and quality assessment (Anon, 2010). The consultant was the CSIR-WRI, commissioned by WRC on behalf of the Government of the Republic of Ghana represented by the Ministry of Finance and Economic Planning (MoFEP) was tasked to carry out the objectives as stipulated in the Terms of Reference (TOR). The borehole data generated within the Tano and Pra Basins include; borehole depth, screen (aquifer section), geology, Static Water Level (SWL) and borehole yield (Anon, 2010).

A study by Ahialey, *et al.*, (2010) on the quality of groundwater in the Lower Pra Basin using physico-chemical parameters showed that approximately 97 % of the waters had TDS values less than 1000 mg/L and the chemical parameters were influenced primarily by silicate weathering, ion-exchange processes and sea aerosol spray. The study also show that, the most abundant cation and anion were Na^+ and Cl^- respectively and that, generally, the waters were Na-Cl in character with minor water types as Ca-Mg-HCO_3, Na-Mg-Ca-Mg-HCO_3 and Na-Cl-SO_4. This study however, was based on limited data available at the time and within a limited portion of the Lower Pra Basin. A recent study carried out by Bayitse in 2011, on the pattern of pollution at Lower Basin of River Pra, also concentrated at the lower and upper reaches of River Pra. The physico-chemical and biological results showed various level of pollution of the Pra River with some water quality parameters above the World Health Organization (WHO,1993) guideline values.

It is against this background that this PhD study is formulated to investigate the hydrogeochemical processes that influence groundwater as well as the level and pattern of contamination within the entire Lower Pra Basin, in order to ensure proper management and development of groundwater resources within the Lower Pra Basin.

1.1 Nature and scope of problem.

Ghana was part of the *Road Map towards the Implementation of the United Nations Millennium Declaration* (Black and White, 2004). Consequently, the international community designated a 10-year period from 2005 to 2015 as "The International Decade for Action—Water for Life." It was nonetheless estimated, that about nine million five hundred thousand (9,500,000) people (nearly 50 %) of the total population in Ghana lacked access to adequate water supply (Ghana Statistical Service, 2000).

According to the Central Region Development Commission (CEDECOM) at that time, an estimated capital cost required to deal with the shortfall over the next five years varied between $1 billion and $1.2 billion. Other estimates showed that about, 40 % of the Ghanaian population did not have direct access to clean and safe drinking water. As part of Government's agenda with respect to the United Nations Millennium Development Goals (MDGs) document, Goal 7 aimed at *'ensuring environmental sustainability'* and Target 10 under this goal aimed at *'halving the proportion of people without sustainable access to safe drinking water and sanitation by 2015'* (UNDP, 2006).

However, most of the rural communities in Ghana still lack sustainable access to safe drinking water. For instance, a reconnaissance survey to identify selected boreholes within the Lower Pra Basin in March 2011 revealed that, among others, Amoakokrom and Odumase Camp communities in the Central Region even though have boreholes, many people in these communities cannot afford the cost of water from borehole sources and therefore resort to drinking raw water from the Bupa (**Plate 1-3**) and Esuodom (**Plate 1-4)** streams respectively, without regard for their aesthetic rights.

Plate 1-3: The Bupa stream at Amoakokrom in the Central Region serving as the main water source to the inhabitants

Plate 1-4: The Esuodom stream at Odumase Camp in the Central Region serving as a drinking water source to the inhabitants.

Plate 1-5 compares clean water from a borehole (BH38) and a water sample from the Bupa stream (ST2). Aesthetically, water from the Bupa and Esuodom streams can be considered unclean and unsafe and therefore, unacceptable for potable purposes. Within the framework of the MDGs this is undoubtedly, a set-back to Government efforts in ensuring MDG 7.

Plate 1-5: Aesthetic comparison between two drinking water sources from a borehole (BH38) and a stream (ST2) source within the Lower Pra Basin.

As state earlier, the Central and Western Regions, and for that matter the Lower Pra Basin depend primarily on groundwater. Reminiscent of hard rock areas however, groundwater within the Lower Pra Basin is poorly buffered due to paucity of carbonate in the rocks ensuing to the mobilization of toxic trace metals into the groundwater if, they are present in the rocks (Smedley *et, al.*, 1995). Sulphide rocks containing the gold ore, which is widespread within the basin often, contain pyrite and arsenopyrites (Smedley *et, al.*, 1995). Exposure of these rocks to the atmosphere often results in acid mine drainage generation and subsequent mobilisation of toxic trace metals principally, Arsenic concentration in high proportions into the groundwater system.

According to Rahman (2002), most groundwater in Bangladesh have been contaminated with arsenic exceeding the World Health Organization (WHO) guideline of 0.01 mg/L and the Bangladesh permissible limit of 0.05 mg/L. Arsenic poisoning of groundwater in Bangladesh can be described as the largest mass poisoning known in history, with more than 29 million people exposed through drinking water [Smith *et al.*, (2000); McLellan, (2002) and Ahmed, (2002)]. Several other occurrences of arsenic poisoning in groundwater have been reported worldwide in the past including such countries as; Taiwan, Chile, and Argentina while, arsenic poisoning in groundwater in other countries such as Nepal and Vietnam, have been discovered more recently (Rahman, 2002). Recently, a number of studies in the Mekong River Basin in Cambodia and Vietnam have revealed exposure levels that are comparable to the concentrations observed in Bangladesh [Luu *et al.*, (2009) and Nguyen *et al.*, (2009)]. Thus, arsenic is capable of infiltrating groundwater systems irrespective of whether mining has taken place or not.

The use of mercury (Hg) and other chemicals indiscriminately during mining operations, which are harmful to human health, is another problem confronting the mining industry. During mining operations, the miners use simple methods to extract and process the gold (Lacerda, 1997).

Mining operations, especially small-scale (*"galamsey"*) are usually located close to water resources, most often along the banks of rivers and therefore, noted for its impacts on water resources through pollution of both ground and surface waters (Lombe, 2003). As a result, water resources including groundwater which hitherto, served as sources of potable water have become contaminated and therefore, unsafe for drinking. For instance, 78 % of water samples collected and analysed from Lake Victoria goldfields in Tanzania, contained mercury in concentrations appreciably above the drinking water standard of 0.001 mg/L (Mpendazoe, 1996). The presence of trace metals including Hg in rivers and river sediments in small-scale mining areas in Tanzania is therefore, a threat to both the environment and to human health.

Lastly, the Mozoe, Luenha, Revue and Zambezi rivers which flows through Mozambique into the India Ocean, from Zimbabwe, Zambia and Malawi, where, the use of mercury is widespread have contributed to water contamination downstream (RTI ITDG, 2001).

In Ghana, previous studies conducted in the area of trace metal pollution of groundwater include; arsenic mobilization and its health implications on rural water supply in the Offin Basin (Amasa 1975; Smedley *et al.*, 1995). A study by Kortatsi (2006), on the concentration of trace metals in boreholes in the Ankobra Basin, one of the principal gold mining areas in Ghana, collected seventy six (76) water samples from boreholes and hand-dug wells. The study concluded that, the concentration of mercury was higher than the WHO (2004) guideline limit of 0.001 mg/L during the rainy season however; mercury concentrations were below detection limits during the dry season and attributed the findings to anthropogenic sources such as gold mining. Kortatsi *et al.*, (2007) also conducted a study on the hydrogeochemical evaluation of groundwater in the Lower Offin Basin, a major gold mining area in Ghana. In this study, a total of one hundred and forty eight (148) samples were collected from boreholes, hand-dug wells and spring and two (2) samples from mine drainage in December 2004. The study concluded that, 19 % of the boreholes had arsenic concentrations exceeding the WHO (2004) guideline for drinking water.

Tay *et al.*, (2006) also conducted a study on trace metal contamination in water from abandoned mining and non-mining areas in the northern parts of the Ashanti gold belt. The study collected water samples from sixty seven (67) boreholes, twenty four (24) hand-dug wells and ten (10) streams. The study concluded that, stream sources were the most affected by mercury concentrations exceeding the WHO (2004) guideline limit of 0.001 mg/L for drinking water during both dry season with a mean value of 0.66 mg/L and wet season with a mean value of 0.32 mg/L, followed by hand-dug wells with a mean value of 0.24 mg/L for dry season and mean value of 0.30 mg/L for wet season, whilst, boreholes had mercury mean concentrations of 0.19 mg/L and 0.22 mg/L during dry and wet seasons respectively. The study attributed the findings to gold recovery through mercury amalgamation.

It is worthy to note that, there are small- scale mining operations taking place within the Lower Pra Basin **(Plate 1-6).**

Plate 1-6: Small-scale mining ("*Galamsey*") operations site at Mpohor community in the Central Region.

The gold ore primarily found in the Birimian is refractory quartz-Fe/As sulphide lode gold (Marston, *et al.*, 1992). Junner *et al*. (1942), reported that pyrite is widespread in many parts of the igneous rocks and quartz veins interrupt the Tarkwaian and Birimian rocks underlying the study area. There is therefore, a probability of Fe and As pollution of the groundwater particularly, in rocks underlain by Birimian Supergroup within the Lower Pra Basin.

Despite the appreciable literature on the susceptibility of groundwater within the Lower Pra basin to pollution the results are difficult to interpret due to the limited nature and scattered distribution of similar studies within the basin. Consequently, it has been historically difficult to obtain an explicit understanding of the scope and levels of pollution of groundwater within the basin. The need to evaluate the natural geochemical and biochemical processes as well as anthropogenic activities that influence the suitability of groundwater for drinking therefore, cannot be over emphasised. An adequate knowledge of the hydrogeochemistry of groundwaters is critical for proper management to meet increasingly growing needs. This knowledge commences with the evaluation of the major controls on the quality of these natural resources.

It is therefore, imperative to conduct an in-depth identification, characterization and assessment of the physico-chemical controls on groundwater resources within the Lower Pra Basin, to determine its healthiness and safety on the consuming public. To ensure efficiency in the management and development of groundwater within the basin, it is important to involve all stakeholders. This study thus, additionally seeks to conduct a social impact study which involves the administration of questionnaires designed to solicit responses from the people who utilize these groundwater resources for drinking and other domestic purposes.

1.2 Aims and objectives

1.2.1 Overall objectives

The overall objective of this study is to provide an improved understanding of the generally acidic character of groundwater and identify the natural geochemical and biochemical processes as well as anthropogenic activities that control the hydrogeochemistry of groundwater within the Lower Pra Basin. The study further seeks to examine the impact (long- term effect) or otherwise of the groundwater acidity as well as assess the perception of users of the boreholes regarding the impact of their socio-economic activities on the quality of groundwater within the basin.

1.2.2 Specific objectives.

The study specifically seeks to:

1 Determine the origin of chemical constituents in groundwater resources within the Lower Pra Basin using; groundwater geochemistry, mass-balance approach (major ions-relationship and equivalent ratios of ions) and stable isotopes.

2 Evaluate the sources of acidity and their extent in groundwater within the basin.

3 Evaluate the hydrochemical evolution of groundwater within the Lower Pra Basin using hydrochemistry of the area as well as categorizing the waters into different groups of similar water quality characteristics using Hierarchical Cluster Analysis (HCA).

4 Delineate the hidden processes responsible for groundwater evolution within the Lower Pra Basin using multivariate statistical technique.

5 Assess the level of trace metal pollution of groundwater within the Lower Pra Basin.

6 Assess the perception of inhabitants about the impact of their socio-economic activities on the quality of groundwater through questionnaire administration.

CHAPTER TWO

2.0 REVIEW OF LITERATURE

Hydrochemical studies reveal the origin of the chemical composition of groundwater and the correlation between water-rock chemistry, especially in relation to groundwater movement (Appelo and Postma, 1999). The geochemistry of groundwater is very complicated, owing to the movement of groundwater through complex geological formations as well as the impact of human activity on flow systems (Appelo and Postma, 1999). A change in the chemistry of groundwater is principally a function of the interaction between the groundwater and the mineral composition of the aquifer materials through which it moves (Appelo and Postma, 1999).

Hydrochemical processes such as precipitation, ion-exchange, sorption, dissolution and desorption, coupled with the residence time of groundwater along the flow-path, control the changes in chemical composition of groundwater (Apodaca *et al.*, 2002). Several factors control the chemical composition of groundwater; and the groundwater system within a region has a distinct chemistry or chemical characteristics due to chemical variation of meteoric water recharging the aquifer system (Drever, 1988; Hem, 1991).

Variations in the chemical quality of meteoric water depends on the geologic structure, constituents of infiltrating rainwater, mineralogical composition of aquifer material, residence time, dissolution and precipitation of mineral species and anthropogenic influences (Hounslow, 1995; Datta and Tyagi, 1996; Andre *et al*,. 2005). Relations amongst the constituents of dissolved species is capable of revealing the origin of solutes and processes that generated the observed water compositions (Jalali, 2007, Singh *et al.*, 2008).Water is a universal solvent, thus, dissolves chemical constituents from dissolvable materials and is altered in composition as it passes through the atmosphere, soil and unsaturated zone into the water-table (Chebotarev, 1955). Chebotarev (1955), have shown that barring local variations (possibly resulting from unusual concentration of some constituents in the soil), the composition of groundwater changes from bicarbonate (HCO_3^-) waters at outcrops to sulphate (SO_4^{2-}) waters at transitional depths to chloride (Cl^-) waters at greater depths of continuous flow. These changes signify the signatures of one or several of such factors as soil/rock composition, prevailing climatic conditions, pH, the residence time and topography (Todd, 1980; Raji and Alagbe, 1997).

In coastal environments, the influence of saline water intrusion on groundwater is often significant and therefore, of primary concern. The overall consequence of these changes is the chemical variation of groundwater in response to its flow-path and geochemical history (Todd, 1980; Raji and Alagbe, 1997). Generally, groundwater movement along its flow-path increases the concentration of the chemical species (Freeze and Cherry, 1979). In any water resource, the concentration of the chemical species is responsible for its properties and qualities, and characterizes that water resource in terms of its water type (Freeze and Cherry, 1979).

The conduct of studies into the origin of dissolved ions in water resources reveals enough information about the water resource. Such information include; general geology, degree of chemical weathering of the various rock types within the area, the quality of recharge water and inputs from sources excluding water-rock interaction and therefore, assist hydrochemists and hydrogeologists in the sustainable management and development of the water resources in that area (Appelo and Postma, 1999). There are different approaches in establishing the origin of dissolved ions in water resources. These include the applications of groundwater geochemistry, source-rock deduction and stable isotopes of ^{2}H and ^{18}O.

Groundwater geochemistry is an interdisciplinary science and one of the approaches used to establish the origin of dissolved ions in water (Appelo and Postma, 1999). It employs the chemistry of water in the subsurface environment and has the potential factors for tracing the origin and the history of water (Appelo and Postma, 1999). The chemical composition of groundwater is the combined chemistry of the composition of water that moves into the groundwater reservoir and their reactions with minerals that exist in the rock (Appelo and Postma, 1999). Water compositions vary through reactions with the environment, and water quality data may reveal immense information regarding the environments through which the water has circulated (Appelo and Postma, 1999).

Naturally, groundwater contains mineral ions which dissolve gradually from soil particles, sediments, and rocks as the water travels along mineral surfaces in the pores or fractures of the unsaturated zone and the aquifer (Appelo and Postma, 1999). In recent years, the effect of pollutants such as nitrate from fertilizers and acid rain also influence groundwater chemistry apart from natural processes as controlling factors on groundwater quality (Appelo and Postma, 1999). Variation of groundwater quality in a region is thus, a function of physical and chemical parameters that are significantly influenced by geological formations and anthropogenic activities (Subramani *et al.*, 2005).

Source-rock deduction technique is another approach which can be employed to establish the origin of dissolved ion in water (Hounslow, 1995). The purpose of source-rock deduction technique is to advance knowledge into the possible origin of water (Hounslow, 1995). It is based on a simplistic mass-balance approach to water quality data (Garrels and MacKenzie, 1967). Deducing the sources of solutes in groundwater using simple mass-balance approaches provide clear results and a practical way of restricting the processes that might affect the major-ion chemistry (Hounslow, 1995). The processes that govern the hydrochemical evolution of groundwater essentially depend on the chemistry of the recharging water, water-aquifer matrix interaction (cation- exchange), or both, as well as groundwater residence time within the aquifer (Garrels and MacKenzie, 1971).

The origin of dissolved ions in water could be conventionally determined from the variation of the characteristic solute-concentration ratios such as Na^+ / Cl^-, Ca^{2+}/Mg^{2+}, SO_4^{2-}/Cl^- (Clark and Fritz, 1997). However, in certain situations, water chemistry may undergo secondary changes such as ion-exchange, oxidation and reduction, precipitation and evaporation, and eventually presents a difficult situation in employing either groundwater geochemistry or the mass-balance approach to identify the sources of dissolved ions (Clark and Fritz, 1997). In such situations, stable isotopes approach is employed to investigate the origin and recharge conditions of groundwater (Clark and Fritz, 1997). Isotope hydrology investigates the inter-relationships between the components of the water cycle, such as evaporation, rainfall, run-off and plant transpiration using stable isotopes of oxygen-18 (^{18}O) and deuterium (^{2}H). Stable isotopes of oxygen-18 (^{18}O) and deuterium (^{2}H) are also used to evaluate groundwater flow-paths, recharge areas and mixing conditions within a region, district or basin (Zaharin *et al.*, 2008).

Stable isotopes hydrology is a technique which can be employed to trace groundwaters to their point of origin via analyses of their deuterium (^{2}H) and oxygen-18 (^{18}O) concentrations (Clark and Fritz, 1997). This technique normally assumes a meteoric origin for the waters being traced, however, may be expanded to take into considerations possible contributions from other sources (Clark and Fritz, 1997). Meteoric processes such as evaporation, condensation and precipitation modify the stable isotopic composition of water, and consequently the recharge waters in particular environments have characteristic isotopic signatures, most often permitting the separation of waters from different environments (Clark and Fritz, 1997). Stable isotopes of water being relatively non-variable over time, are therefore, more suitable to be employed in the study of the complexities of groundwater hydrology in an area (Clark and Fritz, 1997).

Environmental isotopes are routinely used in hydrogeological investigations to complement geochemistry and physical hydrogeology due to their ability to provide information about geochemical evolution, recharge processes, water-rock interactions and the origin of salinity

(Clark and Fritz, 1997; Kendall and McDonell, 1998; Cook and Herezeg, 2000). Unlike other tracers of water such as Cl^- which are still widely in use, stable isotopes (δ^2H and $\delta^{18}O$) are perfect tracers of the origin and movement of water since they constitute water molecules (Akiti, 1986).

The elements; Hydrogen (H_2) and Oxygen (O_2) undergoes changes in the various phases of hydrologic environments- atmosphere, biosphere, hydrosphere and the upper part of the earth's crust ensuing in isotopic fractionation to produce isotopic "fingerprints" due to the different physico-chemical, biochemical, kinetic and thermodynamic effects (Das, *et al.*, 1998).

Owing to the differences in meteorological conditions such as evaporation in precipitation source areas, the fractionation of oxygen and hydrogen do not typically happen under equilibrium conditions and thus, there is a difference between δ^2H and $\delta^{18}O$ (Gibrilla *et al.*, 2010). The use of stable isotopes as tracers of the origins of groundwater also permits conclusions to be arrived at, regarding the recharge processes, the location of recharge and discharge areas, aquifer continuity, sources of ions in water and turnover time (Fontes, 1980; IAEA, 1983).

The isotopic fractionation of oxygen and hydrogen at any location is influenced by the origin of the water, climate (evaporation, condensation, melting), geology of the area and other local effects such as simple mixing at or below the surface (Faure, 1986). However, in most low temperature systems where geothermal effect is non-existent, ^2H and ^{18}O isotopic contents of water can be considered as conservative (IAEA, 1983). This is because as ^2H and ^{18}O move through a catchment, any interactions with oxygen and hydrogen in the geologic materials will have a negligible effect on the ratios of isotopes in the water molecule (IAEA, 1983).

The isotopic compositions of ^2H and ^{18}O in groundwater, nonetheless, may differ depending on such factors as distance from the ocean, the elevation of the recharge site, temperature at the recharge site and seasonal variations (Erickson, 1983). Typically, recharge occurring at a high elevation results in relatively lower or more depleted δ^2H and $\delta^{18}O$ contents than recharge occurring at a local lowland area (Erickson, 1983). Similarly, recharge of ancient groundwater (palaeowater) under climatic conditions different from the present climate produces isotopic signature of the past climate (Gat and Issar, 1974). Generally, the isotopic composition of groundwater may be slightly different from the composition of the recharging rains, being either heavier or lighter due to several processes that may modify its contents during or after infiltration (Mazor, 1976). Figure 2-1 presents a summary of the processes causing modification of the initial stable isotope composition of groundwater. This has been widely accepted and cited by various authors (i.e. Kortatsi, 2004).

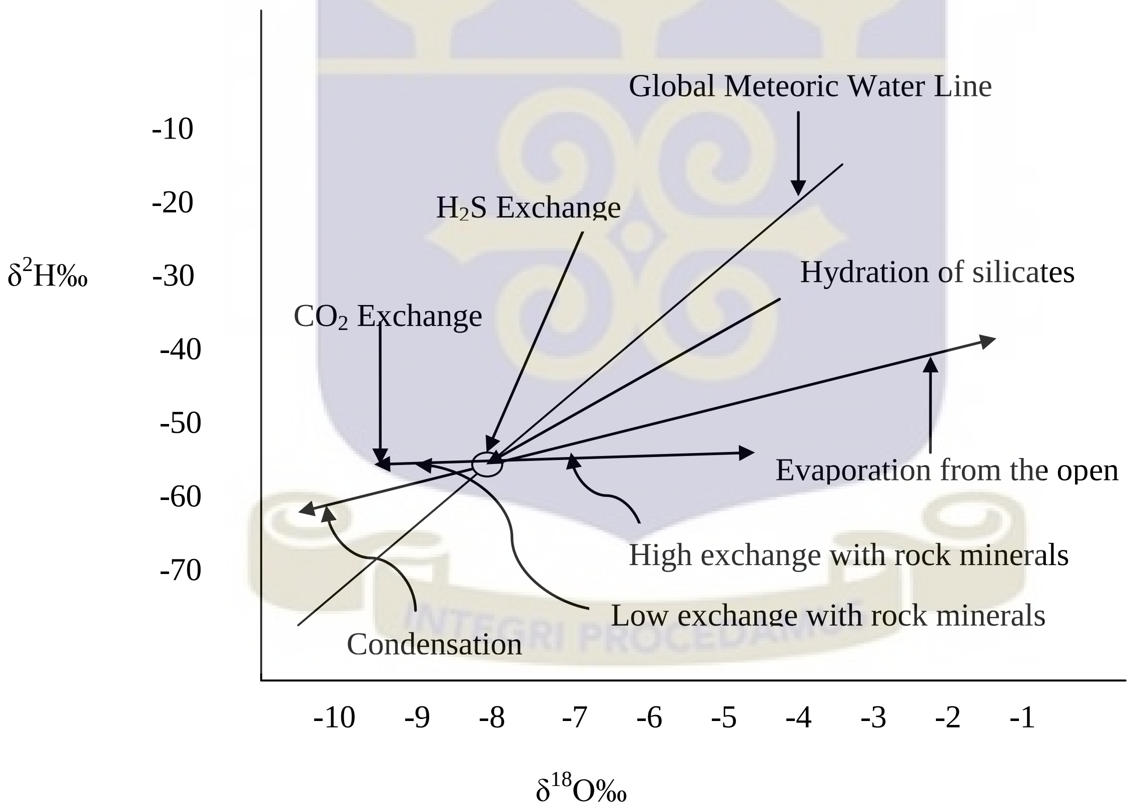


Figure 2-1: Processes causing modifications of initial stable isotope composition of groundwater.
(After IAEA, 1983)

In a study by Craig (1961), aimed at determining a suitable referenced line for the tracing and understanding of local groundwater origins and movements, water samples were collected from rivers, lakes and precipitation sources from several countries and analysed for their ^{2}H and ^{18}O contents. A plot of stable isotopes of $\delta^{2}H$ and $\delta^{18}O$ in water samples from these countries was published by Craig (1961).

The correlation between $\delta^{2}H$ and $\delta^{18}O$ resulted in a significant lining of the data along the best-fit line as defined in Equation 2-1 (Craig, 1961):

$$\delta^{2}H = 8\,\delta^{18}O + 10 \qquad \text{2-1}$$

This line, usually called the *Global Meteoric Water Line (GMWL)* has been found with some local variations, and is valid over several parts of the world (Craig, 1961). The *Global Meteoric Water Line* is thus, a suitable reference line for the understanding and tracing of local groundwater origins and movements (Craig, 1961). The study by Craig (1961) further showed that, in most nascent rainwater (i.e., prior to evaporation), the isotopic ratios of $\delta^{2}H$ and $\delta^{18}O$ vary with temperature controlled fractionation (i.e. water containing heavier isotopes evaporates and condenses at slightly different fractional rates due to mass differences). However, the inter-relationship between $\delta^{2}H$ and $\delta^{18}O$ in rainwater is practically independent of temperature across the globe and follows a simple linear formula. Thus, in every hydrochemical investigation; the *local meteoric water line* has to be established from samples of individual rain events or monthly means of precipitation. Examples of equations of *local meteoric water lines* reported from several parts of the world are presented in Table 2-1.

Thus, with reference to the "Global" meteoric line $\delta^{2}H = 8\,\delta^{18}O + 10$, derived from a plot of $\delta^{2}H$ ‰ vs. $\delta^{18}O$ ‰, precipitation values always lie on a line with slope 8. However, the mean intercept (deuterium excess) vary from one region to another (see Table 2-1) depending on the

Table 2-1: Examples of Regional Meteoric Water Lines

Region	**Meteoric Line (‰)**	**Reference**
"Global" Meteoric Water Line	$\delta^2H = 8\ \delta^{18}O + 10$	Craig (1961)
Northern Hemisphere Continental	$\delta^2H = (8.1 \pm 1)\ \delta^{18}O + (11\pm1)$	Dansgaard (1964)
Tropical Islands	$\delta^2H = (4.6 \pm 0.4)\ \delta^{18}O + (0.1\pm1.6)$	Dandgaard (1964)
Mediterranean or Middle East	$\delta^2H = 8\ \delta^{18}O + 22$	Gat (1971)
Maritime Alps (April, 1976)	$\delta^2H = (8.0 \pm 0.1)\ \delta^{18}O + (12.1\pm1.3)$	Bortolami *et. al*. (1978)
Maritime Alps (Oct, 1976)	$\delta^2H = (7.9 \pm 0.2)\ \delta^{18}O + (13.4\pm 2.6)$	Bortolami *et. al*. (1978)
Northern Chile	$\delta^2H = 7.9\ \delta^{18}O + 9.5$	Fritz *et al*. (1979)
North-eastern Brazil	$\delta^2H = 6.4\ \delta^{18}O + 5.5$	Salati *et. al*., (1980)
Accra Plains	$\delta^2H = 7.86\ \delta^{18}O + 13.61$	Akiti (1986)

(After Mazor, 2004)

origin and the conditions under which the water vapour is formed. Thus, any locality may have its own water (precipitation) line with a slope approximately equal to 8, but different deuterium excess. This water line is known as the *Local Meteoric Water Line* for that particular locality. Globally, however, precipitation appears to have the mean intercept or deuterium excess of 10.

Most groundwaters will plot close to the *Local Meteoric Water Line* (LMWL) provided; they are obtained from local rainfall unless they have been modified by any one of the processes shown in Figure 2-1. Evapotranspiration is likely to have minimal effect on the isotopic content of recharging waters, while, waters subjected to direct evaporation would normally plot on a slope of between 2 and 5 (Fontes, 1980).

As stated earlier, changes in groundwater quality in a region, district or basin is a function of physical and chemical parameters that are significantly influenced by geochemical formations and anthropogenic activities (Subramani *et al*, 2005). The chemical properties of groundwater also depend upon the water chemistry in the recharge zone in addition to the different geochemical processes that are occurring at the subsurface (Matthess, 1982). These geochemical processes are responsible for the seasonal and spatial variations in groundwater chemistry in the area (Matthess, 1982). In assessing the fate and impact of the chemical discharge onto the soil, it is crucial to understand the hydrogeochemistry of the soil-groundwater interactions (Miller, 1985). Usually, groundwater at the discharge zone is likely to have higher mineral concentration (TDS) relative to that at the recharge zone owing to the longer residence time and prolonged contact time with the aquifer matrix (Freeze and Cherry, 1979).

Using the concept of differences in mineral concentrations (TDS), hydrochemical data can be employed to classify waters into different groups of similar water quality characteristics on the basis of Q-mode statistical cluster analysis (El Kammar *et al.*, 2013). The aim is to determine the recharge and discharge zones, groundwater circulation and flow system as well as hydrochemical evolution within a region, district or basin (Freeze and Cherry, 1979). HCA is a multivariate statistical technique envisioned to classify hydrochemical data such that, the members of the resulting groups or subgroups are similar to each other and distinct from the other groups (Ayenew *et al.,* 2009). The characteristics of the groups or subgroups are not predetermined but are obtained after the classification (Ayenew *et al.*, 2009). The results obtained in HCA are validated in accordance with their values in interpreting the data and indicating accurate hydrochemical patterns representing field conditions (Ayenew *et al.*, 2009).

It is therefore, not the number of members of a group that ascertains the robustness of HCA (Ayenew *et al.*, 2009). It is also likely that several single member groups not belonging to any of the multi-member groups are categorized in separate groups (Ayenew *et al.*, 2009). This classification is useful particularly in understanding geological controls on water chemistry under conditions where, useful geochemical data exist, however, clear hydrogeologic models are non-existent (Ayenew *et al.*, 2009). The advantage of HCA is that several variables can be used to classify waters as well as provide a relatively simple but direct way of classifying samples and present results as a dendrogram (tree diagram), which becomes easy to interpret (Davis, 2002). Common tests for the statistical significance of differences between samples are not applicable to clusters because, the cluster algorithms ensure that clusters are significantly different (Everitt, 1993; Swan and Sandilands, 1995; Alberto *et al.*, 2001). The results obtained instead, are justified according to their value in interpreting the data and signifying patterns (Everitt, 1993; Swan and Sandilands, 1995; Alberto *et al.*, 2001). In order for the variables to have equal weight, the raw chemical data is log-transformed and standardized (Ayenew *et al.*, 2009). Log-transforming the chemical data restricts the influences of or the biases caused by the variables that have the greatest or the smallest variances or magnitudes on the clustering results (Ayenew *et al.*, 2009).

The ability of HCA to categorize hydrochemical data into coherent groups that may be distinguished in terms of aquifer type, subsurface residence time and degree of human impact on water chemistry offers a good opportunity to conduct hydrogeochemical modelling in order to understand groundwater geochemical evolution among the different groups or subgroups (Ayenew *et al.*, 2009). Various methods exist for computing similarities between samples or clusters (Helstrup *et al.*, 2007). The relative similarities between samples can be quantified using the Euclidean distance (Helstrup *et al.*, 2007). The Euclidean distance d_{xy} between any two points x and y in *p*-dimensional space is defined by Equation 2-2:

$$d_{xy} = [\sum_{j=1}^{p} (x_j - y_j)^2]^{½} \qquad 2\text{-}2$$

where, j defines each of the parameters.

Ward's method uses an analysis of variance approach to assess the distances between clusters, attempt to minimize the sum of squares of any two clusters that can be formed at each step as well as combine the clusters (Swan and Sandilands, 1995). The result is presented as a dendrogram (tree diagram) providing a visual summary of the clustering (Swan and Sandilands, 1995). This method is widely used in water chemistry investigations (Farnham *et al.*, 2000;

Kuells *et al.*, 2000; Alberto *et al.*, 2001; Gűler and Thyne, 2004). Statistical grouping of geochemical data by Q-mode Hierarchical Cluster Analysis (HCA) has been shown to provide a suitable basis for objective classification of water composition into hydrochemical facies (Meng and Maynard, 2001; Gűler *et al.*, 2002; Gűler and Thyne, 2003; Kebede *et al.*, 2005; Dassi, 2011; Barberá *et al.*, 2012; Bicalho *et al.*, 2012 and Acero *et al.*, 2013). Several plots such as Kurlov formula (1928), Piper (1944) trilinear diagram, Durov (1948), Stif (1951) Schoeller (1965) and radial plots have been used to illustrate hydrochemical facies of water (Hounslow, 1995). Piper trilinear diagrams are fundamentally a combination of cations and anions triangles lying on a common baseline with adjacent sides of the two triangles 60^{o} apart and a diamond-shape between the two triangles where, the overall characteristic of the water is represented by the projection of positions of the plots in the triangular fields (Piper, 1944). Different water types can be delineated depending on the positions they occupy on the diamond- shape.

Four main water types can be delineated in accordance with their positions near the corners of the diamond-shape (Figure 2-2).

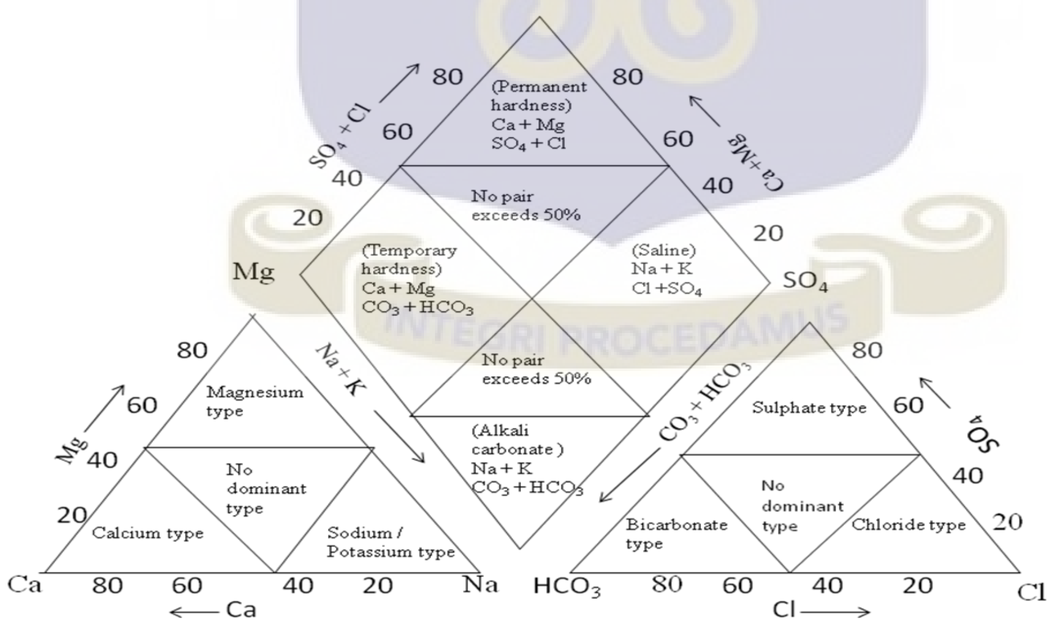


Figure 2-2 : Piper trillinear diagram showing theoretically the different water types in the diamond-shape.

[After Piper (1944); Kortatsi (2004)]

Factor analysis is a technique employed to reduce a large number of variables into fewer numbers of factors (Reghunath *et al*., 2002). The purpose of factor analysis is to interpret the structure within variance-covariance matrix of a multivariate data collection (Reghunath *et al*., 2002). Factor analysis presumes that observed variables are products of linear combinations of some few underlying source variables known as factors (Lawrence and Upchurch, 1982). It therefore, attempts to discover these factors which can be used to explain to a very large degree, the variance of the analytical data (Lawrence and Upchurch, 1982).

The application of these advanced statistical models in recent times in the geosciences has been diverse and ranges from the delineation of zones of natural recharge to groundwater in the Floridan aquifer (Lawrence and Upchurch, 1982), the delineation of areas prone to salinity hazard in Chitravati watershed of India (Briz-Kishore *et al*., 1992), characterization of groundwater contamination using factor analysis (Sabbarao *et al*., 1995), the resolution of simple geo-environmental problems to determine groundwater flow directions (Stetzenbach *et al.*, 2001; Farnham *et al*., 2003) and the determination of the physico-chemical parameters of water and sediment characteristics of Pondicherry mangroves (Satheeshkumar *et al*., 2011).

The application of multivariate statistical methods to geo-environmental datasets have enabled the exposure of hidden structures in datasets and contributed in resolving key geo-environmental problems at various scales (Sandow *et al*., 2012). Multivariate statistical approach allows hidden information in a dataset and the possible influences of the environment on water quality to be unearthed (Reghunath *et al*., 2002). Although, statistical associations cannot establish cause-and-effect relationships, they provide useful associations from which such relationships can be deduced (Sandow *et al.*, 2012). Other classical applications of multivariate statistical methods in the earth sciences are contained in Güler *et al*., (2002); Kim *et al*., (2005); Cluotier *et al*., (2008); Jiang *et al*., (2009); Dassi, (2011); Barberá *et al.*, (2012); Bicalho *et al.*,

(2012) and Acero *et al.*, (2013). In order to unearth the hidden processes responsible for high nitrate concentrations in groundwater, Jiang *et al*., (2009) applied multivariate methods to the major physico-chemical parameters in groundwater from Yunan, China and ascribed anthropogenic contributions to groundwater contamination in the area. In their study, the scientists combined factor analysis with geospatial methods to determine the spatial distribution of the major causes of variation in groundwater quality in the area.

The effectiveness of multivariate statistical methods in groundwater chemistry over the traditional piper and stiffs schemes is rooted in their ability to further reveal hidden inter-variable relationships and allows the use of virtually limitless numbers of variable, thus, trace elements and physical parameters forms part of the classification parameters (Dalton and Upchurch, 1978). Using raw data as variable inputs permits the avoidance of errors arising from close number systems (Dalton and Upchurch, 1978). In addition, because elements are treated as independent variables, the masking effect of chemically similar elements that are often grouped together is avoided (Dalton and Upchurch, 1978). Multivariate statistical analysis of geochemical data is based on the concept that each aquifer zone has its own distinct groundwater quality signature; based on the chemical constituents of the sediments it comprises (Fetter, 1994; Suk and Lee, 1999; Woocay and Walton, 2008).

Principal Component Analysis (PCA) has been used by several authors as indicated earlier in the literature review to identify patterns in chemical data set of high dimension and expressing the data in such a way as to highlight their similarities and differences and at the same time maintain those characteristics of the data set that contribute most to its variance (Güler *et al.*, 2008; Cluotier *et al.*, 2008; Jiang *et al.*, 2009 and Kim *et al.*, 2009). PCA does not require the normality of the data set and thus, can be used as an initial step to other techniques that require normality such as factor analysis (Kreamer *et al.*, 1996). The principal component analysis seeks to transform the observed variables to a new set of variables which are uncorrelated and arrange them in decreasing order of importance to simplify the problem.

PCA reduces the dimensionality of the data set by explaining the correlation amongst large number of variables in terms of a smaller number of underlying factors without losing much information (Vega *et al.*, 1998; Alberto *et al.*, 2001). PCA can be expressed mathematically as presented in Equation 2-3:

$$Z_{ij} = pc_{i1}x_{1j} + pc_{i2}x_{2j} + \ldots\ldots pc_{im}x_{mj} \qquad 2\text{-}3$$

where, *z* is the component score, *pc* is the component loading, *x* is the measured value of the variable, *i* is the component number, *j* is the sample number, and *m* is the total number of variables.

Water pollution, either caused by mining activities or natural geochemical processes such as the oxidation of pyrite and arsenopyrite in an aquifer, is a significant problem in several countries in the world (Tay *et al.*, 2006). Generally, the presence of trace metals in the environment is undesirable, especially if they occur in high concentrations. Trace metals are usually non-biodegradable and persistent in the environment. Trace metals can enter the body as part of food through the food chain, ingestion or by absorption via the skin (Annegarn and Scorgie, 2002).

Trace metals are the largest class of elements on the periodic table and are conventionally defined as elements with metallic properties and have higher atomic numbers with densities greater than 5.0 gcm^{-3} (Adriano, 2001; Thomson, 2005).

The term heavy metals refer generally to metals with specific weight greater than 4.0 gcm^{-3}. From environmental view point, principal metals are mercury, lead, cadmium and arsenic (Ondřej Šráček, 2004). Naturally, trace metals occur at levels that are not considered to have any toxic effects to plants, animals and humans (Alloway, 1995; Al-Chalabi and Hawker, 1996). However, the natural levels of trace metals are increased through various anthropogenic sources

(Alloway, 1995; Al-Chalabi and Hawker, 1996). These sources may include agriculture-fertilizers, animal manures and pesticides; metallurgy- mining, smelting and metal finishing; sewage sludge, scrap disposal and energy production- power plants, leaded and unleaded petrol (Adriano, 2001).

Protracted exposure to high levels of trace metals may be injurious or could cause serious illness or death (ATSDR, 1999). Several cases of human poisoning by trace metals have been reported (ATSDR, 1999). For instance, cadmium (Cd) and its compounds are extremely toxic at all levels and very likely to bio-accumulate in organisms and ecosystems (ATSDR, 1999); mercury-based toxins destroy the central nervous system and symptoms normally include sensory impairment (vision, hearing, speech), disturbed sensation and a deficient coordination (Watts, 2001); and lead poisoning causes learning disability and other neurological diseases (Watts, 2001).

CHAPTER THREE

3.0 THE STUDY AREA

The Lower Pra Basin is located between 05° 0'0"N and 06° 0'0"N and 01°0'0"W and 02° 0'0"W. The total population of the Central Region is two million two hundred and one thousand eight hundred and sixty three (2,201,863), while, in the Western Region it is two million three hundred and seventy six thousand and twenty one (2,376,021) (Statistical Service of Ghana, 2010). Thus, together, the two regions form 18.6 % of Ghana's total population (Statistical Service of Ghana, 2010). The Central and Western Regions are underlain by gently rolling terrain and mostly drained by rivers. The climate is tropical with a mean annual temperature of approximately 26.1° C and characterized by two rainy seasons (Dickson and Benneh, 2004). The map of the Lower Pra Basin showing the sampling communities is presented in Figure 3-1.

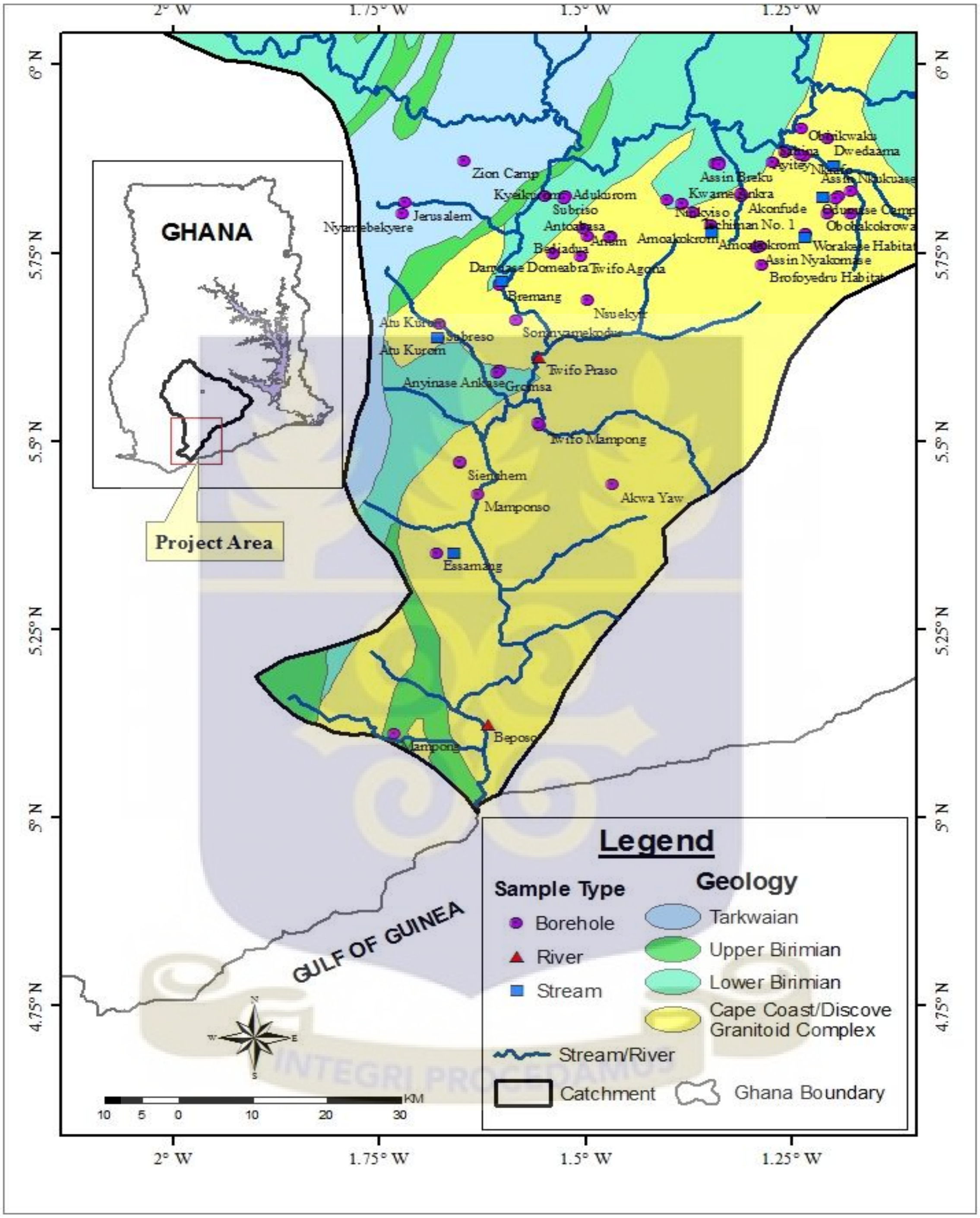
3.1Physical setting of the Lower Pra Basin

3.1.1 Climate

The climate of the Lower Pra Basin has similar characteristics as the wet semi-equatorial climatic zone of Ghana (Dickson and Benneh, 2004). The basin is influenced by the moist South-West monsoons during the rainy season (Dickson and Benneh, 2004). It is quite humid, with relative humidity of 60 – 95 % and annual rainfall in the range of 1500 – 2000 mm (Dickson and Benneh, 2004). The average minimum and maximum temperatures are 21°C and 32°C respectively, for the cooler periods from June to October (Dickson and Benneh, 2004).

3.1.2 Drainage

The Pra River, together with its tributaries, forms the largest river basin of the three principal south-western basins systems in Ghana (i.e. Ankobra, Tano and Pra).



(Modified after Geological Survey Department, 2009)

Figure 3-1 : Map of the study area showing the sampling communities.

The Lower Pra Basin drains about 22.0 % (15.0 % of Central Region and 7.0 % of Western Region) of the total Pra Basin area of approximately 23,200 km² (Water Resources Commission, 2012). The Pra River and its major tributaries–(Rivers Anum, Birim, Offin and Oda), originate from the eastern and north-western fringes and flows southwards (Water Resources Commission, 2012). The main Pra River takes its source from the highlands of Kwahu Plateau in the Eastern Region and flows for some 240 km before entering the Gulf of Guinea near Shama in the Western Region (Water Resources Commission, 2012).

The Pra Basin has an estimated mean annual discharge of 214 m^3s^{-1} (Dickson and Benneh, 2004).

3.1.3 Vegetation

The Pra Basin completely lies within the Forest Ecological Zone in Ghana (Dickson and Benneh, 2004). Its forest is characteristically moist semi-deciduous with valuable timber species (Dickson and Benneh, 2004). The original forest has changed to a secondary forest owing to the expansion of the cocoa industry, and consists of climbers, shrubs and soft woody plants (Dickson and Benneh, 2004). Many of the trees within the upper and middle layers show deciduous characteristics (Dickson and Benneh, 2004). The vegetation generally weakens out towards the coast (Dickson and Benneh, 2004).

3.1.4 Soil characteristics of the Lower Pra Basin

Primarily, the Lower Pra Basin is dominated by forest ochrosols (Dickson and Benneh, 2004).

The soil is similar in appearance to the forest oxysols, and develops over the same kind of highly weathered parent materials (Dickson and Benneh, 2004). They are however, different from the forest oxysols in several other ways under reduced rainfall amounts (Dickson and Benneh, 2004). The soils are also not as highly leached as the oxysols, and therefore, contain high quantities of nutrients and are generally alkaline (Dickson and Benneh, 2004). They support several tree crops including cocoa (Dickson and Benneh, 2004). Undeniably, all the cocoa in Ghana is grown in these soils (Dickson and Benneh, 2004).

Three other major soil groups exist within the basin, and their characteristics are either:

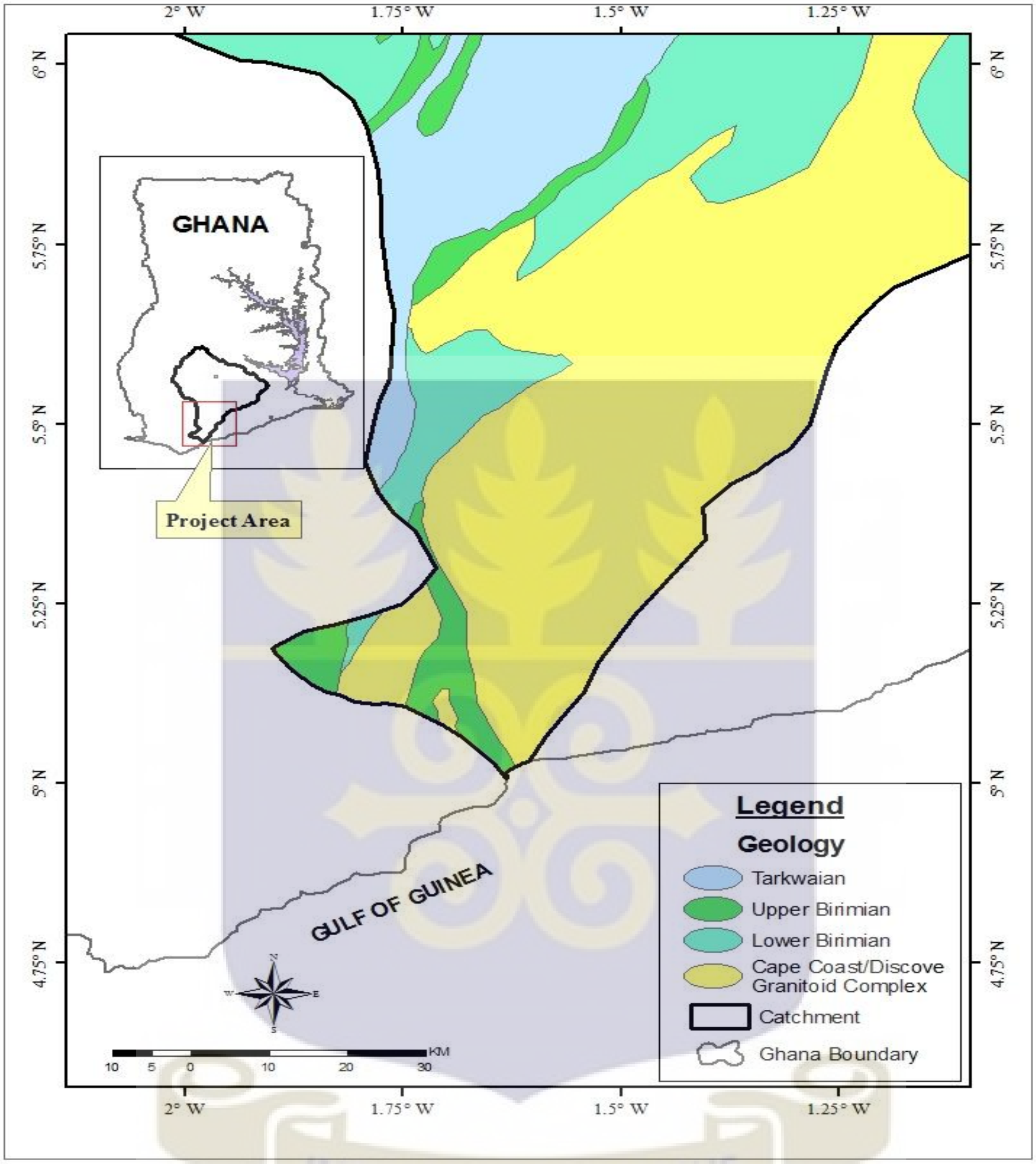
1. Closely related to those of the forest ochrosols,
2. Intermediary between those of the forest ochrosols and oxysols or,
3. Completely different.

The soils under category 1 are known as rubrisol-ochrosol intergrades-soils whose characteristics are intermediary between those of rubric- or dark red soils and ochrosols (Dickson and Benneh, 2004). The rubrisol-ochrosol intergrades soils cover very few and limited areas within the main forest ochrosol region (Dickson and Benneh, 2004).

The parent materials over which the soils develop are not as highly weathered as those for the ochrosols; nor are the soils so leached (Dickson and Benneh, 2004). The soils are therefore, alkaline in nature and are more richly supplied with nutrients (Dickson and Benneh, 2004). They are also more clayey and therefore, highly capable of retaining water for plant use (Dickson and Benneh, 2004). The soils within the basin are one of the best in Ghana for the cultivation of forest crops, (Dickson and Benneh, 2004).

3.2 Geology of the Lower Pra Basin

The Lower Pra Basin is underlain by two main granitoids namely; Cape Coast granitoids and Dixcove granitoids as well as the Birimian and Tarkwaian (Figure 3-2). Leube *et al.*, (1990) and Mauer (1990) introduced the terms “basin” and “belt” to denote Cape Coast granitoids and Dixcove granitoids respectively.



(Modified after Geological Survey Department, 2009)

Figure 3-2: Geological map showing the geology of the Lower Pra Basin

3.2.1 Granitoids

The granitoids found within the Lower Pra Basin are of two kinds, namely; the Cape Coast gronitoids and Dixcove granitoids (Junner 1940; Kesse, 1985). Using the degree of foliation, previous works had assumed that, Cape Coast granitoids intruded during regional deformation and Dixcove granitoids later (Junner, 1940; Kesse, 1985). Igneous crystallization ages of four granitoid plutons were investigated by means of U/Pb zircon and monazite dating (Hirdes *et al.*, 1992). Results showed that, both the basin and belt granitoids formed at about 2,175 Ma but the belt granitoids about 60 or 90 Ma earlier than the basin granitoids.

The belt pluton ages is consistent with a 2,166 ± 66 Ma Sm/Nd whole-rock-isochrone age of belt tholeiites (Taylor *et al.*, 1992), therefore, suggesting that, belt volcanic and belt granitoids are coeval and part of the same igneous event. An early pre-deformation emplacement of belt granitoids also revealed their absence in Tarkwaian sediments, in addition to extensive and intensive retrograde alteration and locally pronounced effects of shearing in these plutons (Hirdes *et al.*, 1992). The aluminous character shows overall I-type characteristics for both the belt and basin granitoids (Hirdes *et al.*, 1993).

3.2.1.1 Cape Coast granitoids

Cape Coast granitoids also known as Sedimentary basin granitoids usually occur as synorogenic foliated batholiths which are peraluminous and generally granodioritic in nature (Leube *et al.*, 1990). Their main Fe-Mg mineral is biotite and is usually accompanied by muscovite (Leube *et. al.*, (1990); Mauer (1990). Characteristic feature of the basin or Cape Coast granitoid is foliation (Kesse, 1985). Their characteristic mafic mineral is hornblende, and biotite (Kesse, 1985). Plagioclase is in the oligoclase-andesine range and usually sericitized to saussuritized (Kesse, 1985). Granitoid types include; tonalite, and trondhjemite, granodiorite, adamellite and granite (more frequent in the basins than the belts) [Leube *et al.*, (1990) and Mauer (1990)].

The bulk of the basin granitoids fall into the peraluminous domain and therefore are considered to have been derived mainly from anatexis of continental crust (Hirdes *et al.*, 1993). However, the isotopic data is not consistent with such a mode of formation; rather they seem to be juvenile additions to the crust, from upper mantle sources (Hirdes *et al.*, 1993). Their peraluminous character might reflect the involvement of a more felsic source, possibly a large-scale contamination of the ascending magma by first-cycle assimilated intermediate to acid volcaniclastic sediment or partial melting of such first-cycle material in high- strain zones at lower levels during crustal shortening (Hirdes *et al.*, 1993).

The average chemical composition of a typical basin granitic rock, despite the wide range of chemical composition include: SiO_2 (57-73 %), Al_2O_3 (14-21 %), Na_2O (4.10 %), K_2O (4.29 %), CaO (3.5 %), FeO (2.67 %) (Kesse, 1985). The most outstanding feature of the basin rock is high Al_2O_3 content, which classifies these granites in the peraluminous category (Kesse, 1985). It is important to note that, collectively, they are known to be enriched in such lithophile elements as Li, Be, Sn, and Tn; and also have relatively high alkaline content (Kesse, 1985). Another important feature is the presence, in some analysis, of high Na_2O which reaches 9.03 % (Kesse, 1985). Over 80 pegmatite bodies occur and are clearly related to the margin of the batholith from which they radiate for as far as 12 km, in the coastal areas, e.g. near Saltpond (Kesse, 1985). Their mineralogical composition usually includes; quartz, muscovite, biotite, microcline, albite, almandine, beryl, spessartite, tourmaline, columbite/tantalite and kaolin (Kesse, 1985). The pegmatites which are farthest from the granites are richer in the later stage minerals (Kesse, 1985).

3.2.1.2 Dixcove granitoids

Dixcove granitoids also known as Volcanic belt granitoids are hornblende-bearing, and most often form late-orogenic unfoliated intrusions with metaluminous character. Volcanic belt granitoids are generally tonalitic in nature (Leube *et al.*, 1990). They comprise relatively small, unfoliated bodies in belt volcanic (Leube *et al.*, 1990). Their characteristic mafic mineral is hornblende, accompanied by biotite (Leube *et al.*, 1990). Plagioclase is in the oligoclase-andesine range and usually sericitized or saussuritized (Leube *et al.*, 1990). Granitoid types include; quartz diorite (rarely found in the basins) tonalite, and trondhjemite, granodiorite and adamellite [Leube *et al.*, (1990) and Mauer (1990)].

According to Kesse (1995), a limited average chemical composition in a typical belt granitoid complex is; SiO_2 (63-71 %), Al_2O (14-17 %), Na_2O (4.43 %), K_2O (1.80 %), CaO (3.36 %), FeO (3.86 %). It is thus, evident that, the belt granitoid complex has slightly lower SiO_2 and Al_2O_3, but slightly higher FeO content than basin granitoid complex (Kesse, 1985). Another astonishing feature is the higher Na_2O/ K_2O ratio (Kesse, 1985). Unlike basin granitoids, the belt granitoids is free of lithophile elements such as Li, Be, Sn (Kesse, 1985).

Geochemical investigations by Hirdes *et al.*, (1993) revealed that, belt granitoids contain higher CaO, MgO, and Na_2O, V and Y but lower K_2O and Rb values than the basin granitoids (Hirdes *et al.*, 1993). The bulk of the belt granitoids fall into the metaluminous field and indicates a cafemic association derived mainly from the mantle (Hirdes *et al.*, 1993).

3.2.2 The Birimian Supergroup

The term "Birimian" was introduced by Kitson (1918) and was used to describe rocks from the River Birim valley in the Atewa-Kibi range in Ghana. The Birimian Supergroup forms an extensive part of the Man shield which occupies roughly the southern part of the West African craton (Hayford *et al.*, 2009). It is bounded to the north, east and south by Pan African belt (Hayford *et al.*, 2009). Principally, southern Ghana is covered by the paleoproterozoic Birimian Supergroup (Hayford *et al.*, 2012).

The prominent feature of the Birimian Supergroup is the existence of five parallel volcanic belts of several hundred kilometers in length (Hayford *et al.*, 2012). These comprise of metabasalt, metadolerite, metarhyolites, quartzites and greywacke (Hayford *et al.*, 2012). They are separated by compressional basins containing metasedimentary rocks made up of arenaceous and argillaceous subseries comprising of metasandstones, metagreywacke, phyllites and tufecious varieties and granitoids (Hayford *et al.*, 2012).

Junner (1935, 1940) established a Birimian stratigraphy in Ghana comprising: (1) a lower series comprising of slates, phyllites, greywackes, tuffs and minor lavas, together with schists and gneisses, and (2) an upper series comprising of greenstones, mainly metamorphosed basic and intermediate lavas and pyroclastic rocks with some hypabyssal igneous rocks and intercalated bands of phyllite and greywacke.

The Birimian rocks of paleoproterozoic age were affected by a major tectonothermal event, the Eburnean event of around 2.15 Ga (Hayford *et al.*, 2012). They strike generally NE, dip steeply to the SE and are isoclinically folded (Manu *et al.*, 2013). Leube *et al.*, (1990); Taylor *et al.*, (1992); Davis *et al.*, (1994) and Hirdes *et al.*, (1996) argued that, both lavas and sedimentary rocks were contemporaneous and therefore, were deposited concurrently.

3.2.2.1 Lower Birimian

The Lower Birimian which represents flyschoid facies accounts for 55 % of the area occupied by the entire Birimian Supergroup (Kesse, 1985). Primarily, the lowest parts of the Lower Birimian succession are phyllites and greywackes (Kesse, 1985). These change upwards to phyllites and weakly metamorphosed tuffs, greywackes and feldspathic sandstones, and the sequence appears to pass conformably into the Upper Birimian, although a local unconformity has been recorded in some places (Kesse, 1985). It is mainly pelitic in origin having muds and silts with beds of coarser sediments (Kesse, 1985). According to Bessoles (1977), the Lower Birimian is most often considered as a derivative of the Liberian-type rocks as found in the nucleus of the West African Craton.

The series is characterized by large thicknesses of isoclinically folded steeply dipping, alternating slates, phyllites, greywacks and argillaceous beds with some tuffs and lavas (Kesse, 1985). The slates and phyllites have generally been modified to quartz-biotite-schist, often with garnet and staurolitic-rich bands while the impure sandstones have changed to granulites and quartz schists (Kesse, 1985). Woodfield (1966), Moon and Mason (1971), have reported the evidence of a shallow water depositional environment for the Lower Birimian rocks.

3.2.2.2 Upper Birimian

The Upper Birimian unconformably overlies the Lower Birimian and occupies 20 % of the entire area of the Birimian Supergroup (Kese, 1985). The Upper Birimian comprise of large thicknesses of basaltic and andesitic lavas, beds of agglomerate, tuff and tuffaceous sediments (Kesse, 1985). Thus, the Upper Birimian is principally of volcanic origin consisting mainly of metamorphosed basaltic and andesitic lavas, now hornblende-actinolite-schists, calcareous chlorite-schists and amphibolites (Kesse, 1985).

According to Woodfield (1966), pillow structures indicating sub-aqueous eruption of the original basaltic lavas are frequently observed in the Upper Birimian of Ghana. The basic volcanics and pyroclastics have been greatly altered to chloritized and epidotised rocks which have been loosely grouped together as greenstones (Kesse, 1985). Where the greenstones have been subjected to dynamothermal metamorphism, they have been converted to hornblende schists and amphibolites (Kesse, 1985). According to Kesse (1985), the schists and amphibolites grade with the addition of feldspar, into hornblende gneisses. Kesse (1985) also reported that, impure arenaceous sediments, when recrystallized, resemble very fine-grained diorites, grade with increasing grain size into diorites.

The Upper Birimian Supergroup is believed to represent a late phase of eugeosynclinal deposition (Kesse, 1985). However, it is also possible that some of the acid volcanic subseries are correlated to island arc type volcanic vents in association with relatively shallow water sediments which include; quartzites, meta-conglomerates, graphitic schists and calcareous chlorite schists (Kesse, 1985).

3.2.3 The Tarkwaian

Whitelaw (1929) first described a sequence of coarse clastic sediments overlying the Birimian rocks in the Tarkwa area as "Tarkwaian", while, the stratigraphy of the Tarkwaian was defined by Hirst (1938) and Junner *et al.* (1942). According to Kesse (1985), the Tarkwaian rocks are concentrated largely at the southwestern part of Ghana in the Tarkwa area where, they outcrop in a northeast-southwest trending belt. This belt stretches from Axim near Agogo in the Ashanti Akim District for a distance of about 25 km and a width of about 16 km (Kesse, 1985).

According to Junner (1935); Woodfield (1966); Moon and Mason (1971), the Tarkwaian is considered to be of shallow water continental origin derived mainly from the Birimian and associated granitoids. It is generally believed that, the rocks of the Tarkwaian were deposited in elongated intracratonic rift basins which are bordered by granite-greenstone belts of the Birimian Supergroup (Kesse, 1985).

The Tarkwaian sediments are believed to have been deposited by high energy alluvial fans entering a steep sided basin filled with fresh water (Kesse, 1985). They consist of coarse, poorly sorted, immature sediments with low roundness, typical in part of a braided stream environment (Kesse, 1985). They comprise slightly metamorphosed shallow-water sediments, mainly sandstone, shale, and conglomerate, resting unconformably on and derived from the Birrimian (Kesse, 1985). They could have been deposited in separate elongate basins as molassic facies derived from erosion of the Birimian, during later stages of the Eburnian orogeny (Kesse, 1985).

Junner (1935); Junner *et al.*, (1942), postulated that, the Tarkwaian is believed to rest unconformably on the Birirmian, though in some places, the Upper Birimian and the Tarkwaian are interfolded due to post- Trakwaian orogenic activity. Woodfield (1966) also reported that, in some localities, no angular unconformity can be observed between the Birimian and the Tarkwaian.

The Tarkwaian series, an erosional product from the Birimian Supergroup consists of conglomerates, sandstones, arkose, quartzite, phyllites and shale with rocks from each group having a Sm-Nd isochron age of 2.17 ± 0.07 Ga (Nartey *et al.*, 2011). According to Hayford *et al.* (2012), the series consists of a sequence of coarse clastic sedimentary rocks consisting of conglomerates, sandstones, arkose, some subordinates of argillites and quartz veins.

The conglomerates comprise hornstone and silicified Birimian greenstone with minor jasper, quartzporphyry, quartz, tourmaline-quartz rocks with Birimian phyllites and schists in a matrix with quartz, magnetite, epidote, feldspar chlorite carbonate, gondite and chert (Kuma, 2004). The sandstone (a quartzite) consists of variable amounts of feldspar, sericite, chlorite, ferriferous carbonate, magnetite or hematite and epidote (Kuma, 2004). The Tarkwa phyllite comprise of magnetite of hematite and chloritoid with sericite and chlorite (Kuma, 2004).

3.3 Hydrogeological conditions of groundwater within the Lower Pra Basin

3.3.1 Groundwater occurrence

The granite and gneiss associated with the Birimian rocks are significantly important in the water economy of Ghana due to the fact that, they underlie extensive and usually well populated areas (Dappah and Gyau-Boakye, 2000). The granite and gneiss are not inherently permeable, but secondary permeability and porosity have developed owing to fracturing and weathering (Dappah and Gyau-Boakye, 2000).

The granite and gneiss commonly have been eroded down to low-lying areas, where precipitation is high and weathering processes penetrate deeply along fracture systems (Dappah and Gyau-Boakye, 2000). Conversely, where the precipitation is relatively low, the granite occurs in massive poorly jointed inselbergs which rise beyond the surrounding lowlands (Dappah and Gyau-Boakye, 2000). Weathered granite or gneiss in some areas, form permeable groundwater reservoirs (Dappah and Gyau-Boakye, 2000). Favourable locations for groundwater storage also include major fault zones (Dappah and Gyau-Boakye, 2000).

The Birimian phyllite, schist, slate, greywacke, tuff and lava are generally strongly foliated and fractured (Dappah and Gyau-Boakye, 2000). Considerable water may percolate through the fractures where, they crop out or are near the surface (Dappah and Gyau-Boakye, 2000). The Tarkwaian rocks consists of slightly metamorphosed, shallow-water, sedimentary strata, mainly sandstone, quartzite, shale, and conglomerate, resting unconformably on and derived from rocks of the Birimian Supergroup (Dappah and Gyau-Boakye, 2000).

3.3.2 Aquifer characteristics

Data available on boreholes (Table A-1) (Appendix A) in the Lower Pra Basin showed that, borehole yield is generally low and largely variable with range 0.4 - 51.7 m^3hr^{-1} and a mean value of 4.55 m^3hr^{-1}. Approximately, 86 % of the rock types identified in the Lower Pra Basin recorded significantly low yields varying 0.4 – 5.0 m^3hr^{-1} (Table A-1) (Appendix A).

Borehole depths range 22 – 96 m with a mean value of 44.42 m (CSIR-WRI, 2010). Although, no distinct pattern of borehole yield in correlation with borehole depth was delineated (Figure 3-3), comparatively, higher yields were obtained from aquifers formed in the schists and granite rock units than the other rock types identified within the Basin (Table A-1) (Appendix A). The granite and schist rocks are exposed whilst; the Birimian and Tarkwian rocks have thick overburdens (Dappah and Gyau-Boakye, 2000). The soils develop over the same kind of highly weathered parent material with lateritic to clayey top soil layer and thickness which ranged 4 – 14 m, however, the soil layer thickness may extend further in some areas (CSIR-WRI, 2010). Since groundwater occurrence is related to regolith/fissure development, it can be argued that the deeper the well, the thicker the overburden or regolith it penetrates and the higher the chances of intercepting several fissures in the sap rock underneath the regolith and therefore, the higher the probability of obtaining higher yields.

It is thus, reasonable to assume that the deeper the well, the higher the expected yield. In order to establish the veracity of this postulation, borehole yields were plotted against borehole depths (Figure 3-3). Figure 3-3 show no distinct pattern as for instance, a borehole as shallow as 48 m had a relatively high yield of 19.5 m^3hr-1, while, a borehole as deep as 96 m had a yield as low as 1.5 m^3hr-1. Thus, depth has little or no effect on the yield of the boreholes within the Lower Pra Basin. The Static Water Levels (SWL) in boreholes (at the time of drilling) ranged 0.4 - 22.4 m with a mean value of 6.37 m (CSIR-WRI, 2010).

From Table A-1 (Appendix A), the composition of rocks within the Lower Pra Basin is as follows: schist (35.7 %), gneiss (8.6 %), granite (8.6 %), granite-gneiss (8.6 %), granite-schist (8.6 %), granite-schist-contact (8.6 %), monzodiorite (11.4 %), phyllite-schist (7.1 %), quartzitic-schist (1.4 %) and diorite (1.4 %).

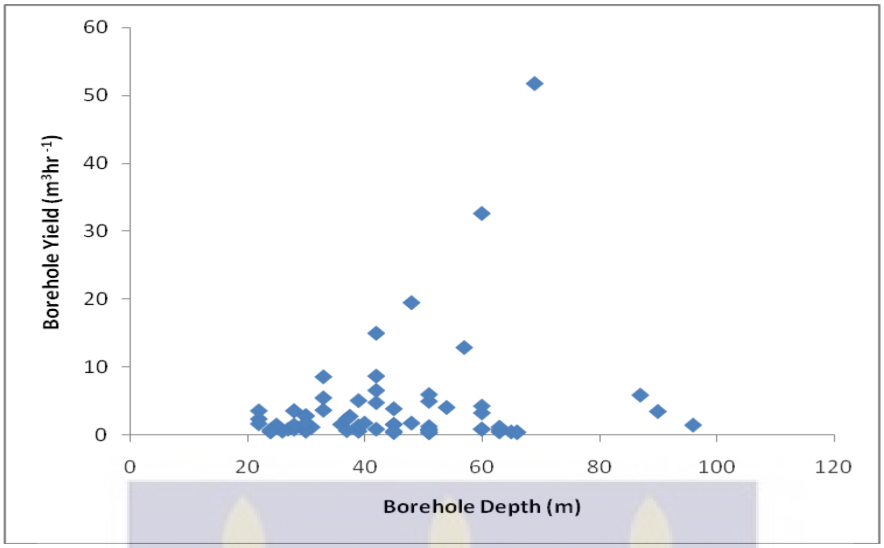


Figure 3-3 : Graph of borehole yield against borehole depth for groundwater collected from boreholes within the Lower Pra Basin.

3.4 Socio-economic activities within the Lower Pra Basin

Primarily, the population of the Lower Pra Basin is made up of farmers, who grow food crops such as plantain, banana, vegetables, oil palm (**Plate 3-1**), and fruits and cash crops such as cocoa (**Plate 3-2**) and coffee. The rural folks within the Lower Pra Basin are also engaged in palm oil extraction (**Plate 3-3**), cutting of trees for fuel wood and charcoal production for domestic uses, use of inorganic fertilizers in agricultural activities.

Land degradation as a result of improper farming practices, and timber extraction from the forest are some of the human induced activities that may cause pollution of the water resources within the basin. The activities of small-scale miners (see **Plate 1-6**) have also degraded the land and littering parts of the basin with trenches and water-filled excavations that has not been reclaimed. These water-filled excavations generally have turbid waters containing other chemical pollutants from gold extraction and diamond mining.

Plate 3-1 : Oil palm plantation at Praso (POPP) in the Western Region.

Plate 3-2: A cocoa farm in Techiman No 1, a farming community in the Central Region.

Plate 3-3: Palm oil extraction process using extraction equipment at Assin Nyankomase in the Central Region.

Mining activities (large and small-scale) in the study area could also result in acid mine drainage which can have serious deleterious impact on water resources and subsequently human health and the environment.

CHAPTER FOUR

4.0 RESEARCH APPROACH AND METHODOLOGY

4.1 Selection of boreholes

The selection of boreholes for this study was based on the concept that each aquifer zone (screen position) has its own unique groundwater quality signature, based upon the chemical make-up of the sediments that comprise it (Fetter, 1994; Suk and Lee, 1999; Woocay and Walton, 2008). Thus, hydrochemical analyses results for groundwater from a multi-screened borehole cannot be ascribed to a unique depth and specific aquifer.

Therefore, a list of boreholes with single-screened aquifer zone within 05^{o} 0'0"N and 06^{o} 0'0"N and 01^{o}0'0"W and 02^{o} 0'0"W which falls within the Lower Pra Basin was compiled from a database at the Groundwater Division of the CSIR-Water Research Institute. In all fifty four (54) boreholes within the basin were selected and investigated.

4.2 Sampling frequency

Reconnaissance sampling involving the selected boreholes and some surface water resources was carried out in March 2011. Subsequently, sampling was carried out once every three months (UNESCO/WHO/UNEP, 1996) for two years. In all, chemical data-base on 397 samples was generated in this study.

4.3 Selection of variables

The selection of chemical variables to be assessed in terms of water quality for this study was based on the objectives of the study, the mineral composition of the study area (Table 4-1), selection of variables for assessment of water quality in relation to non-industrial water use (Table 4-2), selection of variables for the assessment of water quality in relation to non-industrial pollution sources (Table 4-3) and selection of variables for the assessment of water quality in relation to major industrial source of pollution (Table 4-4) (UNESCO/WHO/UNEP, 1996).

Table 4-1: Rock/ Mineral composition of the Lower Pra Basin

Rock	Mineral	Chemical Formula/ Composition	Element of interest
	Quartz	SiO_2	-
	Albite	$NaAlSi_2O_8$	Al
	Anorthite	$CaAl_2Si_2O_8$	Al
	Chlorite	$(MgFe)_5Al(AlSi_3)O_{10}$	Fe, Al
	Ankerite	$Ca(Mg,Fe)(CO_3)_2$	Fe
	Biotite	$K(Mg, Fe)_3AlSi_3O_{10}(OH)_2$	Fe, Al
	Muscovite	$KAl_2(AlSi_3O_{10}(OH)_2$	Al
Granite		Quartz (SiO_2); Feldspar [($KAlSi_3O_8$), ($CaAlSi_2O_8$)]; Mica[$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ and $KAl_2(AlSi_3O_{10}(OH)_2$]; and Hornblende [$Ca_2(Mg, Fe, Al,)_5$ (Al, $Si)_8O_{22}(OH)_2$]	Fe, Al
Granodiorite		Similar to Granite but containing more Plagioclase than potassium feldspar	-
Pegmatite		Same as granite; composed of quartz, feldspar and mica; in essence granites.	-
Gneiss		Quartz (SiO_2); Feldspar [($KAl_2Si_3O_8$), ($CaAlSi_2O_8$)]; Mica[$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$ and $KAl_2(AlSi_3O_{10}(OH)_2$]; and Hornblende [$Ca_2(Mg, Fe, Al,)_5$ (Al, $Si)_8O_{22}(OH)_2$]	Al, Fe
Schist		Medium-grade metamorphic rocks (such as talk, hornblende, graphite, etc.)	-
	Actinolite	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	Fe
Garnet		Almandine [$Fe_3Al_2(SiO_4)_3$; Spessartine [$Mn_3Al_2(SiO_4)_3$]	Fe, Al, Mn

Table 4-2: Selection of variables for assessment of water quality in relation to non-industrial water use

		Agriculture	
	Drinking water sources	Irrigation	Livestock watering
General variables			
Turbidity/transparency	xx		
Conductivity	x	x	
Total dissolved solids	x	xxx	x
pH	x	x	
Total Hardness	xx		
Nutrients			
Ammonia	x		
Nitrate/nitrite	xxx		xx
Phosphorus/phosphate			
Major ions			
Sodium	x	xxx	
Calcium		x	x
Magnesium	x		
Chloride	x	xxx	
Sulphate	x		x
Other inorganic variables			
Fluoride	xx	x	x
Potassium			
Trace elements			
Heavy metals	xxx	x	x
Arsenic & Selenium	xx	x	x

x-xxx: Low to high likelihood that the concentration of the variable will be affected and the more important it is to include the variable in a monitoring programme. Variable stipulated in local guidelines or standards for a specific water use should be included when monitoring for that specific use. The selection of variables should only include those most appropriate to local conditions and it may be necessary to include other variables not indicated under the above headings.

(Modified after UNESCO/WHO/UNEP, 1996)

Table 4-3: Selection of variables for the assessment of water quality in relation to non-industrial pollution sources.

	Agricultural activities
General variables	
Temperature	x
Conductivity	xx
pH	x
Total Hardness	x
Nutrients	
Ammonia	xxx
Nitrate/nitrite	xxx
Phosphorus compounds	xxx
Major ions	
Sodium	xx
Calcium	x
Magnesium	x
Chloride	xx
Sulphate	x
Trace elements	
Copper	xx[1]
Mercury	xxx[1]
Zinc	xx[1]
Arsenic	xxx[1]
Selenium	xxx[1]
Organic contaminants	
Pesticides	xxx[2]

x-xxx: Low to high likelihood that the concentration of the variable will be affected and the more important it is to include the variable in a monitoring programme. The final selection of variables is also dependent on the nature of the water body.

[1] Need only be measured when used locally or occur naturally at high concentrations.
[2] Specific compounds should be measured according to their level of use in the region.

(Modified after UNESCO/WHO/UNEP, 1996)

Table 4-4: Selection of variables for the assessment of water quality in relation to major industrial source of pollution.

	Mining
General variables	
Temperature	x
Conductivity	xxx
pH	x
Eh	x
Total Hardness	x
Nutrients	
Ammonia	x
Nitrate/nitrite	x
Major ions	
Sodium	x
Calcium	x
Magnesium	x
Chloride	xxx
Sulphate	x
Other inorganic variables	
Silica	x
Fluoride	x
Potassium	x
Trace elements	
Heavy metals	xxx
Arsenic	x
Selenium	x

x-xxx: Low to high likelihood that the concentration of the variable will be affected and the more important it is to include the variable in a monitoring programme. The final selection of variables to be monitored depends on the product manufactured or processed together with any compounds present in local industrial effluents. Any standard or guidelines for specific variables should also be taken into consideration.

(Modified after UNESCO/WHO/UNEP, 1996)

4.4 Sample collection, preservation and analysis.

Ground and surface water sample collection and preservation for this study were, conducted based on the flow chart described in Figure 4-1, and the sampling protocols described by Classen (1982), and Barcelona *et al.*, (1985) were observed. Ground and surface water samples were collected using 4-1 acid-washed polypropylene bottles. The bottles were cleaned at the Environmental Chemistry Laboratories of the Council for Scientific and Industrial Research-Water Research Institute (CSIR-WRI) in Accra using detergent and allowing them to stand for a minimum of 24 hours. The cleaned bottles were then rinsed (three times) with distilled water. Samples for trace metals analyses were acidified to a pH < 2 using concentrated HNO_3.

Field measurement of temperature, pH and electrical conductivity were done using Hach Sens ion 156 Meter. The measurement of Eh was also done using Hach Sens ion 1 Meter. A separate sampling bottle was used for field measurements at each sampling station after rinsing three-times with distilled water, followed by the sample to be measured. The meter reading for each field parameter was only recorded after attaining stability in the meter reading. The tendency of collecting non- representative samples from the water sources was negligible in the case of boreholes due to the fact that, most of the boreholes were very well utilized. However, each borehole was pumped for some time (at least five minutes) before sampling was undertaken to avoid collection of non-representative samples.

In the case of streams and rivers, samples were taken from the lower, middle and upper portions at depths (approximately 0.2 m) below the surface. The temperature, pH, Eh and electrical conductivity for boreholes, streams and the Pra River were measured at the water source. All samples were stored on ice in an ice-chest. Samples for physico-chemical (including metals) analyses were transported to the CSIR -Water Research Institute laboratories in Accra, stored in a refrigerator at a temperature of < 4^oC and analyzed within one week.

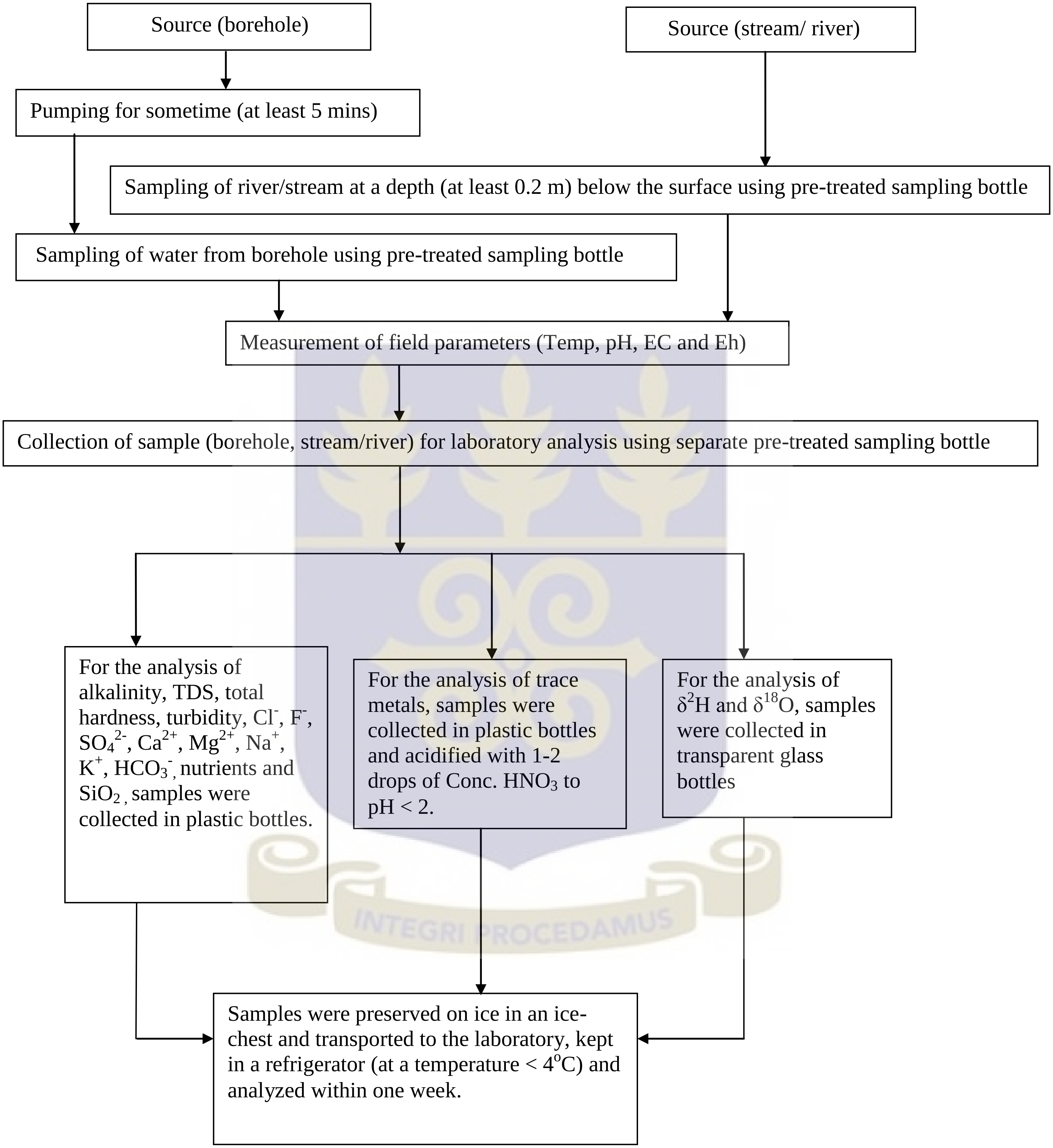


Figure 4-1: Flow chart for ground and surface water sample collection, showing the steps involved in sample collection, on-site measurement of field parameters and sample preservation and storage.

(After Gale and Robins, 1989)

Samples for stable isotopes were collected in pre-cleaned glass bottles and transported to the isotope laboratories of the Nuclear Chemistry and Environmental Research Centre of the Ghana Atomic Energy Commission in Accra, stored in a refrigerator at a temperature of < 4°C and analyzed within one week.

All major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, HCO_3^{-}), minor ions ($NO_3^{-}N$, PO_4-P and F^{-}) and silica (SiO_2) were carried out using appropriate certified and acceptable international procedures outlined in the Standard Methods for the Examination of Water and Wastewater (APHA, 2012); sodium (Na) was analysed by flame photometric method; calcium (Ca) by EDTA titration; Magnesium (Mg) by calculation after EDTA titration of calcium and total hardness; chloride (Cl^{-}) by argentometric titration; Nitrate-nitrogen was analysed by hydrazine reduction and spectrophotometric determination at 520 nm. Stable isotopes were analysed using IAEA Standard Operating Procedure for the Liquid Water Stable Isotope Analyzer (IAEA, 2009). Trace metal concentrations were determined using Agilent 240FS Atomic Absorption Spectrometer.

The methods of measurements of all the parameters considered in this study are presented in Appendix E.

4.5 Water quality parameters measured

The following parameters were measured in each collected sample: temperature, pH, Eh, conductivity, alkalinity, turbidity, total hardness, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, HCO_3^{-}, SO_4^{2-}, NO_2-N, NO_3-N, PO_4-P, Cu, Mn, Zn, Cd, Pb, Fe, Al, Se, As and Hg (Table 4-5). From Table 4-5, Column I comprises of the chemical constituents that are of health importance in drinking water, while, Column II comprises of the chemical constituents that even though, are not necessarily harmful to health, may result to consumer complaints (Kortatsi, 2004) and subsequent abandoning of the water source.

Table 4-5: List of water quality parameters measured in groundwater within the Lower Pra Basin

Parameter (water quality)	
I	**II**
Arsenic (As)	Aluminium (Al)
Cadmium (Cd)	Zinc (Zn)
Copper (Cu)	Iron (Fe)
Fluoride (F^-)	Calcium (Ca)
Lead (Pb)	Magnesium (Mg)
Manganese (Mn)	Sodium (Na)
Mercury (Hg)	Potassium (K)
Selenium (Se)	Chloride (Cl^-)
Nitrite-nitrogen (NO_2-N)	Sulphate (SO_4^{2-})
Nitrate-nitrogen (NO_3-N)	Bicarbonate (HCO_3^-)
Phosphate-phosphorous (PO_4-P)	Silica (SiO_2)

(Modified after Kortatsi, 2004)

4.6 Data validation

An ionic balance was computed for each analysed sample and used as a basis for checking analytical results. In accordance with international standards, results with ionic balance error greater than 5 % were rejected (Freeze and Cherry, 1997; Appelo and Postma, 1999). Charge balances were calculated using Equation 4-1:

$$CB = [(\sum z\ Mc - \sum z\ Ma) / (\sum z\ Mc + \sum z\ Ma)] * 100 \qquad 4\text{-}1$$

where, z is the ionic charge and M the molality, and the subscripts, a and c refer to anions and cations respectively.

4.7 Design of questionnaire and administration

Questionnaires on water resources availability, usage, health impact and associated problems were designed (see APPENDIX D) and administered within the study area. The questionnaire administration was carried out in November 2013. The questionnaires consisted of two parts. The first part focused on demographic information (age, gender, literacy, marital status and etc.) and the water resources availability, usage and associated problems on respondents and the second part collected information on water use and the associated health impacts.

The target population for the study consisted of mostly women (who were more involved in the usage of the boreholes) with a relatively lower percentage of men and children who patronize the water resources.

4.7.1 Sampling size

A sample size of three hundred (300) respondents within the study area was chosen. It was expected that, this sample size would provide data that is statistically representative considering that, the communities within the basin are largely homogeneous and opinions are not expected to vary significantly.

4.7.2 Sampling technique

The sampling technique used was the systematic random sampling method. The team upon entry into a community would either hold discussions with the opinion leaders on their mission after which, the team was allowed to select households at random and administer the questionnaire to the target groups or enter directly into randomly selected homes or engage them in conversations leading to the interviews. It was expected that this technique would provide data that statistically represents the population.

4.7.3 Questionnaire analyses.

In order to analyse the responses of the respondents, the Statistical Package for Social Sciences (SPSS) 16.0 for windows was employed. The statistical analyses used included the descriptive statistics (frequency and percentages) to present tables and charts on demographic data, information on water availability, usage, health impact and associated problems among the inhabitants within the basin.

4.8 Limitations of the study

Due to limited funding this PhD was restricted only to the Lower Pra Basin. The study should have covered the entire Pra Basin for a holistic and comprehensive approach towards sustainable management and development of groundwater within the Pra Basin. The study could not also determined the expected decrease in the concentration of Na^+, Mg^{2+} and Cl^- in surface and groundwater within the basin due to the contribution of sea aerosol spray by collecting samples from surface and groundwater resources within communities near the coast (shortest distance) to communities furthest (longest distance) from the coast.

Secondly, due to lack of adequate maintenance, some of the boreholes which were initially sampled in this study had to be abandoned at some point because they were out of order. Finally, abstraction of water from boreholes fitted with foot pumps was also problematic since most of them had to be doped with water at the wellhead if left unused for a couple of hours or days (see Plate 6-1).

CHAPTER FIVE

5.0 RESULTS AND DISCUSSION

5.1 Variation of borehole depth with selected physical parameters in groundwater within the Lower Pra Basin.

5.1.1 Variation of borehole depth with conductivity of groundwater within the Lower Pra Basin.

Results show that, a graph of borehole depth against conductivity (Figure 5-1) even though show no distinct pattern, to some extent, it reveals that conductivity decreases at higher borehole depths. According to Helstrup *et al.*, (2007), typically, the Total Dissolved Solids (TDS) of groundwater will increase with depth and prolong residence time due to chemical interactions with aquifer materials and possible mixing with older mineralized water along flow-paths.

Using the linear relationship between TDS and electrical conductivity (EC) which can be represented as in Equation 5-1:

$$KA = S \qquad 5\text{-}1$$

where, K is the conductivity (µS/cm), S is the TDS (mg/L) and A is a constant. The value of A defines whether a particular water type is high in bicarbonate, sulphate or chloride. Clark and Fritz (1997) documented that, A = 0.55 shows waters high in bicarbonate concentration, A = 0.75 shows waters high in sulphate concentration and A = 0.90 shows waters high in chloride concentration. Clearly, from Equation 5-1, for any groundwater resource, the conductivity (K) is directly proportional to the total dissolved solids (S).

Thus, from Helstrup *et al*., (2007), it could also be inferred that, typically, the conductivity of groundwater will increase with depth and prolong residence time due to chemical interactions with aquifer materials and possible mixing with older mineralized water along flow-paths.

Therefore, the low mineralized groundwater reflected by the decreased conductivity at higher borehole depths (Figure 5-1) is indicative of short residence time in the aquifer or contact with relatively insoluble silicate minerals or both at higher borehole depths.

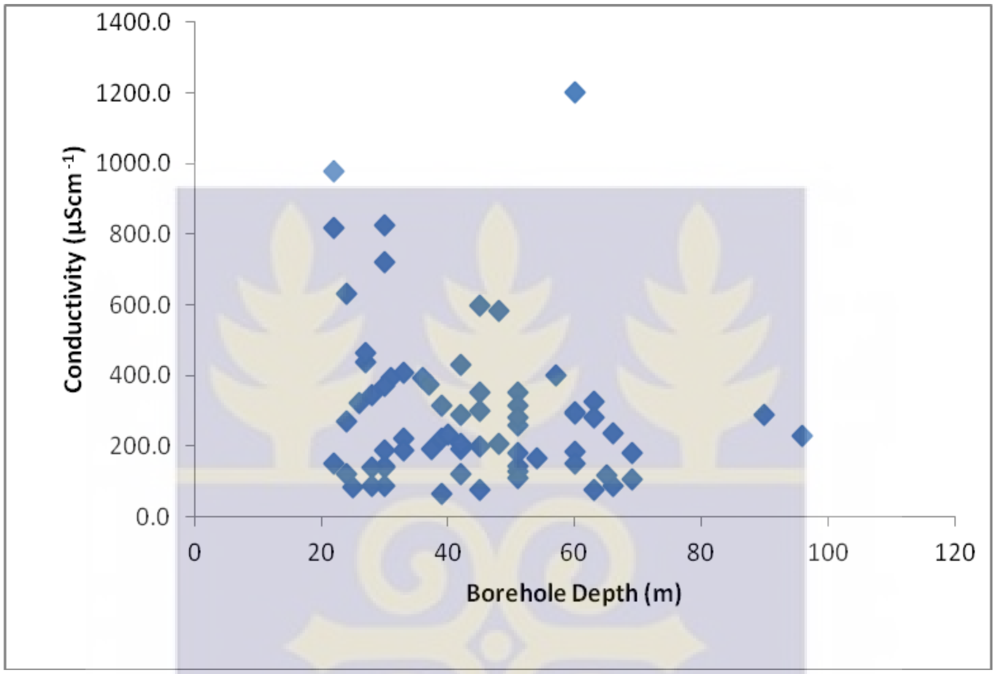


Figure 5-1: Graph of EC against borehole depth for groundwater collected from boreholes within the Lower Pra Basin.

5.1.2 Variation of borehole depth with pH of groundwater within the Lower Pra Basin.

The threat of acidification to groundwater resources within the Lower Pra Basin is illustrated in Figure 5-2. Figure 5-2 show that depth does not seem to have significant difference on groundwater acidification as the pH varies between 5 and 7 for both shallow and deep boreholes within the Lower Pra Basin.

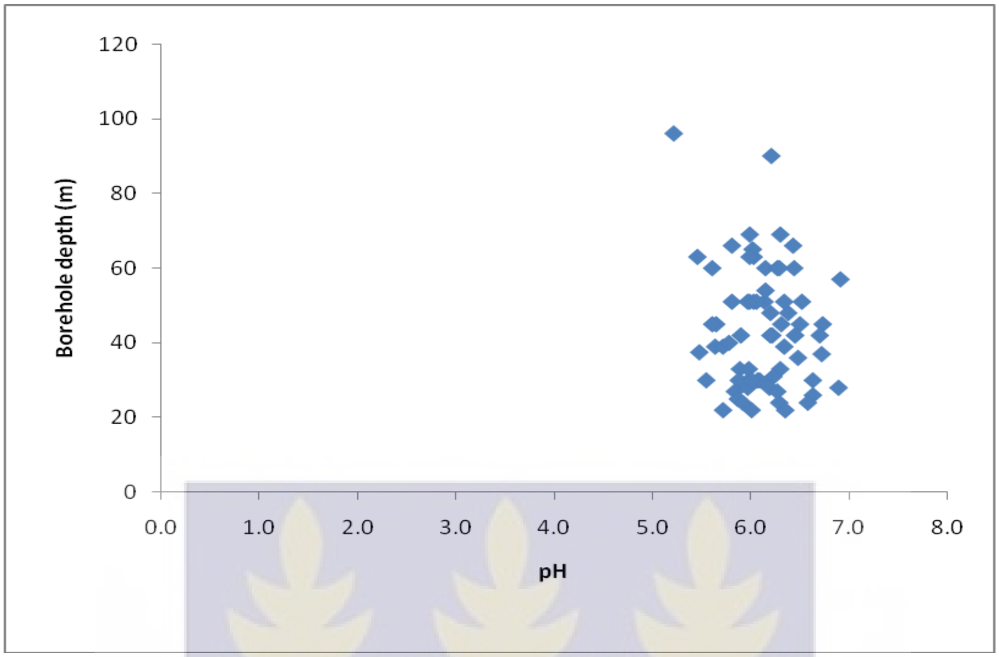


Figure 5-2: Graph of pH against borehole depth for groundwater collected from boreholes within the Lower Pra Basin.

5.2 Physico-chemical characteristics of groundwater within the Lower Pra Basin

Results of the hydrochemical data of groundwater collected within the basin between March 2011 and March 2013 are presented in Appendix B (Tables B-1 to B-8). The trace metal results are presented in Appendix C (Tables C-1 to C-5). The statistical summary of the hydrochemical data is presented in Table 5-1. The statistical summary of the hydrochemical data for the dry season (January- March) is presented in Table 5-2, whilst, the statistical summary of the hydrochemical data for the wet season (June-October) is presented in Table 5-3.

From Tables 5-2 and 5-3, the mean hydrochemical parameters for the wet season are relatively lower than those for the dry season. This was expected due principally to dilution of the hydrochemical parameters during the rainy season. The physical constituents of the groundwater resources are generally low to moderately high. However, some water sources recorded quality values outside the World Health Organization (2004) guideline values for drinking water.

Table 5-1: Summary statistics of hydrochemical data within the Lower Pra Basin (January 2011-October 2012).

Parameter	Min	Max	Mean	Stdev	Median	WHO (2004) Guideline Limit
Temp	25.3	31.8	27.7	1.2	26.3	
pH	3.5	7.3	5.8	0.6	5.9	6.5-8.5
Eh	23.7	185.1	101.9	38.9	104.9	
EC	54.2	1601.0	272.9	214.9	216.0	
TDS	30.0	691.0	153.1	118.9	129.0	1000
TotalHard	7.0	336.0	76.8	61.6	60.5	
Turbidity	0.7	326.0	15.8	34.2	2.6	
Alkalinity	0.0	294.0	68.9	53.2	53.0	
Ca^{2+}	1.6	161.0	21.0	20.6	15.8	200
Mg^{2+}	0.2	115.2	10.1	12.9	7.1	150
Na^{+}	5.3	236.0	30.2	26.9	25.0	200
K^{+}	0.5	69.5	9.3	11.4	5.4	30
HCO_3^{-}	0.0	358.7	96.3	60.8	80.5	
SO_4^{2-}	1.5	371.2	27.4	51.3	18.2	250
Cl^{-}	5.6	693.0	36.1	78.8	16.9	250
SiO_2	1.1	44.1	20.5	8.9	21.4	
NO_3-N	0.003	5.01	0.62	0.9	0.38	10
PO_4-P	0.01	11.2	0.61	1.2	0.34	
F^{-}	0.015	1.36	0.5	0.3	0.3	1.5

All parameters are measured in mg/L, except, Temperature (°C), Eh (mV), EC (µS/cm), pH (pH units).

Table 5-2: Summary statistics of hydrochemical data for dry season (January-March 2011/2012) within the Lower Pra Basin

Parameter	Min	Max	Mean	Stdev	Median	WHO (2004) Guideline Limit
Temp	20.6	27.5	24.2	0.96	27.9	
pH	3.5	7.3	5.9	0.5	5.6	6.5-8.5
EC	58.2	1201.0	283.8	204.0	223.0	
TDS	32.0	661.0	154.2	111.0	147.0	1000
TotalHard	7.2	336.0	80.6	62.1	60.0	
Turbidity	0.9	88.8	5.8	11.4	2.3	
Alkalinity	0.0	294.0	72.5	58.8	52.0	
Ca^{2+}	1.6	160.9	22.2	20.2	16.0	200
Mg^{2+}	1.0	114.2	10.5	12.0	7.4	150
Na^{+}	5.3	236.0	29.1	24.6	24.0	200
K^{+}	0.5	69.5	7.6	9.4	5.0	30
HCO_3^-	0.0	358.7	103.7	62.8	87.8	
SO_4^{2-}	1.6	371.2	34.2	38.8	23.8	250
Cl^-	5.6	692.1	36.2	69.9	7.5	250
SiO_2	1.1	44.1	20.6	8.9	21.4	
NO_3-N	0.003	4.4	0.62	0.83	0.34	10
PO_4-P	0.049	3.3	0.5	0.52	0.3	
F^-	0.12	0.2	0.2	0.05	0.19	1.5

All parameters are measured in mg/L, except, Temperature (°C), EC (µS/cm), pH (pH units).

Table 5-3: Summary statistics of hydrochemical data for wet season (June-October 2011/2012) within the Lower Pra Basin

Parameter	Min	Max	Mean	Stdev	Median	WHO (2004) Guideline Limit
Temp	24.2	31.6	27.6	1.13	27.6	
pH	3.5	7.0	5.8	0.5	5.9	6.5-8.5
EC	57.6	1221.2	280.1	206.1	211.0	
TDS	32.0	691.0	152.9	112.1	117.0	1000
TotalHard	7.0	336.0	76.2	57.8	60.0	
Turbidity	0.9	92.8	7.2	14.1	2.2	
Alkalinity	0.0	294.0	72.9	55.5	54.0	
Ca^{2+}	1.6	160.9	21.1	19.1	16.0	200
Mg^{2+}	1.0	115.2	9.9	27.7	6.9	150
Na^{+}	5.3	231.2	28.7	25.2	22.5	200
K^{+}	0.5	69.5	7.4	9.3	5.1	30
HCO_3^{-}	0.0	348.1	98.2	59.6	80.5	
SO_4^{2-}	1.5	373.5	31.6	39.2	19.7	250
Cl^{-}	5.6	691.3	36.2	72.4	16.9	250
SiO_2	1.1	36.7	19.5	9.2	19.7	
NO_3-N	0.003	4.5	0.6	0.8	0.35	10
PO_4-P	0.045	3.1	0.5	0.6	0.29	
F^{-}	0.015	0.19	0.2	0.04	0.17	1.5

All parameters are measured in mg/L, except, Temperature (^oC), EC (µS/cm), pH (pH units),

The generally high standard deviation in most of the chemical constituents reflected in both the TDS and EC reflects the spatial variability in ionic concentrations in groundwater within the basin. The large spatial differences in TDS values (Tables 5-1, 5-2 and 5-3) could be attributed to lithological variations in the weathering of granitic rocks (biotite and muscovite), schists rocks (biotite, hornblende, and actinolite) and local impact of anthropogenic activities within the basin.

5.2.1 Variations in Temperature

Groundwater temperatures in the basin ranged 25.3 - 31.8^{o}C, with a mean and standard deviation value of 27.7 ^{o}C ± 1.2 (Table 5-1). These values are within the natural background levels of 22.0 – 29.0 ^{o}C for waters in the tropics (Stumm and Morgan, 1981).

5.2.2 Variations in pH and Eh

Groundwater within the basin is mildly acidic to neutral, with range 3.5 - 7.3 pH units and a mean and standard deviation of 5.8 ± 0.6 pH units. The range of pH values within the Lower Pra Basin is between 4.5 and 8.5 for natural waters (Hounslow, 1995; Langmuir, 1997). However, the WHO (2004) guideline value of pH for drinking water is 6.5 - 8.5.

Based on the WHO (2004) guideline values for drinking water, 89.0 % of groundwater sources within the basin have pH values outside acceptable limits and therefore, not suitable for potable and drinking purposes. The mildly acidic characteristics coupled with the low sulphate concentration and low conductivity of most of the shallow groundwater suggests that, acidity results from the production of carbonic acid (H_2CO_3) from atmospheric carbon dioxide during rainfall or the solution of the soil-generated carbon dioxide and dissolved organic acids such as fulvic and humic acids (Langmuir, 1997).

The carbon dioxide in the atmosphere is part of the atmospheric gases that occur through natural processes while, the soil-zone carbon dioxide is produced as a result of root respiration (Langmuir, 1997). Rubrisol-ochrosol intergrade soil types are known to be alkaline and more richly supplied with nutrients and are not so leached (Dickson and Benneh, 2004). The Lower Pra Basin is principally dominated by this soil type (Dickson and Benneh, 2004). Evidence of the high nutrients content in soils within the basin is the brownish colouration of surface waters throughout the year (see Plates 1-3 and 1-4). Figure 5-2 shows that, depth does not seem to have significant difference on groundwater acidification as the pH varies between 5 and 7 for both shallow and deep boreholes within the basin. Eh of groundwater within the basin ranged 23.7 - 185.1 mV with a mean value of 101.9 mV (Table B-8) (Appendix B).

5.2.2.1 Groundwater Acidity in the Lower Pra Basin

Though, pH generally has no direct effect on consumers, it is one of the most significant operational water quality parameters, the optimum pH required is often in the range 6.5–9.5 (WHO, 2003). Low pH in water resources (acidic waters) are often recipes for the mobilization of toxic trace metals in water bodies especially areas where mining activities are prevalent as is the case of the Lower Pra Basin. Acidity in groundwater could be due to natural biogeochemical or anthropogenic processes (Knutsson, 1994). According to Knutsson (1994), natural acidification is evident in areas with weathering-resistant soils and rocks, where, the climate is humid and the predominating water movement in addition to the transport of chemical components is downward, resulting in run off of base cations. This has been widely accepted and cited by previous authors (e.g. Kortatsi, 2004; Ondřej Šráček, 2004).

According to Dickson and Benneh (2004), the Lower Pra Basin has similar soils, rocks and climate characteristics and therefore, Knutsson (1994) postulate applies. Von Brömssen, (1989) and Caritat (1995) used the non-marine total hardness-alkalinity plot to assess the acidification status of ground and surface waters and this has been accepted and subsequently cited by various authors (Kortatsi, 2004 and 2007). Figure 5-3 depicts the relationship between total hardness and alkalinity of groundwater within the Lower Pra Basin.

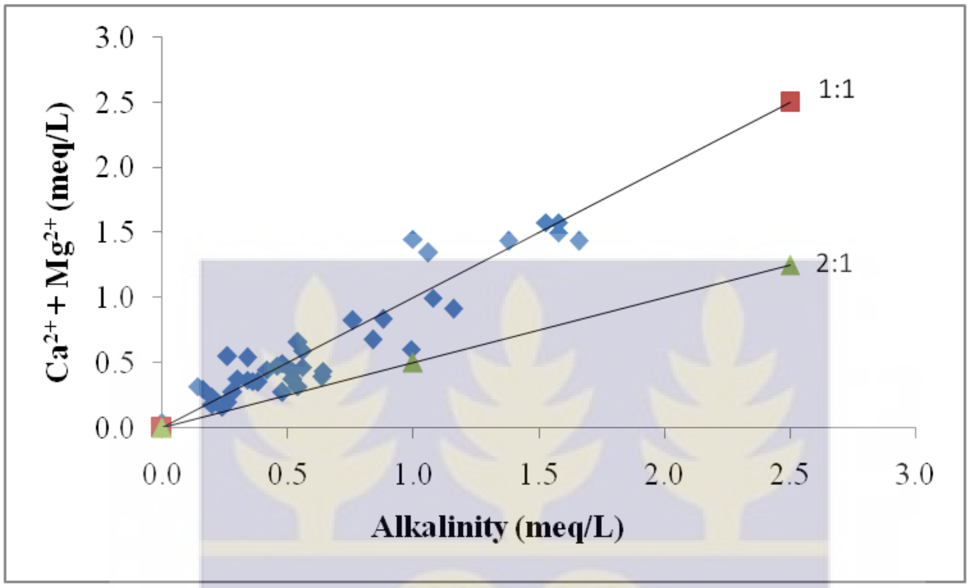


Figure 5-3: Relationship between total hardness and alkalinity (as $CaCO_3$) for groundwater within the Lower Pra Basin.

The total hardness values are assumed to be non-marine due to the nature of chloride, which is conservative and exclusively originates from marine sources, is considered to be very low in concentration (Von Brömssen, 1989; Caritat, 1995). Table 5-4 presents the calculated net acid potential for groundwater within the basin.

The plot of alkalinity against total hardness (Figure 5-3) shows that, majority of the groundwaters plot close to the 1:1 line suggesting that acidification is predominantly due to natural biogeochemical processes (i.e. CO_2 generation in the soil zone via root respiration and decay of organic matter) as evidenced within the Lower Pra Basin by the brownish colour of surface waters sampled throughout the year (see Plates 1-3 and 1-4). Some of the groundwaters also plot along or close to the 2:1 line perhaps, resulting from sulphide (pyrite and/or arsenopyrite) oxidation enhanced by mining activities within the basin.

Groundwater acidification (Aci) can also be defined as loss of alkalinity and calculated using Equation 5-2:

$$Aci = 0.93\,(Ca^{2+} + Mg^{2+}) - 14 - Alk + Al \qquad 5\text{-}2$$

where, all concentrations are expressed in meq/L (Henriksen and Kirkhusmo, 1986; Caritat *et al*., 1998). According to Stumm (1992); Caritat (1998), the Acid Neutralizing Capacity (ANC) of groundwater within the basin can be calculated using Equation 5-3:

$$ANC = (Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}) - (SO_4^{2-} + Cl^{-} + NO_3^{-}) \qquad 5\text{-}3$$

where, all concentrations are expressed in meq/L (Stumm, 1992; Caritat, 1998).

Table 5-4 presents the calculated ANC, Net Acid Neutralizing Capacity (NANC), which is the difference between the ANC and the Aci (i.e. ANC - Aci). The relationships between ANC, NANC and Aci are presented in Figure 5-4. Results from the study show that, the groundwaters are low in acid neutralizing capacity with ANC ranging from -0.43 to 3.72 meq/L and a mean value of 1.31 meq/L, suggesting buffering agents other than carbonates.

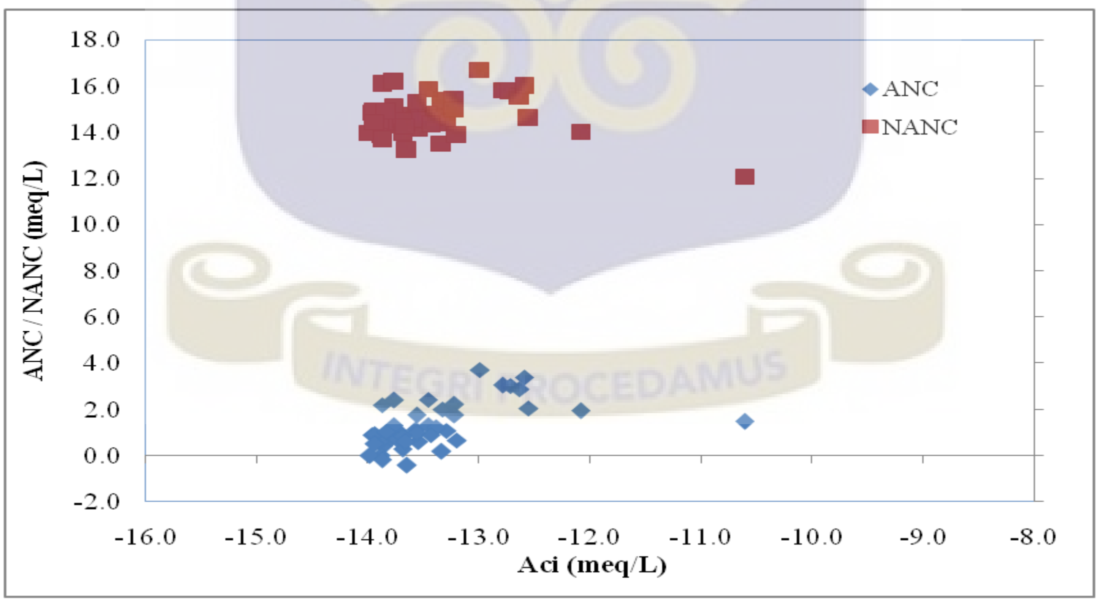


Figure 5-4: Relationship between ANC, NANC and Aci for groundwater within the Lower Pra Basin.

Similarly, the Aci of the groundwaters is also very low ranging from -13.9 to -10.6 meq/L, with a

Table 5-4: Calculated net acid potential for groundwater within the Lower Pra Basin.

Sample Source	BHID	ALK	Ca^{2+}	Mg^{2+}	Ca*+Mg*	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	NO_3-N	Al	Aci	ANC	NANC
Assin Nyakomase		0.340	0.399	0.683	1.082	0.805	0.161	0.671	1.189	0.002	0.001	-13.33	0.186	13.518
Assin Nyakomase		0.160	0.200	0.403	0.603	1.109	0.243	0.420	0.408	0.014	0.027	-13.57	1.113	14.685
Assin Nyakomase		0.140	0.080	0.559	0.639	0.465	0.082	0.195	0.364	0.023	0.001	-13.54	0.604	14.148
Brofoyedru Habitat	101 BU3	0.480	0.439	0.115	0.554	0.726	0.202	0.223	0.358	0.009	0.001	-13.96	0.893	14.856
Akonfudi		1.059	1.158	1.538	2.696	0.465	0.082	0.615	0.567	0.002	0.001	-12.55	2.059	14.610
Akonfudi		0.999	1.402	1.497	2.900	0.726	0.202	0.897	0.988	0.003	0.218	-12.08	1.940	14.025
Assin Breku		0.540	0.788	0.527	1.315	0.987	0.074	0.505	0.792	0.002	0.029	-13.29	1.078	14.366
Assin Breku (Gyidi)		1.579	1.921	1.078	2.999	1.066	0.115	0.251	0.889	0.001	0.001	-12.79	3.038	15.827
Assin Breku (SDA)		0.520	0.719	0.156	0.875	0.592	0.084	0.544	0.081	0.006	0.011	-13.70	0.920	14.615
Techiman No. 1		0.200	0.160	0.206	0.365	0.405	0.087	0.169	0.260	0.007		-13.86	0.420	14.281
Kwame Ankra		0.380	0.599	0.115	0.714	0.779	0.128	0.392	0.196	0.053		-13.72	0.979	14.695
Ninkyiso		0.636	0.509	0.280	0.789	1.244	0.125	0.925	0.495	0.001	0.117	-13.79	0.737	14.523
Sabina		0.879	1.118	0.559	1.677	1.044	0.141	0.449	0.395	0.004		-13.32	2.014	15.334
Ayitey		0.560	0.798	0.395	1.193	0.753	0.166	0.618	0.198	0.009		-13.45	1.287	14.737
Nkrafo	096 BU3	1.659	1.961	0.913	2.874	1.327	0.161	0.561	0.076	0.001		-12.99	3.723	16.709
Obirikwaku	099 BU3	1.079	1.522	0.477	1.999	0.800	0.125	0.307	0.385	0.003		-13.22	2.229	15.449
Odumase Camp	405 BU3	0.200	0.399	0.082	0.481	0.683	0.084	0.307	0.256	0.002	0.023	-13.73	0.683	14.412
Obobakrokrowa		1.379	2.320	0.551	2.872	0.839	0.077	0.618	0.134	0.003		-12.71	3.034	15.742
Obobakrokrowa	246 J BU1	0.340	0.358	0.380	0.739	0.796	0.087	1.176	0.876	0.001	0.010	-13.64	-0.432	13.211
Odumase Camp	407 BU2	0.640	0.599	0.280	0.879	1.462	0.084	0.420	0.715	0.003	0.053	-13.77	1.286	15.055
Dwedaama		1.579	2.041	1.119	3.160	0.979	0.184	1.323	0.105	0.001	0.007	-12.63	2.894	15.527
Dwedaama		1.529	2.041	1.119	3.160	0.979	0.184	0.195	0.730	0.001	0.000	-12.59	3.397	15.988
WoraKesse Habitat		0.260	0.160	0.239	0.398	0.626	0.164	0.420	0.151	0.030		-13.89	0.588	14.477
Antoabasa		0.480	0.519	0.477	0.996	1.044	0.120	0.533	0.652	0.011		-13.55	0.965	14.518
Antoabasa		0.460	0.559	0.395	0.954	1.479	0.130	0.897	0.446	0.009	0.189	-13.38	1.212	14.596
Anum	083 BU3	1.159	1.198	0.633	1.831	1.283	0.153	0.618	0.225	0.002		-13.46	2.423	15.879
Kyeikurom	090 BU3	0.540	0.439	0.197	0.637	0.861	0.074	0.279	0.337	0.003	0.015	-13.93	0.952	14.885
Adukurom	088 BU3	0.420	0.439	0.457	0.896	0.666	0.090	0.477	0.275	0.007	0.156	-13.43	0.892	14.323
Nsuekyir	219 BU1	0.991	0.319	0.889	1.207	1.509	0.153	0.392	0.275	0.001		-13.87	2.202	16.071

Sample Source	BHID	ALK	Ca^{2+}	Mg^{2+}	Ca*+Mg*	Na^{+}	K^{+}	Cl^{-}	SO_4^{2-}	NO_3-N	Al	Aci	ANC	NANC
Danyiase Domeabra	092 BU3	0.839	0.918	0.436	1.354	0.779	0.113	0.307	0.184	0.001	0.021	-13.56	1.753	15.311
Anyinase Ankase	030 BU3	0.380	0.399	0.321	0.720	0.465	0.043	0.169	0.198	0.005	0.033	-13.68	0.856	14.533
Gromsa	032 BU3	0.560	0.667	0.271	0.938	0.600	0.061	0.843	0.485	0.007		-13.69	0.265	13.952
Twifo Agona	263 BU2	0.760	0.838	0.814	1.653	0.657	0.197	0.279	0.460	0.002		-13.22	1.765	14.988
Nyamebekyere	339 BU3	0.520	0.479	0.263	0.742	0.787	0.130	0.533	0.076	0.009		-13.83	1.042	14.871
Jerusalem	0502B1/6/097-01	0.240	0.120	0.206	0.325	0.400	0.136	0.195	0.158	0.006		-13.94	0.503	14.440
Mampong	22/D/73-1	0.660	2.121	2.238	4.359	2.762	0.225	4.313	1.518	0.048		-10.61	1.467	12.073
Mamponso	24/B/85-1	0.260	0.778	0.321	1.099	0.574	0.064	0.307	0.691	0.071	0.041	-13.20	0.668	13.864
Sienchem	24/B/32-1	0.360	0.602	0.119	0.440	2.784	0.373	3.165	0.852	0.055	0.079	-13.87	-0.194	13.678
Sienchem	24/B/32-2	0.300	0.639	0.115	0.689	0.748	0.389	0.643	0.633	0.026		-13.66	0.589	14.248

All parameters are in meq/L, Ca*- non-marine calcium, Mg*- non-marine magnesium, Alk - alkalinity, Aci – acidification, ANC – acid neutralization capacity, NANC – net acid neutralizing capacity.

mean value of -13.3 meq/L. Clearly, from Figure 5-4 and Table 5-4, it is evident that, although the ANC is low it remains positive for the majority of groundwaters, while, Aci remains negative. The NANC is thus, positive for all (100 %) groundwaters, ranging from 12.07 to 16.71 meq/L, and a mean value of 14.68 meq/L. This suggests that, notwithstanding the moderately low pH (97.1 % of boreholes with pH between 3.5 and 6.5 pH units), the groundwaters still have the potential to neutralize acids. Nilsen and Grammeltvedt (1993) postulated that, calcite and dolomite minerals are the two most productive minerals responsible for the bulk alkalinity for the neutralization of acidity generated as a result of mining. Smedley *et al.,* (1995), also postulated that, the Lower Pra Basin is free of carbonate minerals. Consistent with Smedley *et al.,* (1995), the saturation indices as calculated for calcite and dolomite using phreeqc for windows (see Table 5-10) show that, groundwater within the basin is subsaturated ($SI < 1$) with respect to these minerals, suggesting that groundwater within the basin is coming from environments where, these minerals are depleted and therefore, cannot be responsible for the bulk alkalinity for the neutralization of acidity generated as a result of mining.

According to Appelo and Postma (1999), silicate weathering is the most important buffer mechanism against acidification of soil and groundwater in sediments free of carbonate minerals. Ondřej Šráček (2004) also postulated that, the dissolution of silicates/aluminosilicates has a significant impact on acidification. Thus, the presence of silicates/aluminosilicates found within the basin may be responsible for the acid neutralizing potential of groundwater within the basin.

5.2.2.2 Surface water acidification within the Lower Pra Basin.

Table 5-5 presents a summary of the physico-chemical parameters of some investigated surface waters within the basin. Table 5-5 shows that generally, major ion concentrations in surface waters are relatively lower than in groundwater within the basin. According to

UNESCO/WHO/UNEP (1996), since groundwater often occurs in association with geologic materials containing soluble minerals, higher concentrations of dissolved salts are normally expected in groundwaters relative to surface waters. Surface water results from this study are thus, consistent with UNESCO/WHO/UNEP (1996). Table 5-5 shows that the pHs of the surface waters are mildly acidic with values which ranged 5.4 - 6.9 pH units with a mean value of 6.0 pH units. Sulphate ion concentrations in surface waters ranged 10.5 - 24.6 mg/L, with a mean value of 16.7 mg/L. Sulphate ion concentrations in surface waters are thus, relatively lower than the sulphate ion concentrations (1.52 - 371.2 mg/L, with mean value of 40.3 mg/L) in groundwaters within the basin. Generally, trace metal levels in the surface waters are relatively lower than the levels in the groundwaters within the Lower Pra Basin. Table 5-5 also show that, calcium ion concentrations in the surface waters ranged 4.4 - 7.6 mg/L, with a mean value of 6.1 mg/L. The sulphate ion and calcium ion concentrations in the surface waters are too low to support gypsum and anhydrite dissolution to produce SO_4^{2-}. Additionally, there is no petrographic evidence to support the presence of gypsum and anhydrite in the rock matrix within the basin.

Table 5-6 presents a summary of the trace metal concentrations within the basin. Table 5-6 show that, Cu ranged 0.01 – 0.033 mg/L, with a mean and standard deviation value of 0.0.03 ±0.001 mg/L. Mn ranged 0.028 – 0.0.54 mg/L, with a mean and standard deviation value of 0.193 ±0.0.16 mg/L. Cd ranged 0.001 – 0.006 mg/L, with a mean and standard deviation value of 0.0.003 ±0.05 mg/L. Zn ranged 0.002 – 0.144 mg/L, with a mean and standard deviation value of 0.045 ±0.05 mg/L. Al ranged 0.001 – 0.066 mg/L, with a mean and standard deviation value of 0.017 ±0.02 mg/L. Pb ranged 0.003 – 0.034 mg/L, with a mean and standard deviation value of 0.02 ±0.01 mg/L. Hg ranged 0.003 – 0.06 mg/L, with a mean and standard deviation value of 0.023 ±0.02 mg/L. As ranged 0.0 – 0.006 mg/L, with a mean and standard deviation value of 0.004 ±0.002 mg/L. Se ranged 0.0 – 0.052 mg/L, with a mean and standard deviation value of 0.014 ±0.02 mg/L.

Table 5-5: Summary of the chemical characteristics of surface waters within the Lower Pra Basin

Sample source	Sample ID	Longitude	Latitude	T	pH	EC	TDS	ALK	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	$NO_3.N$	$PO_4.P$	SO_4^{2-}	E.Bal	CBE(%)
Odumase Camp	Esuodom	5.82422	-1.19105	26.0	6.02	80.1	43.0	37	19.6	6.6	2.0	14.2	4.7	9.9	45.6	0.148	0.491	15.8	-0.13	-4.87
Amoakokrom	Bupa	5.78629	-1.34669	25.7	5.65	60.3	34.8	37.0	22.2	6.7	2.4	12.8	4.2	7.9	45.1	0.096	0.368	14.8	-0.08	-3.07
Assin Nkukuase	Fumsuo	5.86473	-1.19748	27.7	6.09	90.2	57.8	45.4	31.0	7.6	3.9	14.9	6.0	9.9	55.4	0.132	0.393	21.5	-0.14	-4.31
WoraKesse Habitat	Frodor	5.76964	-1.23320	24.5	5.35	80.4	38.0	37.6	18.2	4.4	3.7	12.9	3.7	7.9	45.9	0.082	0.101	12.3	-0.05	-2.19
Twifo Praso (Bridge)	River Pra	5.61055	-1.55632	28.3	6.44	100.7	56.1	41.0	34.4	6.3	5.1	13.0	7.7	9.9	50.0	0.482	0.202	24.6	-0.12	-3.93
Bremang	Apakamba	5.71210	-1.60150	27.3	6.07	70.5	42.7	36.0	25.0	6.4	3.2	12.0	3.9	7.9	43.9	0.123	0.668	17.0	-0.09	-3.75
Atu Kurom	Osini	5.63660	-1.67900	25.0	5.59	70.4	41.4	33.2	36.4	5.3	5.6	10.9	3.4	9.9	40.5	0.214	0.563	10.5	0.92	4.94
Essamang	Esuosham	5.35059	-1.67924	25.0	5.93	60.8	34.8	35.0	25.4	6.0	2.5	12.1	1.6	6.0	42.7	0.161	0.383	10.5	-0.02	-0.83
Beposo (Bridge)	River Pra	5.12278	-1.61845	27.5	6.91	90.9	52.6	37.8	41.4	5.9	6.5	13.5	6.8	8.9	46.1	0.463	0.161	21.2	0.13	4.43

All parameters are in mg/l, except, pH (pH units), EC (μS/cm), Temperature (^{o}C), Longitude (N), Latitude (W)

Table 5-6: Summary of the trace metal concentration in surface waters within the Lower Pra Basin

Sample source	Sample ID	Longitude	Latitude	**Fe**	**Cu**	**Mn**	**Cd**	**Zn**	**Al**	**Pb**	**Hg**	**As**	**Se**
Odumase Camp	Esuodom	5.82422	-1.19105	0.460	<0.02	0.028	<0.002	<0.004	0.001	<0.005	0.019	<0.001	0.052
Amoakokrom	Bupa	5.78629	-1.34669	0.221	<0.02	0.524	<0.002	0.017	0.004	<0.005	0.026	<0.001	0.019
Assin Nkukuase	Fumsuo	5.86473	-1.19748	0.326	<0.02	0.066	0.003	0.022	0.013	<0.005	0.0027	0.0004	<0.005
WoraKesse Habitat	Frodor	5.76964	-1.23320	0.408	<0.02	0.075	<0.002	0.015	0.005	<0.005	<0.010	0.0004	0.001
Twifo Praso (Bridge)	River Pra	5.61055	-1.55632	0.305	<0.02	0.096	0.006	0.021	0.005	0.010	0.060	0.0029	0.000
Bremang	Apakamba	5.71210	-1.60150	0.749	0.033	0.245	0.003	0.005	0.009	<0.005	0.016	0.0003	0.000
Atu Kurom	Osini	5.63660	-1.67900	0.329	0.031	0.253	0.002	0.144	0.066	0.034	0.0120	0.0068	0.000
Essamang	Esuosham	5.35059	-1.67924	0.512	0.033	0.089	0.004	0.04	0.005	0.014	0.049	0.0008	0.000

All parameters are in mg/l. Longitude (N), Latitude (W)

From Table 5-6, Fe ranged 0.221 – 0.749 mg/L, with a mean and standard deviation value of 0.428 ± 0.16 mg/L. Table 5-7 presents the Fe^{2+}/SO_4^{2-} molar ratios for the surface waters within the basin. From Table 5-7, the iron to sulphate (Fe^{2+}/SO_4^{2-}) molar ratios for the surface waters within the basin ranged 0.003 - 0.084, with a mean value and standard deviation of 0.044 (±0.003). However, the iron to sulphate (Fe^{2+}/SO_4^{2-}) molar ratios for the stoichiometry of pyrite and arsenopyrite are 0.5 and 1.0 respectively. This suggests that, pyrite and arsenopyrite oxidation cannot be responsible for SO_4^{2-} concentration in the surface waters within the basin. This is supported by the very low SO_4^{2-} concentrations in the surface waters.

Table 5-7: Fe^{2+}/SO_4^{2-} ratios for surface water within the Lower Pra Basin.

Sample source	Sample ID	Fe^{2+}(mg/L)	Fe^{2+}(mmol/L))	SO_4^{2-} (mg/L)	SO_4^{2-} (mmol/L)	Fe^{2+}/SO_4^{2-}
Odumase Camp	Esuodom	0.460	0.008	15.8	0.16	0.05
Amoakokrom	Bupa	0.221	0.004	14.8	0.15	0.03
Assin Nkukuase	Fumsuo	0.326	0.006	21.5	0.22	0.03
WoraKesse Habitat	Frodor	0.408	0.007	12.3	0.13	0.06
Twifo Praso (Bridge)	River Pra	0.305	0.005	24.6	0.26	0.02
Bremang	Apakamba	0.749	0.013	17.0	0.18	0.07
Atu Kurom	Osini	0.329	0.006	10.5	0.11	0.05
Essamang	Esuosham	0.512	0.009	10.5	0.11	0.08
Beposo (Bridge)	River Pra	0.032	0.001	21.2	0.22	0.00

According to Smedley *et al.*, (1995) arsenic occurs in high concentrations in association with manganese and iron ores especially sulphide minerals and particularly, pyrites. The low Fe^{2+}/SO_4^{2-} ratio of the surface waters within the basin is perhaps, the result of iron co-precipitating with other trace metals particularly arsenic as iron-oxyhydroxides. Other sources of sulphate in the surface waters may include chemical products such as ammonium sulphate fertilizers which may be introduced into the surface waters through farming. Additionally, aluminium ion concentrations in surface waters within the basin ranged, 0.001 – 0.066 mg/L, with a mean and standard deviation value of 0.018 (± 0.02) mg/L. This suggests that, the acid neutralization capacity of the surface waters is characteristically similar to the groundwaters owing to the low pH.

Thus, additional acid neutralization capacity of the surface waters may be derived from the dissolution of clay minerals particularly, kaolinite which is the most stable secondary aluminosilicate mineral phase for the groundwater system (see Figures 5-14 and 5-16).

5.2.2.3 Acid mine drainage (AMD) in groundwater within the basin

Acid mine drainage (AMD) is a natural process that becomes faster and intensified through mining activities (Brick, 1998). When rocks are exposed to weathering, they release minerals as they attain equilibrium with their environments (Brick, 1998). When in contact with water, any dissolved metal leached from the rock and hydrolyzes to produce acid (Brick, 1998). However, the principal metal associated with acid mine drainage is iron (Brick, 1998). Mixed with sulphate and/or sulphide, iron can pose real problems (Brick, 1998). Pyrite, which is an iron sulphide found in both coal and metal mines has the ability to produce more acid than any other mineral (Brick, 1998). Sulphides especially iron sulphides such as pyrites (FeS_2), arsenopyrite (FeAsS) and chalcopyrite ($CuFeS_2$), when exposed, reacts with water and oxygen to produce sulphuric acid (H_2SO_4) resulting primarily in the production of acid mine drainage (Banks *et al.*, 1997).

Acid mine drainage generation is however, not limited only to iron sulphides, but other metallic sulphides as well (Banks *et al.*, 1997). Table 5-8 presents the major minerals generally associated with the production of acid mine drainage. The term acid water is used for waters with zero carbonate alkalinity ($pH < 4.5$) and with free ions of strong acid such as H_2SO_4 (Banks *et al.*, 1997). In some cases, pH is even lower than 2.0 (Banks *et al.*, 1997).

Primary sources of acid waters are mining residuals and the mechanism responsible for generation of acidity is the oxidation of sulphides like pyrite, FeS_2 (Banks *et al.*, 1997). In the absence of mining, acid waters are not common because the oxygen supply is insufficient to oxidize enough pyrite and to produce acidity higher than alkalinity of groundwater (Banks *et al.*, 1997). Water usually contains less than 10 mg/L (0.33 mmol/L) of dissolved oxygen (Banks *et al.*, 1997). The situation however, varies significantly when mining residuals with high concentration of pyrite are discarded (Banks *et al.*, 1997).

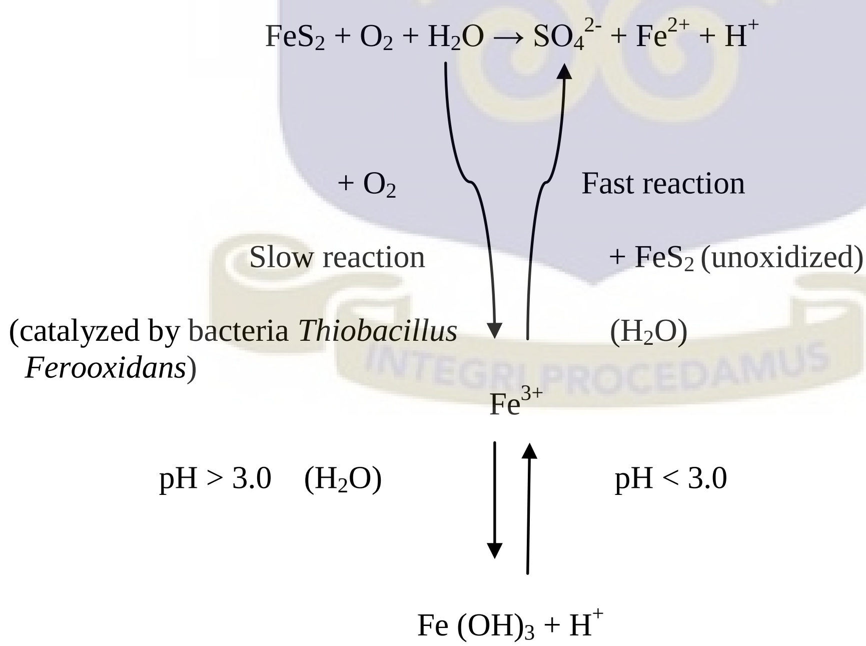
Table 5-8: Major minerals associated with acid mine drainage (AMD) and those that occur within the Lower Pra Basin

Mineral	Composition
Arsenopyrite	*FeS_27FeAs*
Bornite	$CuFeS_4$
Chalcocite	Cu_2S
Chalcopyrite	$CuFeS_2$
Covellite	CuS
Galena	PbS
Millerite	NiS
Mobybdenite	MoS_2
Pyrite	*FeS_2*
Pyrrhhdite	$Fe_{11}S_{12}$
Sphalerite	ZnS

Italic- minerals that occur within the Lower Pra Basin

(Modified after Gray, 1997)

The conceptual model of pyrite oxidation is as presented below:



(Modified after Stumm and Morgan, 1981)

To start with, pyrite is oxidized by oxygen in the presence of water and ferrous iron to produce;

Fe^{2+}, SO_4^{2-} and H^+ ions as in Equation 5-4:

$$FeS_2 + {}^7/_2O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad 5\text{-}4$$

Ferrous iron is then oxidized to ferric iron (Fe^{3+}) as in Equation 5-5 in a relatively slow reaction which can be catalyzed by bacteria *Thiobacillus Ferooxidans*:

$$Fe^{2+} + {}^1/_4O_2 + H^+ = Fe^{3+} + {}^1/_2H_2O \quad 5\text{-}5$$

Reaction Equation 5-5, is the primary rate-determining step of acid drainage formation (Stumm and Morgan, 1981). Further development depends on the pH of water (Stumm and Morgan, 1981). If pH is higher than 3.0 (as is the case of the Lower Pra Basin with 97.1 % of boreholes having pH between 3.5 and 6.5 pH units), then there is precipitation of ferric hydroxide [$Fe(OH)_3$] as described in Equation 5-6 (Stumm and Morgan, 1981):

$$Fe^{3+} + 3H_2O = Fe\,(OH)_3 + 3H^+ \quad 5\text{-}6$$

This suggests that, possible acid mine drainage reactions in groundwater within the basin produces principally Fe $(OH)_3$ which is perhaps a secondary source of iron in groundwater within the basin.

Conversely, if pH is less than 3.0 and Fe^{3+} is in contact with unoxidized pyrite, then, Fe^{3+} is consumed by pyrite oxidation because Fe^{3+} is a strong oxidant as presented in Equation 5-7 (Stumm and Morgan, 1981):

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad 5\text{-}7$$

This suggests that oxygen is only necessary to start the oxidation of pyrite and to recycle Fe^{2+} to Fe^{3+} (Stumm and Morgan, 1981). However, if an accumulation of mining residuals contains high quantities of dissolved Fe^{3+} from the previous oxidation period, then the oxidation of pyrite will continue for a long time even when, there is no more oxygen supply (Stumm and Morgan, 1981). When both oxidation of ferrous iron and precipitation of ferric hydroxide take place, the coupled reaction is as described in Equation 5-8 (Stumm and Morgan, 1981):

$$Fe^{2+} + {}^1/_4O_2 + {}^5/_2H_2O = Fe\,(OH)_3 + 2H^+ \quad 5\text{-}8$$

This suggests that there is generation of acidity in surface water bodies by the oxidation of Fe^{2+} and precipitation of ferric hydroxide even when discharging groundwater originally has a neutral pH value (Stumm and Morgan, 1981). However, majority (97.1%) of groundwater within the basin had pH greater than 3. This suggests that Equations 5-6 and 5-7 are unlikely. This is consistent with the pH of the surface waters within the basin as the surface waters are only mildly acidic with values which ranged 5.4 - 6.9 pH units and a mean value of 6.0 pH units. Thus, possible acid mine drainage reactions within the basin do not seem to have significant influence on the pH of surface waters within the Lower Pra Basin.

The oxidation of arsenopyrite by oxygen undergoes similar reactions (Stumm and Morgan, 1981). The overall reaction equation can be presented as in Equation 5-9 (Stumm and Morgan, 1981):

$$4FeAsS + 13O_2 + 6H_2O = 4Fe^{2+} + 4AsO_4^{3-} + 4SO_4^{2-} + 12H^+ \qquad 5\text{-}9$$

Thus, in areas where, acid mine drainage processes are possibly taking place in groundwater within the Lower Pra Basin, the processes are primarily the result of the oxidation of pyrite and/or arsenopyrite by oxygen through proton production to produce principally, $Fe(OH)_3$.

5.3 Variations in Electrical Conductivity (EC) and Total Dissolved Solids (TDS)

Electrical conductivity (EC) of the groundwaters is varied, with range 54.2 - 1601 µS/cm and a mean (standard deviation) value of 272.9 (± 214.9) µS/cm. Based on the conductivity results, 89.9 % of the waters are fresh (< 500 µS/cm). Low mineralized groundwater, reflected by low EC (~150 µS/cm), is an indication of short residence time in the aquifer and/or contact with relatively insoluble minerals (Hounslow, 1995). A plot of conductivity against borehole depth (See Figure 3-4) even though showed no distinct pattern, reveals that conductivity decreases at higher borehole depths, suggesting short residence time in the aquifer or contact with relatively insoluble silicate minerals or both at higher borehole depths.

Total dissolved solids (TDS) of the groundwaters are low, with range 30 - 691 mg/L, and a mean (standard deviation) value of 153.1 (± 118.9) mg/L. Results show that, 98.0 % of groundwater within the Lower Pra Basin is fresh with TDS values < 500 mg/L, suggesting silicate weathering process as partly responsible for the weathering processes taking place within the aquifers with which the waters are in contact (Hounslow, 1995).

5.4 Variations in Total Hardness

Hardness of water is a property attributable to the presence of alkaline earth metals (Ashwani *et al.*, 2014). Groundwater within the basin is generally soft and falls within the WHO (2004) recommended limit of 500 mg/L. Hardness values ranged 7.0 – 336.0 mg/L with a mean (standard deviation) value of 76.8 (± 61.6) mg/L (Table 5-1). Sawyer and McCarty (1967); Todd (1980), classified water hardness into four categories as soft, moderately hard, hard and very hard. Table 5-9 presents the different classifications of water hardness. Of the three hundred and eighty eight (388) groundwater samples collected and analysed 62.6 % are soft, 28.4 % are moderately hard, 6.2 % are hard and 2.8 % are very hard. Hardness of water is a property attributable to the presence of alkaline earths ($Ca^{2+}$and Mg^{2+}) in a water body. Based on the classification by Sawyer and MaCarty (1967); Todd (1980), 90.7 % of the groundwater within the basin can be said to be potable for drinking and domestic uses. The consequences of water hardness are the prevention of lather formation with soap and the increase in the boiling point of water. Water hardness may also cause precipitation of calcium carbonate and encrustation on water supply distribution systems (Ashwani *et al.*, 2014).

Table 5-9: Classification of groundwater based on hardness values.

Hardness (mgL^{-1}as $CaCO_3$)	Water classification	Number of groundwater	Percentage (%)
0 – 75	Soft	243	62.6
75 – 150	Moderately hard	110	28.4
150 – 300	Hard	24	6.2
> 300	Very hard	11	2.8
Total		**388**	**100.0**

[After Sawyer and MaCarty (1967); Todd (1980)]

5.5 Variations in Turbidity

Turbidity is one of the main physical parameters for water quality monitoring and defines the presence of suspended solids in water and therefore, causes the muddy or turbid appearance of a water body (Hounslow, 1995). The consumption of high turbid water may cause a health risk as excessive turbidity can protect pathogenic microorganisms from effects of disinfectants and stimulate the growth of bacteria during storage (Hounslow, 1995). Groundwater turbidity within the basin is generally varied (low to highly turbid), with range 0.65 – 326 NTU and a mean and standard deviation of 15.8 NTU and ± 34.2 respectively (Table 5-1). The WHO (2004) guideline value of turbidity for drinking water is 5 NTU. Based on WHO (2004), 30.7 % of groundwater within the basin is turbid.

5.6 Variations in Alkalinity

Alkalinity of a solution is defined as the ability of the solution to react with strong acid (Hounslow, 1995). According to Hounslow (1995), in most natural waters, alkalinity is produced by dissolved carbon dioxide species, bicarbonate and carbonate. Groundwater alkalinity within the basin ranged 0.0 - 294.0 mg/L (as $CaCO_3$) with a mean and standard deviation of 68.9(± 53.2) mg/L (as $CaCO_3$) (Table 5-1). Groundwater alkalinity within the basin is generally less than total hardness, with mean values as 68.9 and 76.8 mg/L respectively. This study suggests that, alkalinity equals temporary hardness for groundwater within the basin. Figure 5-6a shows the spatial distribution of alkalinity concentrations in groundwater within the basin.

5.7 Variations in Major ions

The major cation constituents are generally low and are within the WHO (2004) guideline values for drinking water (Table B-1 to B-8) (Appendix B). Calcium and magnesium ions are essential elements for bone formation, nervous system, as well as cell development. (Ashwani *et al.*,

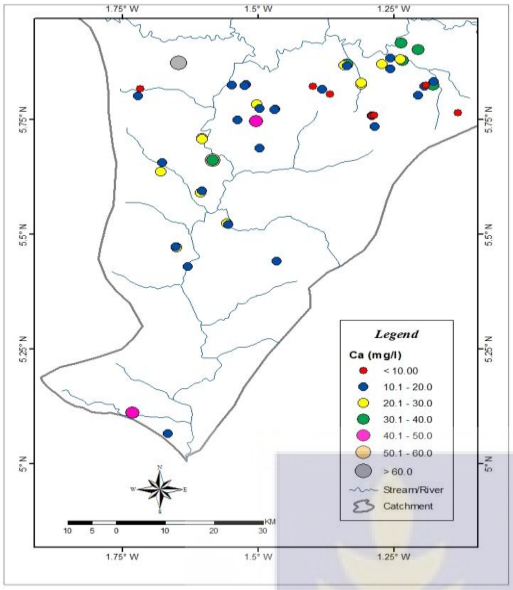


Figure 5-5a: Spatial distribution of Ca^{2+}

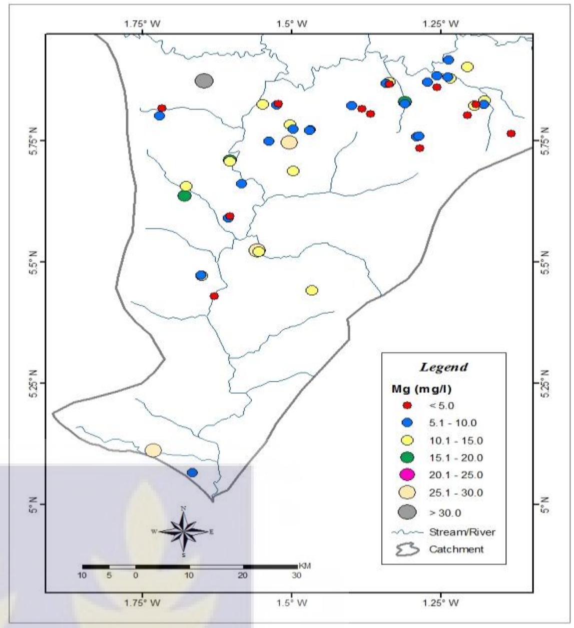


Figure 5-5b: Spatial distribution of Mg^{2+}

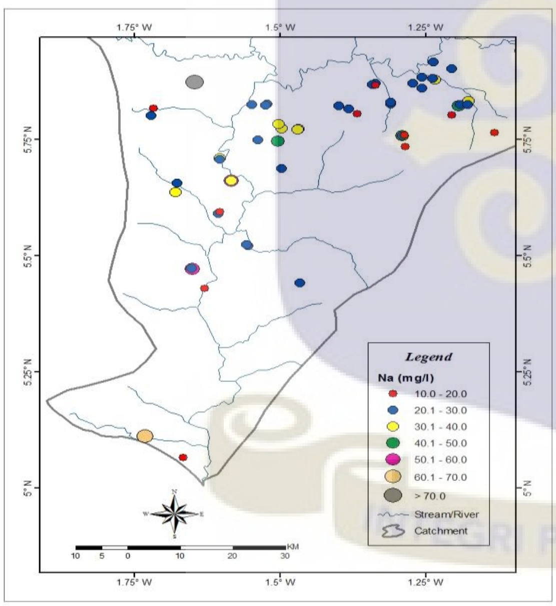


Figure 5-5c: Spatial distribution of Na^{+}

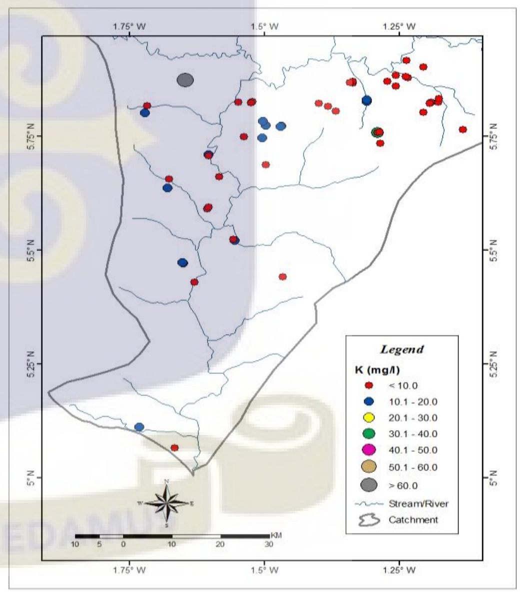


Figure 5-5d: Spatial distribution of K^{+}

Figures 5-5 (a-d): Map of the spatial distribution of major ions (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) concentrations in groundwater within the Lower Pra Basin

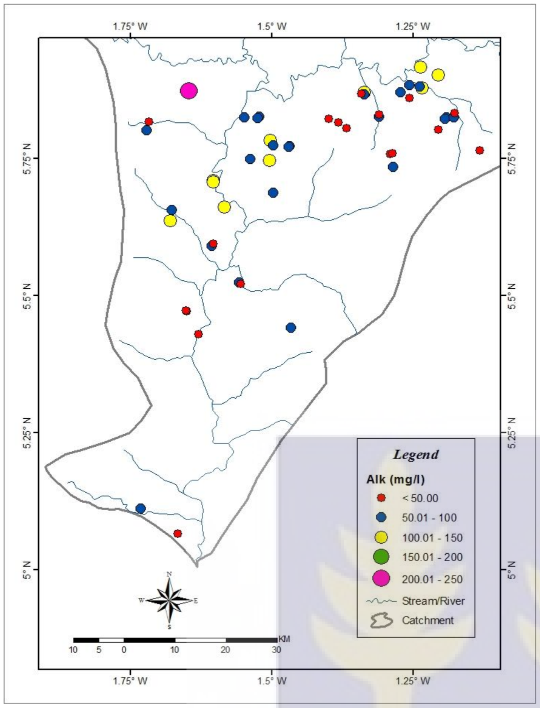


Figure 5-6a: Spatial distribution of alkalinity

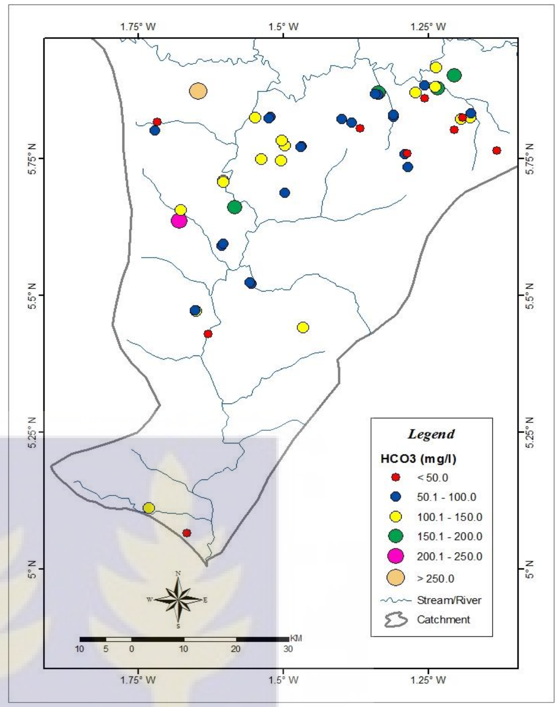


Figure 5-6b: Spatial distribution of HCO_3^-

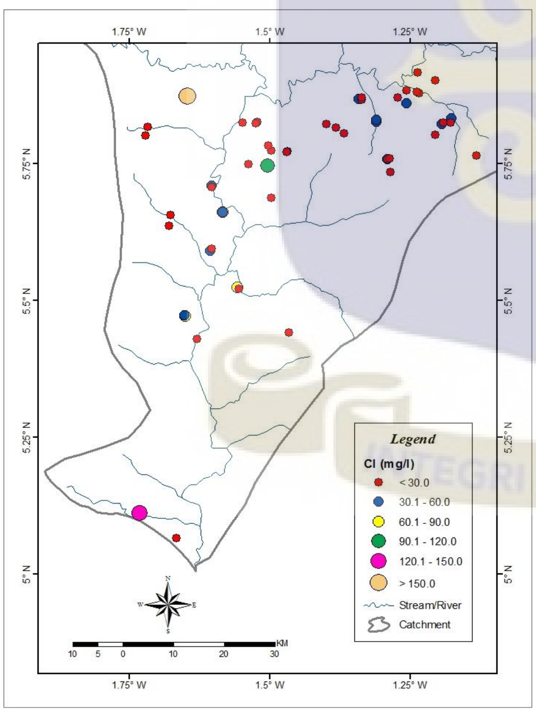


Figure 5-6c: Spatial distribution of Cl^-

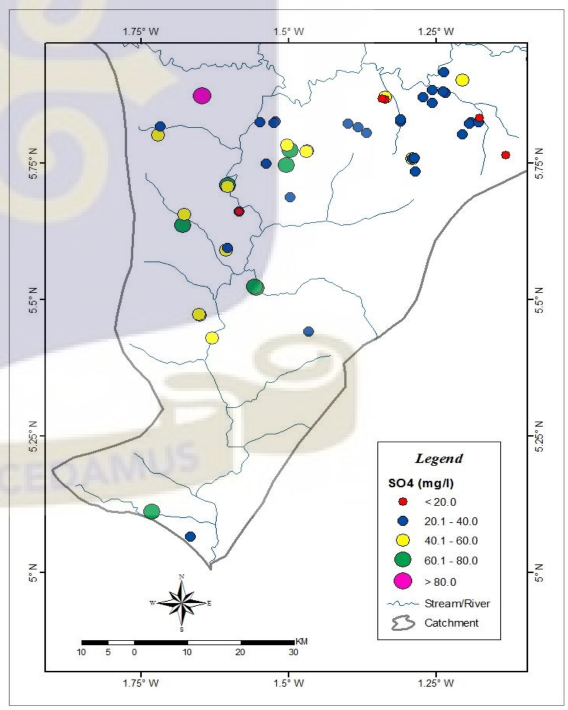


Figure 5-6a: Spatial distribution of SO_4^{2-}

Figures 5-6 (a-d): Map of the spatial distribution of alkalinity and major anions (HCO_3^-, $Cl^-$and SO_4^{2-}) concentrations in groundwater within the Lower Pra Basin.

2014). A possible adverse effect of long-term ingestion of excess concentration of Ca^{2+} is an increased risk of kidney stones (Maragella *et al.*, 1996). Ca^{2+} concentrations in groundwater within the basin ranged 1.6 – 160.9 mg/L, with a mean (standard deviation) value of 21.1(±20.6) (Table 5-1). Spatial distribution maps are very useful in depicting pictorially the pattern and trend of the concentrations of water quality parameters in an area. Figure 5-5a shows the spatial distribution of Ca^{2+} concentrations in groundwater within the basin. Mg^{2+} concentrations in groundwater within the basin ranged 0.2 – 115.2 mg/L, with a mean (standard deviation) value of 10.1(±12.9) (Table 5-1). Figure 5-5b shows the spatial distribution of Mg^{2+} concentrations in groundwater within the basin.

Within the recommended limits, Na^{+} is one of the most important ions required for human health. However, when in excess, Na^{+} may cause hypertension, congenial heart disease, nervous disorder and kidney problems (Ashwani *et al.*, 2014). Na^{+} concentrations in groundwater within the basin ranged 5.3 – 236.0 mg/L, with a mean (standard deviation) value of 30.2 (± 26.9) (Table 5-1). Figure 5-5c shows the spatial distribution of Na^{+} concentrations in groundwater within the basin. K^{+} concentrations ranged 0.5 – 69.5 mg/L, with a mean (standard deviation) value of 9.3 (± 11.4) (Table 5-1). Figure 5-5d shows the spatial distribution of K^{+} concentrations in groundwater within the basin.

Similarly, the major anion constituents are generally low and are within the WHO (2004) guideline values for drinking water (Table B-1 to B-8) (Appendix B). HCO_3^- concentrations ranged 0.0 – 358.7 mg/L, with a mean (standard deviation) value of 96.3 (± 60.8) (Table 5-1). According to Ashwani *et al.*, (2014), HCO_3^- and Cl^- concentrations in water have no known adverse effects; however, their concentrations should not exceed their WHO guideline limits for drinking water as higher concentrations of Cl^- than would normally be desirable would have a laxative effect and therefore, may not be acceptable to consumers. Figure 5-6b shows the spatial distribution of HCO_3^- concentrations in groundwater within the basin. Cl^- concentrations ranged

5.6 – 693.0 mg/L, with a mean (standard deviation) value of 36.1(± 78.8) (Table 5-1). Figure 5-6c shows the spatial distribution of Cl^- concentrations in groundwater within the basin. SO_4^{2-} concentrations ranged 1.52 –371.2 mg/L, with a mean (standard deviation) value of 40.3 (± 51.3) (Table 5-1).

According to Berner and Berner (1987), sulphate ion concentration in natural water is usually in the range 2 - 80 mg/L and higher concentration may be attributed to: (1) weathering of sulphide minerals (2) industrial activities and (3) agricultural effluents. However, the generally very low SO_4^{2-} concentrations of 0.04 -0.95 $mmolL^{-1}$ coupled with the fact that, no groundwater satisfied the Fe^{2+}/ SO_4^{2-} molar ratios of 0.5 and 1.0 for the stoichiometry of pyrite and arsenopyrite oxidation respectively (see Table 5-27) do not wholly support the weathering of sulphide minerals. Industrial activities within the Lower Pra Basin are also minimal and therefore cannot produce substantial sulphate that could possibly leach into the groundwaters within the basin.

Thus, the only possible source of sulphate in groundwaters within the basin is the application ammonium sulphate fertilizers via agricultural activities. Figure 5-6d shows the spatial distribution of SO_4^{2-} concentrations in groundwater within the basin. From the hydrochemical results of this study, HCO_3^- is the dominant anion in groundwater within the basin.

The relatively high proportion of bicarbonate in relation to other anions suggests weathering of primary silicate minerals dominated by alkaline earths (Rose, 2002). Compared with other cations, the concentration of Na^+ is relatively high. The relative abundance of cations and anions in the groundwater is generally in the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$ respectively. The relative proportions (cationic and anionic mass balance) of the major dissolved constituents in groundwater within the basin are presented in Figure 5-7a-b.

5.8 Variations in Minor ions

The minor chemical constituents considered in this study included nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), ammonium-nitrogen (NH_3-N), phosphate-phosphorus (PO_4-P), silica

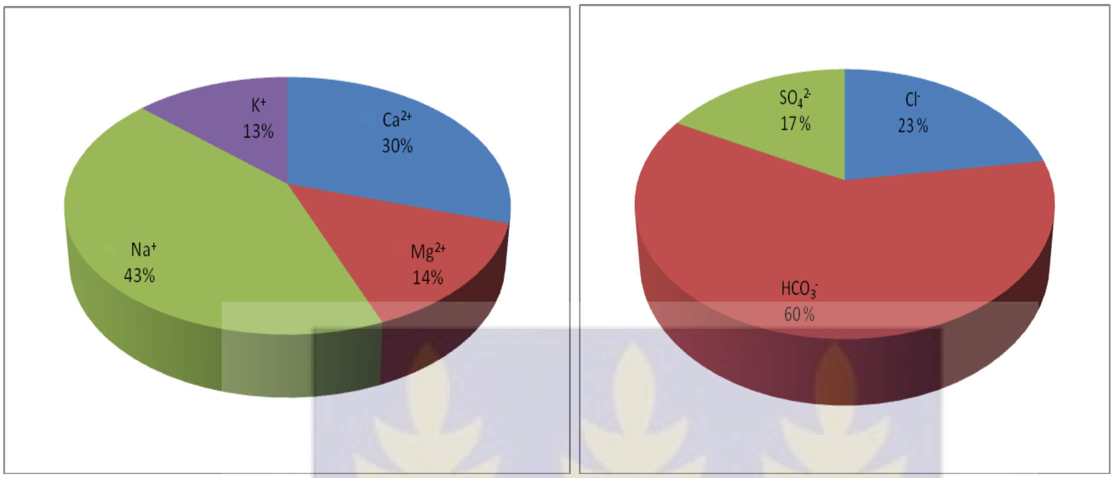


Fig. 5-7a: Proportion of cations   Fig. 5-7b: Proportion of anions

Figures 5-7 (a-b): Relative proportions of the major dissolved constituents in groundwater within the Lower Pra Basin.

NB: cations (positively charged ions- (a) and anions (negatively charged ions-(b).

(SiO_2) and fluoride (F^-). NO_2-N concentrations ranged 0.002 -1.285 mg/L, with mean and a standard deviation of 0.06 (±0.1) mg/L. NO_3-N concentrations ranged 0.003 - 5.014 mg/L, with mean and standard deviation of 0.686 (±0.8) mg/L.

According to Appelo and Postma (1996), nitrate is an important pollutant in the environment, generally derived from atmospheric precipitation, agricultural fertilizers, human and animal excreta, biological fixation and nitrification of organic N and NH_4.

NH_4-N concentrations are below detection limits (< 0.001), suggesting low anthropogenic impact on groundwater within the Lower Pra Basin. PO_4-P concentrations ranged 0.010 - 11.2 mg/L, with mean and a standard deviation of 0.51 (±1.2) mg/L. SiO_2 concentrations ranged 1.1 - 44.1 mg/L, with mean and a standard deviation of 20.5 (±8.9) mg/L. Fluoride ion concentrations ranged 0.02 - 1.36 mg/L, with mean and a standard deviation of 0.5 (±0.3) mg/L (Table 5-1).

5.9 Saturation Indices

Mineral equilibrium calculations are very useful in predicting the presence of reactive minerals in groundwater systems and estimating mineral reactivity (Deutsch, 1997). Saturation indices (SI) provide useful information of the reactive minerals within host rocks and the type of water-rock reactions taking place underground (Deutsch, 1997). Saturation indices measure deviations from thermodynamic equilibrium and are also useful indicators of whether a mineral is likely to dissolve or precipitate in a fluid such as groundwater (Deutsch, 1997).

The saturation index for a solid species is based on the chemical characteristics of the fluid, and is ascertained by comparing the actual ion activity product of the dissolved constituents of the solid species with its solubility product (Deutsch, 1997). By using saturation indices (SI), it is possible to predict the reactive mineralogy of the subsurface from groundwater data without collecting the samples of the solid phase and analyzing mineralogy (Deutsch, 1997). Variations in saturation state are useful in differentiating between the different stages of hydrochemical evolution and help identify which geochemical reactions are important in controlling water chemistry (Langmuir, 1997; Drever, 1997; Coetsiers and Walraevens, 2006).

Saturation index (SI) is defined as the logarithm of the ratio of ion activity product (IAP) to the mineral equilibrium constant at a given temperature and can be expressed as in Equation 5-10:

$$SI = \log(IAP/Ksp) \qquad 5\text{-}10$$

where, IAP is the ion activity product and Ksp is the solubility product of the mineral (Langmuir, 1997). The saturation index (SI) quantitatively describes the deviation of water from equilibrium with respect to dissolved minerals (Garrels and Mackenzie, 1971; Stumm and Morgan, 1981). A negative saturation index ($SI < 0$) signifies subsaturation conditions and dissolution of mineral phase (Garrels and Mackenzie, 1971; Stumm and Morgan, 1981). Such an index value indicates the character of groundwater discharging from a formation with insufficient amount of mineral in solution or short residence time (Garrels and Mackenzie, 1971; Stumm and Morgan, 1981). A positive index (SI > 0) reflects supersaturation with respect to that particular mineral phase and thus, incapable of dissolving more of that mineral and under suitable physico-chemical condition, the mineral phase in equilibrium may precipitate (Garrels and Mackenzie, 1971; Stumm and Morgan, 1981). Such an index value reflects groundwater discharging from an aquifer containing sufficient amount of mineral with sufficient resident time to reach equilibrium (Garrels and Mackenzie, 1971; Stumm and Morgan, 1981). A neutral index (SI = 0) is in equilibrium state with the particular mineral phase and would neither dissolve nor precipitate under equilibrium conditions (Garrels and Mackenzie, 1971; Stumm and Morgan, 1981).

The plot of the computed saturated indices for calcite against dolomite is presented in Figure 5-8, while, the computed saturation indices using the hydrochemical data and measured field temperatures and pHs for groundwater within the Lower Pra Basin is presented in Table 5-10. According to Nilsen and Grammeltvedt (1993), this plot fundamentally, provides information on the two most productive minerals responsible for the bulk alkalinity for the neutralization of acidity produced as a result of mining. This has been widely accepted and cited in literature (Alan *et al.*, 1996; Kortatsi, 2004; Nyende *et al.*, 2014).

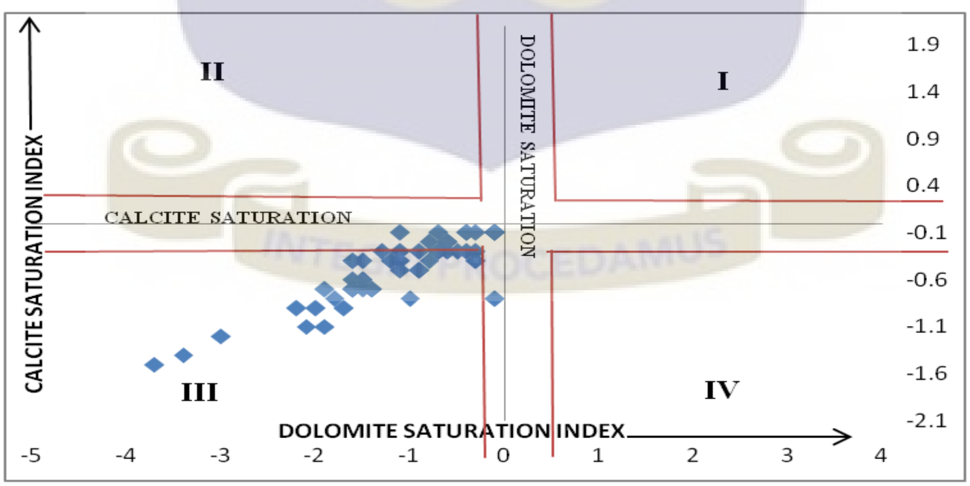


Figure 5-8: A plot of calcite against dolomite saturation indices of groundwater within the Lower Pra Basin.

In Figure 5-8, dolomite saturation is indicated on the x-axis and the calcite saturation on the y-axis. A central band of thickness 0.4 units along both x- and y- axes symbolize important equilibrium with respect to calcite and dolomite (Langmuir, 1997). This central band compensates for the occurrence of possible errors in the measurement of pH, Ca^{2+} and Mg^{2+} (Langmuir, 1997). In Figure 5-8, quadrants I, II, III and IV which are outside the equilibrium depicts the different types of non-equilibrium conditions with respect to calcite and dolomite species (Langmuir, 1997).

Quadrant I depict supersaturation with respect to both calcite and dolomite and indicate groundwater discharging from an aquifer that contains sufficient calcite and/or dolomite with sufficient residence time to reach equilibrium (Langmuir, 1997). From Figure 5-8, no groundwater plotted in this field. This is expected since there is no petrographic evidence of the existence of neither calcite nor dolomite in the rock matrix within the basin.

Quadrant II depicts supersaturation with respect to calcite but subsaturation with respect to dolomite (Langmuir, 1997). Waters that plot in this field depicts waters that are neither undergoing incongruent dissolution nor precipitation (Langmuir, 1997). Figure 5-8 shows that, no groundwater plotted in this field.

Quadrant III depicts subsaturation with respect to both calcite and dolomite (Langmuir, 1997). Waters plotting in this field depicts waters emerging from environments where calcite and dolomite are depleted or where Ca^{2+} and Mg^{2+} exist in other forms or have not reached equilibrium with the carbonates due to short residence time (Langmuir, 1997). Figure 5-8 shows that, groundwaters within the basin generally plot in this field.

This is consistent with earlier suggestions that, groundwaters within the basin originate from environments where calcite and dolomite are depleted or where Ca^{2+} and Mg^{2+} are introduced into the groundwater system as a result of aluminosilicate weathering and that, groundwaters have short residence time and therefore may not have had enough time to reach equilibrium with the carbonates. This is further explained by the observed low conductivity and TDS of the groundwaters.

Table 5-10: Saturation indices for groundwater calculated using Phreeqc for Windows

Sample source	BHID	T°C	pH	$Anh_{(SI)}$	$Cal_{(SI)}$	$Dol_{(SI)}$	$Fe(OH)_{3\ (SI)}$	$Goe_{\ (SI)}$	$Mel_{(SI)}$	$Gyp_{(SI)}$	$Hem_{(SI)}$	$Sid_{(SI)}$	SiO_2 (a) $_{(SI)}$
Assin Nyankomase		28.6	5.1	-0.4	-1.4	-3.4	-3.6	2.3	-5.0	-0.1	6.8	-1.5	-0.7
Assin Nyankomase		27.6	5.6	-0.8	-1.1	-1.9	-1.9	4.0	-4.9	-0.6	10.2	-0.6	-1.2
Assin Nyankomase		29.6	6.1	-1.1	-0.8	-1.0	-0.6	5.3	-5.2	-0.9	12.8	-0.3	-0.6
Sabina	094BU3	28.5	6.1	-0.5	-1.2	-3.0	-3.0	3.0	-5.4	-0.3	7.8	-1.6	-0.7
Ayitey	098BU3	27.6	6.1	-0.3	-0.9	-2.2	-3.4	2.5	-5.4	-0.1	7.2	-1.5	-1.2
Nkrafo	096BU3	27.1	6.1	-0.4	-1.1	-2.1	-3.4	2.5	-5.5	-0.2	7.0	-1.5	-1.1
Nkrafo	099BU3	27.5	7.0	-0.7	-0.2	-0.6	-1.7	4.1	-5.4	-0.5	10.5	-0.3	-1.3
Obirikwaku	405BU2	27.9	6.2	-0.2	-0.6	-1.5	-3.5	2.4	-5.4	-0.1	6.8	-1.4	-1.1
Odumase Camp	407BU2	28.1	6.0	-0.8	-1.5	-3.7	-3.6	2.3	-5.6	-0.6	6.6	-1.7	-0.6
Odumase Camp	246JBU1	27.8	5.9	-0.8	-0.7	-1.4	-0.6	5.3	-5.4	-0.7	12.8	-0.4	-0.4
Obobakokrowa		29.4	5.5	-0.5	-0.4	-1.6	-1.8	4.1	-5.5	-0.3	10.3	-0.8	-1.1
Dwedaama		27.5	6.4	-0.7	-0.9	-1.7	-2.6	3.3	-5.8	-0.5	8.9	-1.4	-1.0
Dwedaama	097BU3	26.5	5.6	-0.2	-0.6	-1.5	-2.6	3.3	-5.2	-0.3	9.0	-0.9	-1.2
WoraKesse Habitat	101BU3	27.5	5.5	-0.7	-0.1	-0.4	-1.0	4.9	-5.4	-0.5	12.0	-0.1	-0.1
Brofoyedru Habitat		26.4	5.9	-0.6	-0.7	-1.5	-2.9	2.9	-5.3	-0.4	8.2	-0.7	-0.2
Akonfude		26.7	5.8	-0.5	-0.2	-0.8	-0.2	5.7	-4.2	-0.3	13.7	-0.8	-1.2
Akonfude		27.9	5.4	-0.1	-0.4	-1.5	-2.7	3.2	-5.1	-0.1	8.8	-0.8	-1.1
Assin Breku (SDA)	100BU3	27.9	6.1	-0.7	-0.1	-0.1	-0.5	6.4	-4.6	-0.5	15.0	-0.6	-0.5
Assin Breku (Gyidi)	102BU3	26.2	6.9	-0.2	-0.7	-1.4	-0.7	5.2	-0.1	-3.4	12.7	-0.7	-0.9
Assin Breku		27.6	6.2	-0.4	-0.7	-1.9	-3.6	2.3	-0.2	-0.6	6.9	-1.3	-0.3
Techiman No.1	396BU2	26.7	5.5	-0.6	-0.8	-1.8	-3.6	2.3	-0.4	-5.6	6.9	-1.1	-0.8
Kwame Ankra	411BU2	26.5	5.5	-0.3	-0.3	-1.3	0.5	6.3	-0.1	-3.4	15.0	-1.1	-1.0
Ninkyiso		27.6	5.1	-1.1	-0.3	-0.4	0.1	-0.9	-5.4	-0.5	14.1	-0.1	-0.9
Amoakokrom	337BU3	28.4	5.3	-0.4	-0.3	-0.9	-1.7	4.2	-5.7	-0.2	10.6	-1.0	-1.1
Nyamebekyere	339BU3	26.9	5.8	-0.3	-0.2	-0.6	0.1	6.0	-0.1	-4.0	14.3	-0.7	-0.9
Jerusalem	339BU3	26.5	5.4	-0.4	-0.4	-1.2	-2.3	3.6	-0.2	-5.8	9.6	-1.2	-1.0
Antoabasa	0502B1/01/097-01	27.5	5.8	-0.3	-0.4	-1.1	-2.9	-0.1	-5.9	-0.2	8.3	-1.4	-1.2

Sample source	BHID	T°C	pH	$Anh_{(SI)}$	$Cal_{(SI)}$	$Dol_{(SI)}$	$Fe(OH)_{3\ (SI)}$	$Goe_{\ (SI)}$	$Mel_{(SI)}$	$Gyp_{(SI)}$	$Hem_{(SI)}$	$Sid_{(SI)}$	SiO_2 (a) $_{(SI)}$
Anto abasa		27.8	5.6	-0.4	-0.9	-2.0	-1.9	4.0	-0.3	-4.1	10.5	-0.2	-0.9
Bediadua		28.1	6.5	-0.5	-0.6	-1.6	-0.5	5.4	-0.3	-4.0	13.1	-0.6	-1.2
Anum		26.9	5.9	-1.1	-0.3	-0.3	-2.1	3.8	-0.9	-6.5	10.1	-1.0	-0.9
Kyeikurom	086BU3	27.3	5.8	-0.3	-0.3	-0.5	-0.3	5.6	-0.1	-3.9	13.4	-0.7	-0.9
Adukrom	088BU3	26.8	6.4	-0.5	-0.3	-1.1	-2.2	3.7	-0.3	-5.4	9.5	-0.7	-1.0
Subriso		26.8	6.8	-0.2	-0.1	-1.1	-1.5	4.4	-0.2	-4.7	13.0	-0.1	-1.2
Nsuekyir	219BU1	28.0	6.0	-0.5	-0.7	-1.6	-2.2	3.7	-0.3	-4.9	10.9	-0.3	-0.9
Denyease Domeabra	093BU3	27.1	6.7	-0.5	-0.7	-1.6	-2.0	4.0	-0.3	-4.6	9.8	-0.4	-1.0
Twifo Mampong		27.4	6.0	-0.3	-0.4	-0.8	-2.6	3.3	-0.1	-5.3	10.2	-0.1	-1.2
Twifo Mampong		27.9	6.2	-0.3	-0.5	-0.9	-1.4	4.5	-0.1	-4.7	8.7	-0.9	-1.1
Akwa Yaw		26.5	6.2	-0.2	-0.1	-0.1	-0.7	5.2	-0.1	-4.8	11.2	-0.3	-1.1
Breman	260BU2	27.4	6.7	-0.1	-0.7	-1.6	-3.2	2.7	-0.1	-4.7	12.6	-0.1	-1.3
Breman		27.9	6.6	-0.3	-0.5	-0.9	-2.7	3.2	-0.1	-5.1	7.8	-0.7	-1.0
Twifo Agona	236BU2	26.8	5.9	-0.1	-0.5	-1.1	-2.6	3.3	-0.1	-4.9	8.6	-0.6	-1.0
Zion Camp	014BU3	26.4	6.8	-1.0	-0.1	-0.1	-3.2	2.7	-1.2	-4.5	7.6	-0.9	-1.1
Somnyamekordur	138BU1	27.7	6.7	-0.2	-0.3	-0.6	-0.1	5.9	-0.1	-3.4	8.8	-0.7	-1.2
Somnyamekordur	033BU3	27.3	5.8	-0.2	-0.3	-0.7	-1.4	4.5	-0.1	-4.6	14.0	-1.2	-1.1
Atu Kurom		28.3	5.6	-1.1	-0.3	-0.7	-0.2	5.7	-0.9	-4.7	11.3	-0.1	-0.9
Subreso		26.4	6.5	-1.2	-0.1	-0.1	1.6	7.5	-1.0	-4.7	13.6	-0.7	-0.9
Gromsa	032BU3	27.5	6.4	-0.3	-0.1	-0.1	-1.7	4.2	-0.1	-5.3	17.2	-1.1	-0.9
Anyinase Ankase	030BU3	27.3	5.9	-1.4	-0.1	-0.4	0.4	6.3	-1.2	-5.8	10.6	-0.4	-1.0
Sienkyem	24/B/32/1	26.6	5.4	-0.3	-0.4	-0.3	-0.4	4.2	-1.3	-5.0	14.6	-0.3	-0.8
Sienkyem	24/B/32/1	26.4	5.5	-0.1	-0.2	-0.6	-1.9	4.0	-0.1	-4.9	14.6	-0.7	-1.2
Mamponso	24-B-85-1	27.2	5.8	-0.3	-0.1	-0.7	-0.3	5.6	-0.1	-4.7	10.1	-0.4	-0.8
Essamang		26.8	5.3	-1.4	-0.8	-0.1	-1.8	4.0	-0.3	-1.1	13.4	-0.1	-1.1
Mampong	22/D/73-1	27.8	5.5	-0.3	-0.1	-0.3	-1.4	4.5	-0.7	-4.5	8.8	-0.4	-0.7

SI= saturation index, Anh=anhydrite, Cal=calcite, Dol=dolomite, Hem=Hematite, Sid= Siderite, Goe=goethite, Gym=gypsum, Mel= Melantherite, $SiO_{2(a)}$=amorphous silica.

Quadrant IV depicts supersaturation with respect to dolomite but subsaturation with respect to calcite (Langmuir, 1997). Figure 5-8 shows that, no sample plotted in this field. Table 5-10 also shows that groundwater within the basin is generally subsaturated with respect to anhydrite, melantherite and gypsum. This further explains the generally low sulphate and calcium ion concentrations in groundwater within the basin. Table 5-10 further shows that groundwater within the basin is generally supersaturated with respect to goethite and suggests that, depending on equilibrium conditions goethite would continuously be precipitated in groundwater within the basin.

5.10 Mechanisms controlling water chemistry within the Lower Pra Basin

Three general processes that contribute to solutes generation in groundwater are: evaporate dissolution, carbonate dissolution and silicate weathering (Garrels and MacKenzie, 1971). Apart from bulk chemistry of the matrix, the chemistry of the evolving water also depends on the rate of weathering (Garrels and MacKenzie, 1971). Gibbs (1970) has shown that generally, the chemistry of water is controlled by the rate of evaporation, chemical compositions of the rocks (rock weathering) and chemical composition of rainwater (precipitation). This has been widely accepted and subsequently, cited in earlier studies (Zhu *et al.*, 2007; Singh *et al.*, 2010; Ahialey *et al.*, 2010; Sandaw *et. al*, 2012).

Figure 5-9 presents the scatter plot of TDS (mg/L) vs $Na^+/(Na^+ + Ca^{2+})$ (meq/L) based on Gibbs (1970), showing the mechanisms controlling groundwater chemistry within the Lower Pra Basin. Figure 5-9 show that rock dominance weathering is one of the hydrogeochemical processes responsible for the chemical evolution of groundwater within the Lower Pra Basin. Additionally, the $Cl^-/(\sum$ anions) ratios for all (100 %) of the groundwaters (see Table 5-13) were less than 0.8, suggesting rock weathering as one of the dominant hydrogeochemical processes responsible for the chemical evolution of groundwater within the basin (Hounslow, 1995).

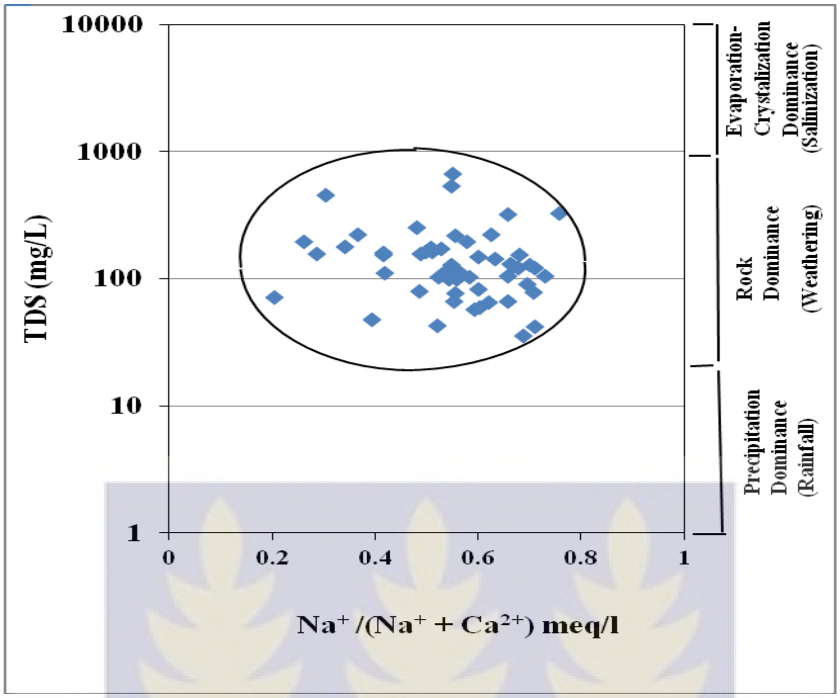


Figure 5-9: Scatter plot of TDS (mg/L) against $Na^{+}/(Na^{+} + Ca^{2+})$ (meq/L) showing rock dominant weathering in groundwater within the Lower Pra Basin.

(After Gibbs, 1970)

5.11 Silicate weathering in groundwater within the Lower Pra Basin

The saturation indices as calculated for amorphous silica in groundwater within the basin using Phreeqc for Windows (see Table 5-10) have shown that, the groundwaters are subsaturated with respect to amorphous silica. This is consistent with natural waters with low silica concentrations (Hounslow, 1995), suggesting that in a stability diagram for plagioclase minerals, majority of the groundwaters would plot in the kaolinite-stability field. This further suggests that, perhaps the most stable secondary alluminosilicate mineral phase for the groundwater system is kaolinite.

Primary sources of silica in groundwater within the basin are silicate and aluminosilicate minerals found within the rock matrix of the basin (see Table 4-1). According to Appelo and Postma (1999), the effect of silicate weathering on the chemistry of groundwater is principally the addition of cations and silica. This further suggests that, the weathering of silicate and aluminosilicate minerals within the basin are responsible for silica concentrations in groundwater within the basin. The saturation indices for calcite and dolomite minerals in groundwater within the Lower Pra Basin (see Table 5-10), suggests that the groundwaters emanated from environments where calcite and dolomite are depleted or where Ca^{2+} and Mg^{2+} exist in other forms.

The predominant mineralogy of the granitic rocks and schists of the Lower Pra Basin comprises of plagioclase (primarily, biotite), hornblende, biotite, muscovite and actinolite (Anon, 1978). The composition of the groundwater is influenced by the reaction between these mineral phases and the groundwater. Hem (1989), postulated that, the degree to which the mineral phases react with the groundwater depends on the availability of protons (H^+), the contact time and the surface area per unit volume of the water. The vegetation of the forest and the humid climatic conditions of the basin provides the basis for the decay of leaves and other organic matter as well as root respiration which generates huge amounts of carbon dioxide in the soil zone (Dickson and Benneh, 1980) and therefore, the hydrogen proton (H^+) availability for circulation in the groundwater.

The concentration of silica in groundwater within the basin ranged 1.1 - 44.1 mg/L, with a mean and standard deviation value of 20.5 (±8.9) mg/L. The stoichiometric relationships of dissolved ions in groundwater within the basin have been assessed in order to identify the main hydrogeochemical processes occurring in the aquifer. 98.1 % of the groundwaters had [(Na + K) /Cl] ratios greater than 1 [i.e. (Na + K) / Cl >1], probably suggesting silicate weathering (Mukherjee *et al.*, 2008). Meteoric water dissolving Na^+ from albite (plagioclase) results in Na-HCO_3 waters having $Na^+/Cl^- > 1$ (Garrels and Mackenzie, 1967). Results from the study shows that, 83.0 % of the groundwaters within the basin had $Na^+/Cl^- > 1$. Additionally, molar ratios for H_4SiO_4/HCO_3^- and H_4SiO_4/Na^+ for groundwater within the basin ranged 0.48 - 2.50 and 0.7 - 1.9 with mean values of 1.2 and 1.0 respectively, suggesting that, although, plagioclase weathering to produce kaolinite cannot explicitly explain the excess of Na^+ over Cl^-, plagioclase weathering undoubtedly contributes to the concentration of Na^+, H_4SiO_4 and HCO_3^- into groundwater within the basin. The H_4SiO_4/Na^+ molar ratios suggests that, albite weathering to secondary clay mineral- kaolinite, may have occurred in groundwater within the basin. The stability of albite and its secondary weathering products gibbsite, kaolinite, and Na- morntmorillonite with respect to groundwater within the basin (see Figure 5-15) shows that, the groundwaters plot mostly in the kaolinite-stability field. Thus, suggesting silicate weathering of albite within the basin.

Similarly, the dissolution of silicate or aluminosilicate minerals such as tremolite [$Ca_2Mg_4Al_2Si_7O_{22}$ $(OH)_2$] as in Equation 5-11, present within the basin is partially responsible for the source of Ca-Mg-HCO_3 water type and produces kaolinite as the most stable secondary clay mineral in groundwater within the basin. According to Hounslow (1995), meteoric water dissolving Ca^{2+} and Mg^{2+} from Ca- and Mg- bearing minerals results in Ca-Mg-HCO_3 waters having $Ca^{2+} > SO_4^{2-}$ (80.0 % of groundwaters), $Ca^{2+}/(Ca^{2+} + SO_4^{2-}) > 0.5$ (74.0 % of groundwaters) and $HCO_3^-/ SiO_2 < 5$ (75.0 % of groundwaters) (see Table 5-13) within the basin, suggesting that, silicate weathering (mainly; plagioclase, hornblende and actinolite) in groundwater within the basin is possible.

The stability of anorthite and its secondary weathering products gibbsite, kaolinite, and Ca-morntmorillonite with respect to groundwater within the basin (see Figure 5-13) shows that, the groundwaters plot mainly in the kaolinite-stability field suggesting silicate weathering of anorthite in groundwater within the basin. Thus, meteoric water dissolving Ca^{2+} and Mg^{2+} from aluminosilicates (such as tremolite and anorthite) results in Ca-Mg-HCO_3 water type whilst, meteoric water dissolving Na^+ from aluminosilicates (such as albite) results in Na- HCO_3 water type in groundwater within the basin.

5.12 Water types of groundwater within the Lower Pra Basin

The Piper (1944) trilinear plot of the hydrochemical data as presented in Figure 5-10 shows that, majority (50.0 %) of the groundwaters clustered towards the Ca-Mg- HCO_3 dominant section (B). This water type depicts active recharge and/or contact with relatively soluble silicate minerals within the aquifer and is characterized by temporary hardness.

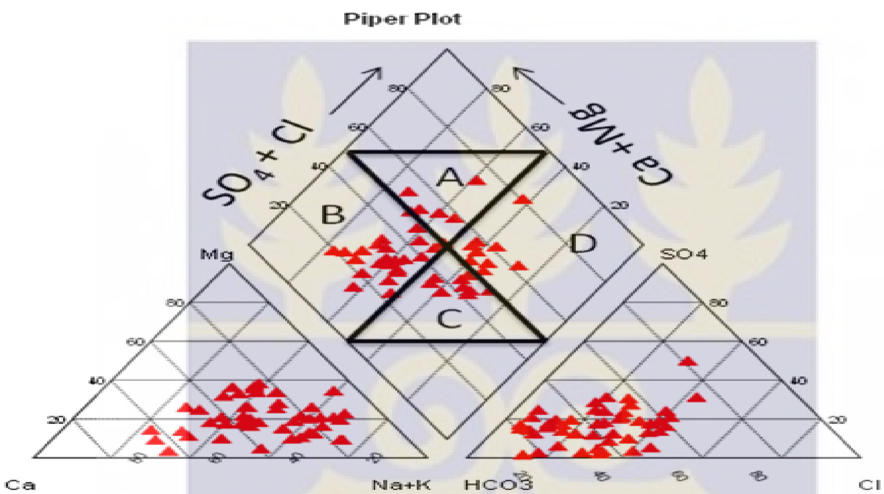


Figure 5-10 : Piper trilinear diagram for groundwater within the Lower Pra Basin.

This water type is indicative of aggressive recharging water reacting with schists, quartzites and granites. According to Anon (1978), these minerals are common characteristics of the Cape Coast/Dixcove granitoids. Surface water charged with atmospheric carbon dioxide and biogenically carbon dioxide charged water infiltrating the subsurface and, reacting with aluminosilicates including plagioclase and tremolite which are common rock features of the Cape Coast/Dixcove granitoids, releasing cations such as Ca^{2+} and Mg^{2+} into the groundwater. The reaction between tremolite and biogenically charged carbon dioxide to release Ca^{2+} and Mg^{2+} into the groundwater within the basin can be represented as in Equation 5-11:

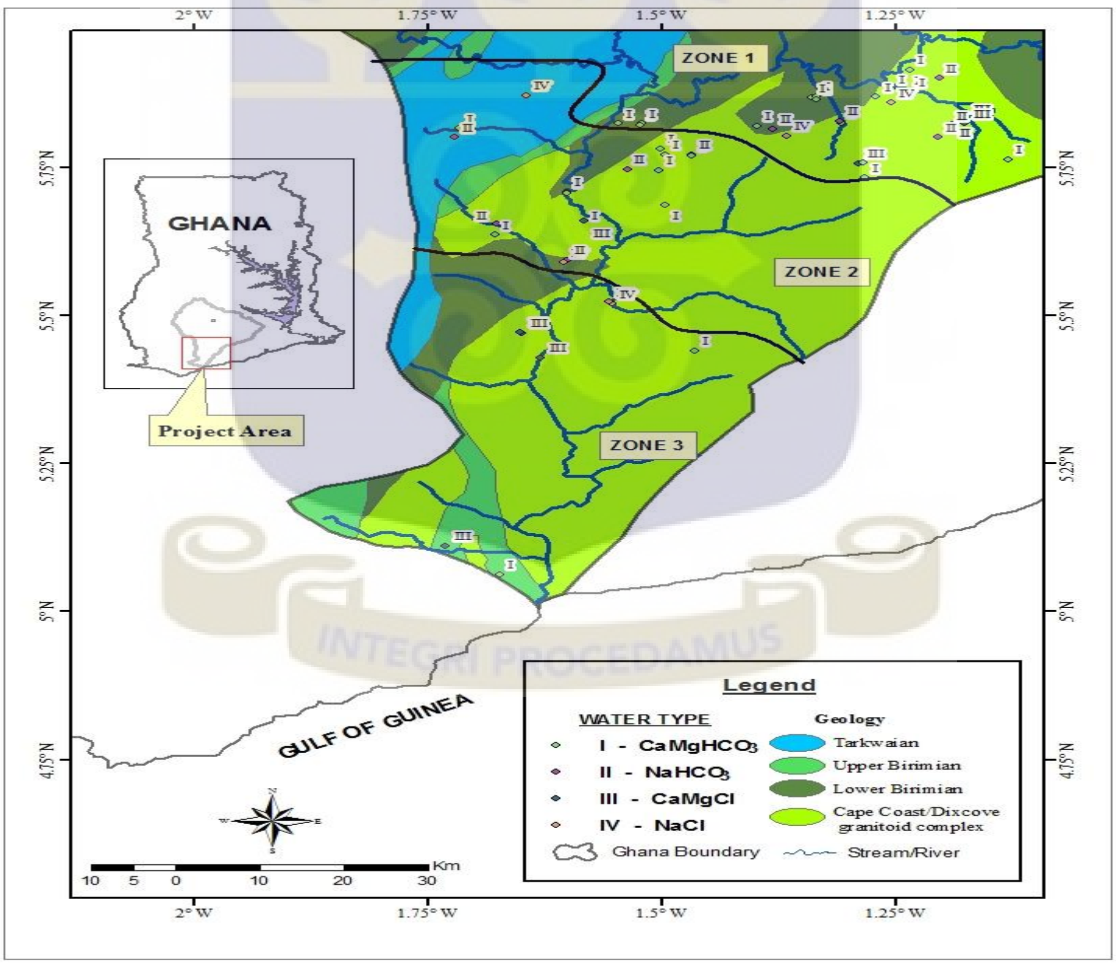
$$\underset{\text{(Tremolite)}}{Ca_2Mg_4Al_2Si_7O_{22}(OH)_2} + 12CO_2 + 17H_2O \longrightarrow Al_2Si_2O_5(OH)_4 + 2Ca^{2+} + 4Mg^{2+} + 12HCO_3^- + 5H_4SiO_4 \quad \text{5-11}$$

As a result of this dissolution, a rise in pH and concentration of HCO_3^- is observed in groundwater within the basin (Freeze and Cherry, 1979). According to Plummer *et al.* (1990); Edmunds and Smedley (2000); Adams *et al.* (2001), geochemical groundwater evolution studies from different parts of the world have shown that, the Ca-Mg-HCO_3 water type is generally considered as recharge area waters at their early stage of geochemical evolution and are rapidly circulating groundwaters which have not undergone pronounced water-rock interaction. Some of the groundwaters (26.0 %) also clustered towards the Na-HCO_3 dominant section (C).

From the hydrochemical data (see Table 5-1), the mean Na^+ concentrations for majority of the groundwaters were greater than the mean Ca^{2+} concentrations. Additionally, the relative proportion of Na^+ (43.0 %) was relatively greater than Ca^{2+} (30.0 %) (Figure 5-7 a). It was therefore, expected that groundwater within the basin would primarily be Na-HCO_{3-} water type and not Ca-Mg-HCO_3 water type. This suggests that, ion-exchange reaction is one of the hydrogeochemical processes influencing groundwater quality within the basin in which case, both Ca^{2+} and Mg^{2+} are being removed from the water and replaced by Na^+ evidenced by a major increase in Na^+ over Cl^-. The reaction for this ion-exchange process is presented in Equation 5-11:

$$Na_2\text{-Clay} + Ca^{2+} \longrightarrow 2Na^+ + Ca\text{-Clay} \qquad 5\text{-}11$$

The milliequivalent per litre (meq/L) ratio of $Na^+/(Na^+ + Cl^-)$ is greater than 0.5 when ion-exchange occurs or when albite weathering occurs (Hounslow, 1995). Results (Table 5-13) show that, approximately, 71.0 % of the groundwaters had $Na^+/(Na^+ + Cl^-)$ ratios significantly greater than 0.5, suggesting a significant Na^+ source other than halite-albite; perhaps cation-exchange reaction is taking place in groundwater within the basin. Additionally, computation of the Chloro-Alkaline indices for Base Exchange in groundwater within the Lower Pra Basin (see Table 5-14) has also confirmed ion-exchange processes in groundwater within the basin in which case, Ca^{2+} and Mg^{2+} are being removed from the water and replaced by Na^{+}. Some of the groundwaters (15.0 %) clustered towards Na-Cl dominant section (D). The Na-Cl water type may be due to the influence of local rain and illustrate the importance of local recharge conditions within the basin. A few of the groundwaters (9.0 %) also clustered towards the Ca-Mg-Cl dominant section (A). This water type is characteristic of mixed waters, where, neither cation nor anion dominates and are reminiscent of permanent hard waters. The spatial distribution of water types with reference to geology of the Lower Pra Basin is presented in Figure 5-11.



(Modified after Geological Survey Department, 2009)

Figure 5-11 : Spatial distribution of water types with reference to geology of the Lower Pra Basin.

5.13 The origin of dissolved ions in groundwater within the Lower Pra Basin.

5.13.1 Using groundwater geochemistry to determine the origin of dissolved ions in groundwater within the Lower Pra Basin.

In unpolluted fresh water, the range of concentration of chemical constituents can reveal the origin of elements (Appelo and Postma, 1999) and therefore, the water chemistry of a region, district or basin. Table 5-11 presents the range of concentration of dissolved ions in groundwater within the Lower Pra Basin and their probable sources.

Table 5-11: The range of concentration of dissolved ions in groundwater within the Lower Pra Basin and their probable sources

Dissolved ion	Concentration ($mmolL^{-1}$)	Probable Source
Na^+	0.23 – 9.83	Albite (plagioclase), sea aerosol, atmosphere
K^+	0.01 - 1.78	Biotite, muscovite, microline
Mg^{2+}	0.04 - 4.30	Biotite, actinolite, chlorite, tremolite, hornblende
Ca^{2+}	0.04 – 4.01	Actinolite, tremolite, anorthite (plagioclase)
Cl^-	0.16 – 19.5	Sea aerosols, atmosphere
HCO_3^-	0.40 – 5.88	Silicate/aluminosilicate weathering by carbon dioxide charged water, carbon (organic matter)
SO_4^{2-}	0.02 – 3.86	Pyrite, arsenopyrite, atmosphere
NO_3^-	0.00 – 0.07	Carbon (organic matter), atmosphere
SiO_2	0.02 – 2.43	Silicates and aluminosilicates

[After Appelo and Postma, (1999)]

Table 5-12 summarises the chemistry of the chemical evolution of groundwater within the basin based on Table 5-11. From Tables 5-11 and 5-12, it is evident that, the chemical composition of groundwater within the Lower Pra Basin is the combined chemistry of the composition of water that enters the groundwater reservoir and their reactions with the mineralogy of the granitic rocks (biotite, muscovite), schists rocks (biotite, hornblende, and actinolite), pyrites and arsenopyrites as the water travels along mineral surfaces in the pores or fractures of the unsaturated zone and

Table 5-12: Summary of the possible chemistry of the chemical evolution of groundwater within the Lower Pra Basin.

Dissolved ion	Geologic source / anthropogenic source	Probable chemical reaction responsible for chemical evolution
Ca^{2+}	Anorthite ($CaAl_2Si_2O_8$), Tremolite- [$Ca_2Mg_4Al_2Si_7O_{22}(OH)_2$]	$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^-$ $Ca_2Mg_4Al_2Si_7O_{22}(OH)_2 + 12CO_2 + 12H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Ca^{2+} + 4Mg^{2+} + 12HCO_3^- + 5H_4SiO_4$
Mg^{2+}	Tremolite- [$Ca_2Mg_4Al_2Si_7O_{22}(OH)_2$; Biotite [$K(Mg)_3AlSi_3O_{10}(OH)_2$]	$Ca_2Mg_4Al_2Si_7O_{22}(OH)_2 + 12CO_2 + 12H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Ca^{2+} + 4Mg^{2+} + 12HCO_3^- + 5H_4SiO_4$ $2KMg_3AlSi_3O_{10}(OH)_2 + 14CO_2 + 10H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 6Mg^{2+} + 14HCO_3^- + 4H_4SiO_4$
Na^+	Albite ($NaAlSi_3O_8$) , sea aerosol spray, and the atmosphere	$2NaAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4$
K^+	Microline ($KAlSi_3O_8$), Muscovite[$KAl_3Si_3O_{10}(OH)_2$] Biotite[$K(Mg)_3AlSi_3O_{10}(OH)_2$]	$2KAlSi_3O_8 + 2CO_2 + 11H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 4HCO_3^- + 4H_4SiO_4$ $2KAl_3Si_3O_{10}(OH)_2 + 2CO_2 + 5H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2K^+ + 2HCO_3^-$ $2KMg_3AlSi_3O_{10}(OH)_2 + 14CO_2 + 10H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 6Mg^{2+} + 14HCO_3^- + 4H_4SiO_4$
Cl^-	Sea aerosol spray and the atmosphere	-
HCO_3^-	Silicate/aluminosilicate weathering by CO_2 – charged water : e.g. Biotite[$K(Mg)_3AlSi_3O_{10}(OH)_2$], Anorthite ($CaAl_2Si_2O_8$) and decay of organic matter (carbon)	$2KMg_3AlSi_3O_{10}(OH)_2 + 14CO_2 + 10H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 6Mg^{2+} + 14HCO_3^- + 4H_4SiO_4$ $CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_5(OH)_4 + Ca^{2+} + 2HCO_3^-$
SO_4^{2-}	Pyrite (FeS_2) Arsenopyrite ($FeAsS$) and the atmosphere	$2FeS_2 + 7.5O_2 + 7H_2O \rightarrow 2(Fe(OH)_2 + 4SO_4^{2-} + 8H^+$ $4FeAsS + 13O_2 + 6H_2O \rightarrow 4Fe^{2+} + 4AsO_4^{3-} + 4SO_4^{2-} + 12H^+$
NO_3^-	Ammonification of organic matter (carbon) and subsequent nitrification of ammonium ion as a result of anthropogenic activities, and the atmosphere	$\text{Organic matter} \xrightarrow{\text{ammonification}} NH_4^+ \xrightarrow{\text{nitrification}} NO_3^-$
SiO_2	Aluminosilicates such as: Anorthite ($CaAl_2Si_2O_8$), Muscovite [$KAl_3Si_3O_{10}(OH)_2$] Biotite [$K(Mg)_3AlSi_3O_{10}(OH)_2$], etc.	$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O \rightarrow Al_2Si_2O_3(OH)_4 + Ca^{2+} + 2HCO_3^-$ $2KAl_3Si_3O_{10}(OH)_2 + 2CO_2 + 5H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2K^+ + 2HCO_3^-$ $2KMg_3AlSi_3O_{10}(OH)_2 + 14CO_2 + 10H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2K^+ + 6Mg^{2+} + 14HCO_3^- + 4H_4SiO_4$

the aquifer. Thus, from groundwater geochemistry considerations, the major dissolved ions in groundwater within the Lower Pra Basin originate from granites, schists, pyrites and arsenopyrites primarily, through rock weathering.

5.13.2 Using source-rock deduction (ratios of major ions) to determine the origin of chemical constituents in groundwater within the Lower Pra Basin.

According to Hounslow (1995), to systematically determine the source-rock from a set of water quality data from a region, district or basin, the pH of the water should not be less than 5 - 6, as acid waters (low pH) dissolve significant quantities of clay minerals and release uncharacteristically high silica (and alumina) into the water. From the hydrochemical data of groundwater within the Lower Pra Basin, approximately 96.0 % of groundwater had pH with range 5-7 pH units. Thus, the mass-balance approach can be used to deduce the source- rock in groundwater within the basin. The concentration of SiO_2 (mmol/L) can also reveal whether groundwater is hydrothermal or not (Hounslow, 1995). A SiO_2 concentration > 0.5 indicates hydrothermal waters (Hounslow, 1995). Results of SiO_2 from this study show that only 18.1 % of groundwater within the basin had SiO_2 > 0.5, suggesting that, groundwater within the basin is largely non- hydrothermal at borehole depths of 22 - 96 m.

5.13.2.1 Sources of major ions

Sources of Ca^{2+} and Mg^{2+} in groundwater within the Lower Pra Basin

According to McLean and Jankowski (2000), in a plot of Ca^{2+} + Mg^{2+} ($meqL^{-l}$) vs HCO_3^- + SO_4^{2-} ($meqL^{-l}$), a 1:1 relationship suggests calcite, anhydrite, dolomite and gypsum dissolution as the major processes influencing solution composition, while, groundwater falling below the 1:1 line represents ion-exchange, in which case Ca^{2+} + Mg^{2+} are being depleted with respect to

$HCO_3^- + SO_4^{2-}$. From Figure 5-12, majority of the groundwaters plot on or close to the 1:1 line, suggesting calcite, dolomite, anhydrite and gypsum dissolution. Nonetheless, calculated saturation indices for calcite, dolomite, anhydrite and gypsum using Phreeqc for Windows (Parkhurst and Appelo, 1999) show negative SI values for all these minerals. This suggests subsaturation of these minerals in groundwater within the basin and indicates that, groundwater within the basin originates from a formation with deficient quantities of these minerals in solution or short residence times of these minerals in groundwater within the basin. This is consistent with earlier study by Smedley *et al.,* (1995) that, groundwater within the Lower Pra Basin is poorly buffered due to the paucity of carbonates. According to Datta *et al.*, (1996); Rajmohan and Elango (2004) and Sandow (2009), in a plot of Ca^{2+}+ Mg^{2+} vs. HCO_3^- + SO_4^{2-}, waters plotting above the equiline (1:1) shows carbonate weathering dominance while, waters plotting below the equiline shows silicate weathering dominance. Figure 5-12, shows neither carbonate nor silicate weathering dominance.

Additionally, the saturation indices as calculated for calcite and dolomite minerals in groundwater within the Lower Pra Basin have suggested that, groundwaters have come from environments where, calcite and dolomite are depleted ruling out widespread carbonate weathering in groundwater within the basin. However, the analytical results show that, 75.0 % of the groundwaters had HCO_3^-/ SiO_2 ratios varying between 1 and 5. According to Hounslow (1995), this suggests that, silicate (mainly; plagioclase, hornblende and actinolite) weathering is probable in groundwater within the basin. Brady (1974); Brady and Walther (1989) and Appelo and Postma (1999), postulated that, the type of weathering product formed in silicate weathering is dependent on the hydrological conditions as well as the rate of mineral weathering. Weathering of primary silicate minerals to montmorillonite is mainly favoured in drier climate where, the rate of soils flushing is relatively slow (Appelo and Postma, 1999).

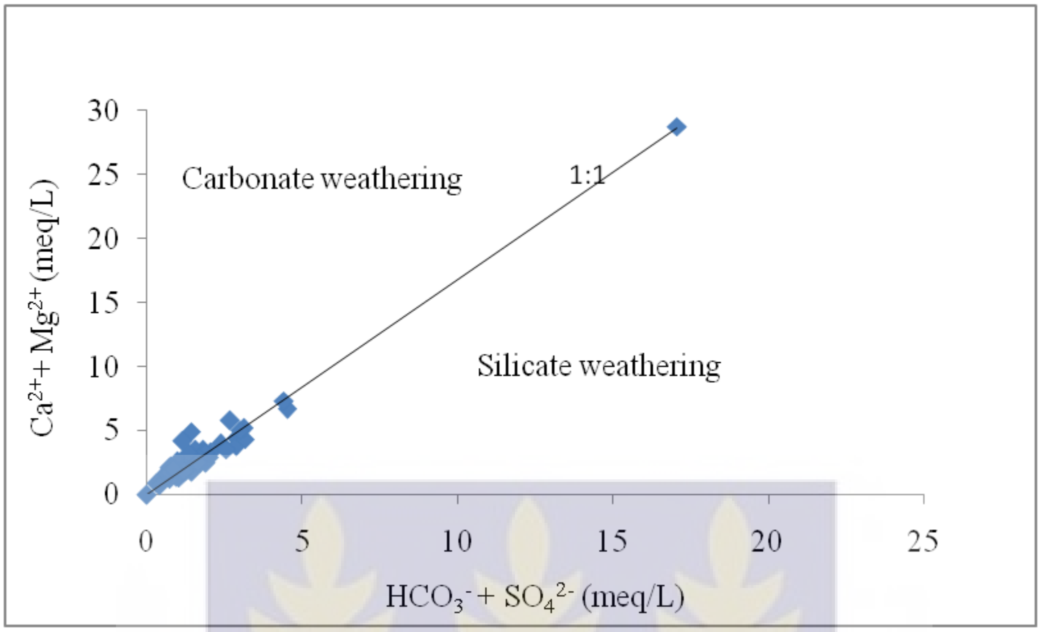


Figure 5-12: Relationship between Ca^{2+} + Mg^{2+} vs. HCO_3^- + SO_4^{2-} for groundwater within the Lower Pra Basin.

According to Dickson and Benneh (2004), the types of soil found within the Lower Pra Basin contain higher quantities of nutrients and are usually alkaline coupled with an average annual rainfall of 1500 - 2000 mm. The hydrological conditions within the Lower Pra Basin therefore, do not favour the possible weathering of primary silicate minerals to montmorillonite.

The weathering of anorthite/albite to montmorillonite is thus, not expected within the Lower Pra Basin where, the soils are relatively poorly drained and alkaline in nature (Brady, 1992; Langmuir, 1997; Appelo and Postma, 1999). Thus, the most probable secondary minerals are kaolinite, gibbsite or iron oxides. Figure 5-13 presents the stability of plagioclase (anorthite) and its secondary weathering products gibbsite, kaolinite and Ca-montmorillonite with respect to groundwater within the Lower Pra Basin. Figure 5-13 was drawn with the assumption that, all aluminum is preserved in the weathering products (Appelo and Postma, 1999). End-member compositions were also assumed using equilibrium relationships of Tardy (1971) for standard temperature (25^{o}C) and pressure (1 atmosphere) which more or less reflects conditions in the groundwater. Computations of constituents' activities were done using Phreeqc for Windows Version 2.8.01 (Appelo and Postma, 1999).

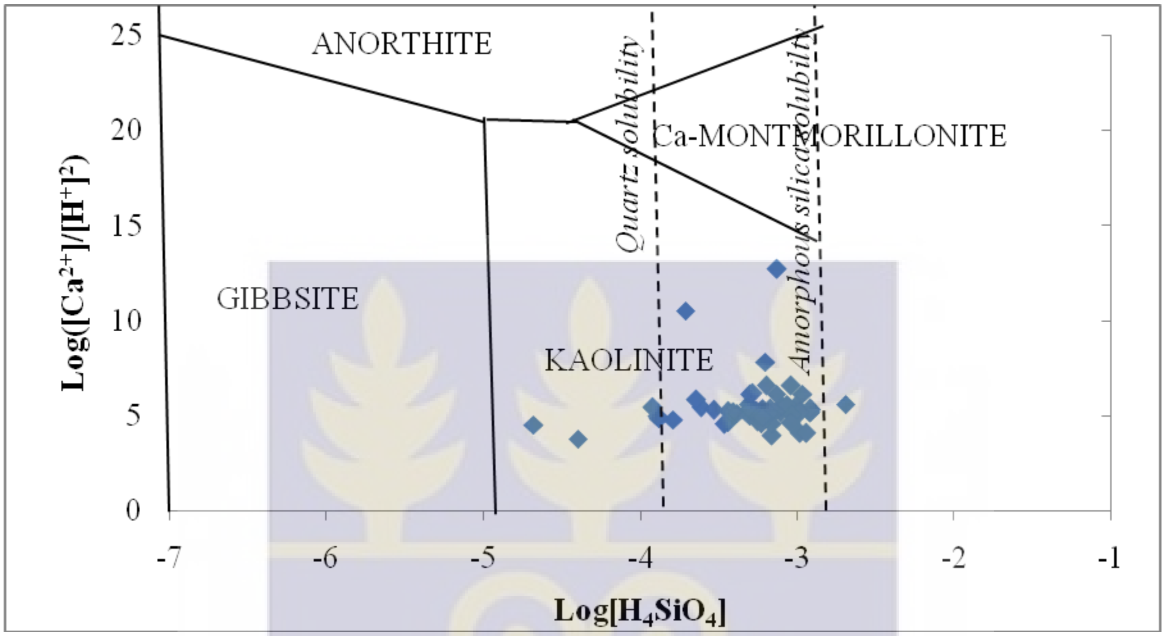


Figure 5-13 : The stability of anorthite and its possible weathering products gibbsite, kaolinite, and Ca-montmorillonite with respect to groundwater within the Lower Pra Basin.

(After Tardy, 1971)

Consistent with natural waters with low silica concentrations (Hounslow, 1995), majority of the groundwaters plot in the kaolinite- stability field indicating that; kaolinite is the most stable secondary aluminosilicate mineral phase for the groundwater system. Such weathering processes can be presented as in Equation 5-13:

$$\underset{\text{(Anorthite)}}{CaAl_2Si_2O_8} + 2CO_2 + 3H_2O \longrightarrow \underset{\text{(Kaolinite)}}{Al_2Si_2O_5(OH)_4} + Ca^{2+} + 2HCO_3^- \quad \text{5-13}$$

Additionally, the presence of Mg^{2+} in groundwater within the basin may possibly be as a result of leaching from silicates such as chlorite [$(MgFe)_5Al(AlSi_3)O_{10}$], biotite [$K(Mg,Fe)_3AlSi_3O_{10}(OH_2)$] and actinolite [$Ca_2(Mg,Fe^{2+})_5Si_8O_{22}(OH)_2$] which are present in the rock matrices within the basin (see Table 4-1). Thus, silicate weathering processes may have contributed significantly to the Ca^{2+} and Mg^{2+} concentrations in groundwater within the Lower Pra Basin.

Sources of Na^+ in groundwater within the Lower Pra Basin.

Sources of sodium (Na^+) usually include; halite (NaCl), sea spray, hot springs, brines, silicates such as plagioclase–albite ($NaAlSi_3O_8$). Generally, sodium is produced from natural ion-exchange; however, the atmosphere could also be a source of sodium in groundwater (Hounslow, 1995). Reverse ion- exchange (regeneration) which occurs, when substantial local rains come into contact with calcium- rich clays is the only common sink for sodium (Hounslow, 1995).

Chloride (Cl^-) is also derived from similar sources as Na^+ except, hot springs, ion-exchange and silicates (Hounslow, 1995). Consequently, for any groundwater, the $Na^+/(Na^+ + Cl^-)$ ratios would be similar to the $Na^+/(Na^+ + Cl^-)$ ratios in halite, brines or hot springs assuming the groundwater is derived from these sources [i.e. $Na^+/(Na^+ + Cl^-) = 0$] if, halite dissolution is the principal process through which Na^+ enters the groundwater (Hounslow, 1995).

According to Duce and Hoffman (1976), between 30.0 and 75.0 % of the total 'natural' global particulate production (< 20 µm) originates from sea aerosol spray, and approximately 10.0 % of the salts mobilized through the atmosphere are deposited on land. Particularly in countries with a maritime climate, oceanic aerosol is the principal source of Na^+, Mg^{2+} and Cl^- (Duce and Hoffman, 1976). This suggests that a major source of Na^+, Mg^{2+} and Cl^- in groundwaters in Ghana could come from sea aerosol spray as Ghana enjoys maritime climate particularly along the coast where the study area is located.

Figure 5-14 presents the plot of Cl^- vs Na^+. As expected, majority of the groundwaters plot on or close to the 1:1 line on the Na^+ vs Cl^- graph [i.e. $Na^+/(Na^+ + Cl^-) = 0$], suggesting that, halite dissolution is partly responsible for Na^+ concentration in groundwater within the basin. However, there is no petrographic evidence of the existence of halite in the rock matrices within the basin. Additionally, according to Hounslow (1995), halite dissolution in water releases equal quantities of Na^+ and Cl^- in solution resulting in Na^+/Cl^- molar ratio equal to one. However, the Na^+/Cl^- molar ratios for groundwater within the basin ranged 0.51 - 5.86 meq/L, with a mean value of 2.09 meq/L, with 81.5 % of groundwaters having Na^+/Cl^- molar ratios >1, suggesting that, halite dissolution cannot not be responsible for the Na^+ concentration in groundwater within the basin. This leaves sea aerosol spray as a significant source of Na^+ and Cl^- in groundwater within the basin. Additionally, the $Na^+/(Na^+ + Cl^-)$ ratios for 81.0 % of the groundwaters were greater than 0.5 [i.e. $Na^+/(Na^+ + Cl^-) > 0.5$] (Table 5-13) suggesting sodium source other than halite- albite dissolution or ion-exchange being partly responsible for Na^+ concentration in groundwater within the basin.

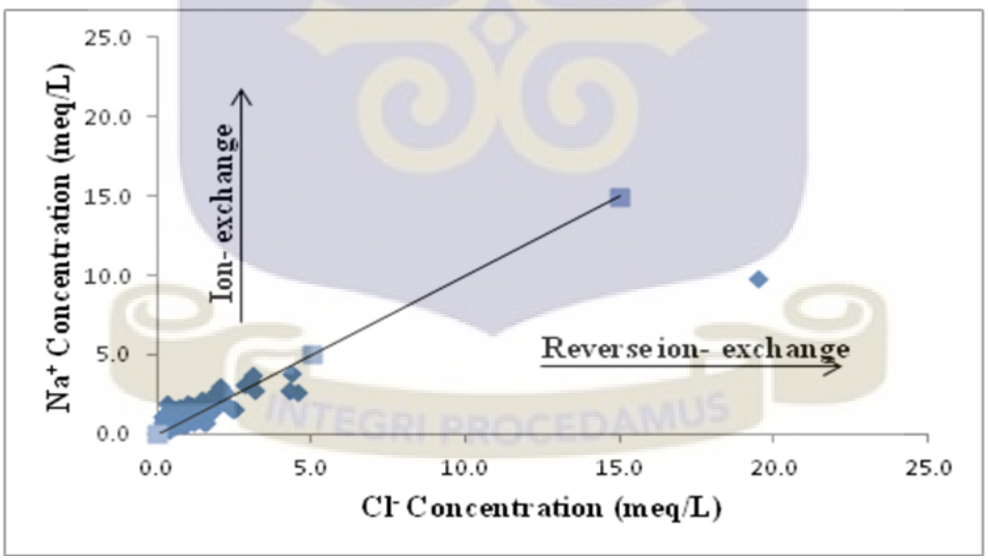


Figure 5-14: Relationship between Na^+(meq/L) and Cl^- (meq/L)for groundwater within the Lower Pra Basin.

Additionally, the $(Na^++K^+-Cl^-)/(Na^++K^+-Cl^-+Ca^{2+})$ ratios for 67.0 % of the groundwaters were > 0.2 and < 0.8 [i.e. $0.2 < (Na^++K^+-Cl^-) / (Na^++K^+-Cl^-+Ca^{2+}) < 0.8$] (Table 5-13). This suggests that, plagioclase ($Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8$) weathering is possible. According to Kortatsi (2004), the reaction involving the incongruent dissolution of plagioclase with carbon dioxide charged water to produce Na^+ and Ca^{2+} can be represented as in Equation 5-14:

$$1.45Na_{0.62}Ca_{0.38}Al_{1.38}Si_{2.62}O_8 + 2CO_2 + 6.6H_2O = Al_2Si_2O_5(OH)_4 + 0.9Na^+ + 0.55Ca^{2+} + 2HCO_3^- + 1.8H_4SiO_4 \quad 5\text{-}14$$

Hypothetically, the weathering of plagioclase in Equation 5-14 has molar ratios for H_4SiO_4/HCO_3^- and H_4SiO_4/Na^+ as 0.9 and 2.0 respectively (Kortatsi, 2004). In sharp contrast, the molar ratios for H_4SiO_4/HCO_3^- and H_4SiO_4/Na^+ for groundwater within the basin ranged 0.48 - 2.50 and 0.7 - 1.9 with mean values of 1.2 and 1.0 respectively. Clearly, the molar ratios for H_4SiO_4/HCO_3^- and H_4SiO_4/Na^+ for groundwater within the basin show that although, plagioclase weathering to produce kaolinite cannot explicitly explain the excess of Na^+ over Cl^-, plagioclase weathering undoubtedly contributes to the concentration of Na^+, H_4SiO_4 and HCO_3^- in groundwater within the basin. Similarly, the incongruent dissolution of albite to produce kaolinite, morntmorillonite and/or gibbsite according to Kortatsi (2004), can be presented in Equations 5-15, 5-16 and 5-17 respectively:

$$2NaAlSi_2O_8 + 2CO_2 + 11H_2O = Al_2Si_2O_5(OH)_4 + 2Na^+ + 2HCO_3^- + 4H_4SiO_4 \quad 5\text{-}15$$

(Albite) (Kaolinite)

$$3NaAlSi_2O_8 + Mg^{2+} + 4H_2O = 2Na_{0.5}Al_{1.5}Mg_{0.5}Si_4O_{10}(OH)_2 + 2Na^+ + H_4SiO_4 \quad 5\text{-}16$$

(Albite) (Morntmorillonite)

$$NaAlSi_2O_8 + CO_2 + 8H_2O = Al(OH)_3 + Na^+ + HCO_3^- + 3H_4SiO_4 \quad 5\text{-}17$$

(Albite) (Gibbsite)

Similarly, the hypothetical H_4SiO_4/Na^+ molar ratios for the dissolution of albite to kaolinite, morntmorillonite and gibbsite are 2.0, 0.5 and 3.0 respectively (Kortatsi, 2004). Results from this study show that, H_4SiO_4/Na^+ molar ratios for groundwater within the Lower Pra Basin ranged 0.7-1.9, with a mean value of 1.0. This suggests that, albite weathering to clay minerals (kaolinite and gibbsite) may have occurred in groundwater within the basin. Thus kaolinite, gibbsite or iron oxides are the most likely secondary minerals from the dissolution of albite. The stability of albite and its secondary weathering products gibbsite, kaolinite, and Na-morntmorillonite with respect to groundwater within the basin is presented in Figure 5-15.

Figure 5-15 was drawn with the assumption that, all aluminum is preserved in the weathering products (Appelo and Postma, 1999). End-member compositions were also assumed using equilibrium relationships of Tardy (1971) for standard temperature (25°C) and pressure (1 atmosphere) which more or less reflects conditions in the groundwater. Computations of constituents' activities were done using Phreeqc for Windows Version 2.8.01 (Appelo and Postma, 1999).

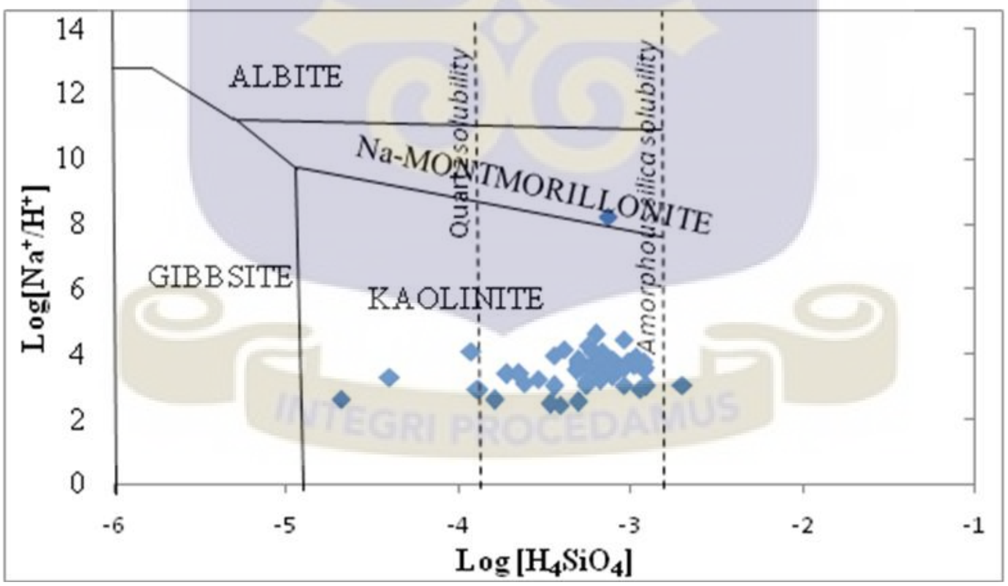


Figure 5-15: The stability of albite and its possible weathering products gibbsite, kaolinite, and Na-montmorillonite with respect to groundwater within the Lower Pra Basin.
(After Tardy, 1971)

Consistent with natural waters with low silica concentrations (Hounslow, 1995), majority of the groundwaters plot in the kaolinite- stability field indicating that; kaolinite is the most stable secondary aluminosilicate mineral phase for the groundwater system. Thus, silicate weathering contributes to the Na^+ content in groundwater within the basin. The SiO_2/ (Na^++K^+-Cl^-) ratios for all (100 %) the groundwaters were less than one [i.e. SiO_2/ (Na^++K^+-Cl^-) < 1] (Table 5-13), suggesting cation-exchange reactions as significant processes through which Na^+ enters groundwater within the basin.

According to Jankowski *et al.*, (1998), waters undergoing ion- exchange would typically plot along a line whose slope is -1 while, waters plotting close to the zero value on the x-axis are not influenced by ion- exchange. In order to investigate the occurrence of cation-exchange reaction in groundwater within the basin, Ca^{2+} + Mg^{2+}- (HCO_3^- + SO_4^{2-}) (meq L^{-I}) was plotted against Na^+ - Cl^- (meq L^{-I}). Given that, the most likely additional sources of contribution of Ca^{2+} and Mg^{2+} to groundwater apart from cation-exchange are calcite, dolomite, gypsum and anhydrite, in plotting this diagram, possible contributions of Ca^{2+} and Mg^{2+} from calcite, dolomite, gypsum and anhydrite dissolution to lithogenic Ca^{2+} and Mg^{2+} in the groundwater were compensated for by subtracting the equivalent concentrations of HCO_3^- and SO_4^{2-} (Nkotagu, 1996; McClean and Jankowski, 2000).

Similarly, to compensate for lithogenic Na^+ available for cation-exchange, Na^+ contribution from meteoric origin was assumed to be balanced by equivalent concentration of Cl^- and therefore, equivalent Cl^- concentration was subtracted from that of Na^+ (Nkotagu, 1996; McClean and Jankowski, 2000). The Ca^{2+} + Mg^{2+}- (HCO_3^- + SO_4^{2-}) (meq L^{-I}) vs Na^+ - Cl^- for groundwater within the basin showing Na^+/ (Na^+ + Cl^-) ratios greater than 0.5 is presented in Figure 5-16. Figure 5-16 show that, the groundwaters plot along a line with slope -1.0121 (away from the zero value of the x-axis), suggesting that indeed, cation-exchange processes are taking place in groundwater within the basin.

Table 5-13: Ratios of major ions and silica in groundwater within the Lower Pra Basin

Sample source	Sample ID	SiO_2	HCO_3^-	HCO_3^-/SiO_2	$SiO_2/(Na^++K^+-Cl^-)$	$Na^++K^+-Cl^-/(Na^++K^+-Cl^-+Ca^{2+})$	$Na^+/(Na^++Cl^-)$	$Ca^{2+}/(Ca^{2+}+SO_4^{2-})$	$Cl/\sum anions$	$HCO_3/\sum anions$
Assin Nyakomase		0.54	1.84	3.39	0.09	0.9	0.58	0.43	0.36	0.33
Assin Nyakomase		0.44	1.12	2.54	0.22	0.9	0.69	0.39	0.24	0.47
Assin Nyakomase		0.60	0.62	1.03	0.40	0.9	0.63	0.21	0.23	0.29
Brofoyedru Habitat	101BU3	0.16	1.01	10.05	0.15	0.7	0.76	0.51	0.10	0.50
Akonfudi		0.56	1.56	2.86	0.22	0.7	0.46	0.61	0.30	0.39
Akonfudi		0.41	1.60	3.88	0.13	0.7	0.48	0.68	0.40	0.39
Nkrafo	098BU3	0.61	3.11	5.10	0.18	0.6	0.54	0.94	0.30	0.67
Nkrafo	096BU3	0.40	1.02	2.54	0.30	0.6	0.51	0.79	0.29	0.50
Obirikwaku	099BU3	0.55	2.32	4.22	0.43	0.4	0.67	0.81	0.11	0.72
Odumase Camp	405BU2	0.37	0.73	1.97	0.22	0.8	0.45	0.64	0.41	0.33
Odumase Camp	407BU2	0.28	1.37	4.91	0.09	0.8	0.57	0.51	0.34	0.35
Obobakrokrowa		0.07	2.81	40.93	0.04	0.4	0.49	0.95	0.21	0.74
Obobakrokrowa		0.57	1.56	2.73	0.20	0.8	0.57	0.65	0.35	0.45
Ayitey	094BU3	0.59	1.10	1.86	0.37	0.7	0.56	0.79	0.30	0.54
Danyiase Domeabra	093BU3	0.47	1.84	3.96	0.34	0.6	0.72	0.84	0.14	0.75
Anyinase Ankase	030BU3	0.15	0.70	4.77	0.16	0.7	0.61	0.67	0.22	0.45
Gromsa		0.40	1.17	2.92	0.25	0.5	0.42	0.76	0.30	0.39
Somnyamekodur	138BU1	0.29	2.44	8.43	0.06	0.9	0.58	0.76	0.42	0.50
Twifo Agona	236BU2	0.29	1.55	5.28	0.26	0.5	0.63	0.67	0.13	0.58
Nyamebekyere	339BU3	0.26	1.07	4.10	0.18	0.8	0.58	0.86	0.31	0.61
Jerusalem		0.22	0.45	2.07	0.28	0.9	0.68	0.47	0.18	0.39
Assin Breku		0.53	1.65	3.11	0.22	0.7	0.48	0.50	0.26	0.36
Assin Breku (Gyidi)	102BU3	0.50	3.00	6.04	0.31	0.5	0.82	0.67	0.06	0.67
Assin Breku (SDA)	100BU3	0.10	1.07	10.75	0.08	0.6	0.55	0.91	0.29	0.61
Techiman No. 1	396BU2	0.26	0.45	1.72	0.37	0.8	0.68	0.41	0.13	0.29
Kwame Ankra	411BU2	0.56	0.94	1.68	0.37	0.7	0.61	0.80	0.29	0.50
Ninkyiso		0.30	1.07	3.51	0.16	0.8	0.63	0.55	0.29	0.48
Sabina		0.57	1.84	3.23	0.32	0.6	0.72	0.72	0.16	0.64

Sample source	Sample ID	SiO_2	HCO_3^-	HCO_3^-/SiO_2	$SiO_2/(Na^++K^+-Cl^-)$	$Na^++K^+-Cl^-/(Na^++K^+-Cl^-+Ca^{2+})$	$Na^+/(Na^++Cl^-)$	$Ca^{2+}/(Ca^{2+}+SO_4^{2-})$	$Cl/\sum anions$	$HCO_3/\sum anions$
Dwedaama		0.49	3.24	6.56	0.23	0.5	0.47	0.95	0.24	0.73
Dwedaama		0.30	0.90	3.02	0.37	0.5	0.54	0.76	0.18	0.49
WoraKesse Habitat	097BU3	0.26	0.52	1.99	0.21	0.9	0.59	0.53	0.31	0.37
Antoabasa		0.26	0.86	3.37	0.14	0.8	0.68	0.42	0.19	0.30
Antoabasa		0.37	1.05	2.81	0.14	0.8	0.63	0.57	0.32	0.36
Anum	086BU3	0.44	2.27	5.18	0.21	0.6	0.67	0.85	0.20	0.71
Mampong		0.34	1.33	3.96	0.04	0.8	0.37	0.56	0.53	0.15
Essamang		0.30	0.48	1.58	0.61	0.6	0.66	0.90	0.22	0.64
Mamponso	24-B-85-1	0.15	0.54	3.58	0.13	0.6	0.52	0.55	0.18	0.19
Sienchem	24/B/32/1	0.37	1.94	5.28	0.07	0.8	0.55	0.63	0.40	0.35
Sienchem	24/B/32/1	0.19	0.61	3.20	0.10	0.7	0.56	0.50	0.21	0.20
Kyeikurom		0.35	1.02	2.95	0.28	0.7	0.75	0.56	0.14	0.51
Adukurom	088BU3	0.29	1.20	4.16	0.22	0.7	0.58	0.69	0.24	0.58
Nsuekyir	219BU1	0.26	1.15	4.47	0.15	0.7	0.49	0.63	0.28	0.41
Assin Nyakomase		0.18	0.51	2.89	0.03	0.9	0.58	0.42	0.29	0.09
Assin Nyakomase		0.41	1.02	2.51	0.23	0.9	0.73	0.33	0.19	0.45
Assin Nyakomase		0.57	0.61	1.07	0.77	0.9	0.71	0.18	0.11	0.34
Brofoyedru Habitat	101BU3	0.16	0.96	6.04	0.14	0.7	0.77	0.55	0.12	0.50
Akonfudi		0.60	1.53	2.55	0.16	0.8	0.41	0.66	0.39	0.38
Akonfudi		0.40	1.57	3.96	0.12	0.8	0.48	0.65	0.39	0.39
Assin Breku		0.56	1.62	2.87	0.22	0.7	0.47	0.89	0.40	0.53
Assin Breku (Gyidi)	102BU3	0.55	3.16	5.79	0.38	0.4	0.81	0.68	0.05	0.69
Assin Breku (SDA)	100BU3	0.57	1.04	1.84	0.46	0.6	0.52	0.90	0.31	0.60
Techiman No. 1	396BU2	0.35	0.40	1.14	0.53	0.8	0.71	0.38	0.11	0.27
Kwame Ankra	411BU2	0.61	0.92	1.52	0.47	0.7	0.67	0.75	0.23	0.54
Ninkyiso		0.32	1.10	3.43	0.17	0.8	0.67	0.59	0.27	0.51
Sabina		0.52	1.76	3.38	0.32	0.6	0.70	0.74	0.16	0.62
Ayitey	094BU3	0.46	1.12	2.43	0.30	0.7	0.55	0.80	0.29	0.53
Nkrafo	098BU3	0.35	3.32	9.36	0.17	0.5	0.70	0.96	0.14	0.83

Sample source	Sample ID	SiO_2	HCO_3^-	HCO_3^-/SiO_2	$SiO_2/(Na^++K^+-Cl^-)$	$Na^++K^+-Cl^-/(Na^++K^+-Cl^-+Ca^{2+})$	$Na^+/(Na^++Cl^-)$	$Ca^{2+}/(Ca^{2+}+SO_4^{2-})$	$Cl/\sum anions$	$HCO_3/\sum anions$
Nkrafo	096BU3	0.37	1.10	3.00	0.36	0.5	0.57	0.78	0.20	0.56
Obirikwaku	099BU3	0.57	2.16	3.78	0.46	0.4	0.72	0.80	0.10	0.71
Odumase Camp	405BU2	0.25	0.56	2.30	0.23	0.7	0.69	0.61	0.19	0.36
Obobakokrowa	246JBU1	0.45	2.76	6.14	0.29	0.4	0.58	0.95	0.17	0.78
Obobakokrowa		0.57	1.54	2.70	0.23	0.8	0.58	0.70	0.33	0.50
Odumase Camp	407BU2	0.33	1.45	4.41	0.10	0.8	0.57	0.55	0.35	0.37
Dwedaama		0.16	3.16	20.02	0.06	0.5	0.43	0.95	0.29	0.68
Dwedaama		0.30	0.59	1.99	0.35	0.6	0.53	0.69	0.21	0.34
WoraKesse Habitat	097BU3	0.27	0.52	1.94	0.22	0.9	0.60	0.51	0.30	0.38
Antoabasa		0.26	0.96	3.73	0.15	0.8	0.66	0.44	0.19	0.34
Antoabasa		0.36	1.08	3.03	0.14	0.8	0.62	0.56	0.32	0.38
Anum	086BU3	0.29	2.32	8.05	0.14	0.6	0.68	0.84	0.19	0.71
Kyeikurom		0.33	1.08	3.26	0.27	0.7	0.76	0.57	0.14	0.54
Adukurom	088BU3	0.21	1.17	5.66	0.17	0.7	0.58	0.61	0.22	0.54
Nsuekyir	219BU1	0.28	1.12	4.05	0.19	0.7	0.48	0.63	0.25	0.42
Danyiase Domeabra	093BU3	0.30	1.68	5.64	0.25	0.6	0.72	0.83	0.13	0.74
Anyinase Ankase	030BU3	0.16	0.76	4.80	0.23	0.6	0.73	0.67	0.12	0.55
Gromsa		0.37	1.12	3.05	0.24	0.5	0.42	0.77	0.29	0.39
Somnyamekodur	138BU1	0.29	2.31	7.98	0.06	0.9	0.59	0.71	0.43	0.48
Twifo Agona	236BU2	0.31	1.52	4.89	0.27	0.6	0.70	0.65	0.11	0.59
Nyamebekyere	339BU3	0.28	1.04	3.74	0.19	0.8	0.60	0.86	0.31	0.60
Jerusalem		0.22	0.48	2.17	0.30	0.9	0.67	0.43	0.17	0.41
Mampong		0.15	1.32	8.78	0.02	0.8	0.39	0.58	0.52	0.16
Essamang		0.30	0.46	1.53	0.60	0.6	0.68	0.89	0.22	0.64
Mamponso	24-B-85-1	0.15	0.52	3.46	0.16	0.5	0.65	0.53	0.11	0.18
Sienchem	24/B/32/1	0.35	1.21	3.45	0.06	0.8	0.47	0.65	0.53	0.20
Sienchem	24/B/32/1	0.18	0.60	3.35	0.10	0.7	0.54	0.50	0.22	0.20
WoraKesse Habitat	097BU3	0.36	0.72	2.00	0.42	0.6	0.46	0.77	0.27	0.49
Brofoyedru Habitat	101BU3	0.36	1.52	4.26	0.55	0.4	0.39	0.70	0.14	0.61

Sample source	Sample ID	SiO_2	HCO_3^-	HCO_3^-/SiO_2	$SiO_2/(Na^++K^+-Cl^-)$	$Na^++K^+-Cl^-/(Na^++K^+-Cl^-+Ca^{2+})$	$Na^+/(Na^++Cl^-)$	$Ca^{2+}/(Ca^{2+}+SO_4^{2-})$	Cl/∑anions	HCO_3/∑anions
Akonfude		0.39	0.52	1.35	0.33	0.5	0.43	0.67	0.22	0.19
Akonfude		0.36	0.45	1.25	0.20	0.6	0.45	0.59	0.20	0.10
Akonfude		0.28	0.36	1.26	0.13	0.7	0.77	0.51	0.12	0.09
Nkrafo	098BU3	0.36	2.00	5.62	0.17	0.7	0.77	0.51	0.12	0.55
Nkrafo	096BU3	0.39	5.88	15.18	0.12	0.5	0.67	0.77	0.12	0.73
Obirikwaku	099BU3	0.38	3.44	9.07	0.18	0.6	0.77	0.78	0.10	0.77
Odumase Camp	405BU2	0.32	1.28	3.99	0.16	0.8	0.78	0.46	0.14	0.43
Obobakokrowa		0.31	0.68	2.21	0.15	0.7	0.40	0.46	0.29	0.17
Odumase Camp	407BU2	0.49	2.36	4.81	0.17	0.7	0.61	0.52	0.21	0.47
Dwedaama		0.36	3.48	9.58	0.15	0.7	0.85	0.43	0.06	0.63
Dwedaama		0.29	1.44	5.03	0.21	0.7	0.70	0.47	0.13	0.51
Assin Nyankomase		0.12	0.68	5.72	0.03	0.9	0.47	0.52	0.50	0.18
Assin Nyankomase		0.29	0.40	1.39	0.18	0.8	0.55	0.25	0.13	0.08
Assin Nyankomase		0.28	0.88	3.10	0.12	0.8	0.57	0.51	0.32	0.31
Amoakokrom	337BU3	0.38	0.88	2.33	0.16	0.8	0.57	0.51	0.32	0.31
Nyamebekyere	339BU3	0.30	0.88	2.89	0.26	0.6	0.72	0.47	0.10	0.29
Jerusalem		0.29	1.48	5.07	0.15	0.7	0.63	0.48	0.18	0.38
Antoabasa		0.57	1.68	2.93	0.20	0.8	0.59	0.64	0.31	0.46
Antoabasa		0.57	2.40	4.20	0.30	0.6	0.75	0.65	0.11	0.63
Anum	086BU3	0.55	1.80	3.27	0.31	0.8	0.74	0.75	0.18	0.74
Kyeikurom		0.42	1.36	3.28	0.28	0.6	0.66	0.47	0.12	0.38
Adukurom	088BU3	0.59	3.16	5.38	0.24	0.6	0.64	0.66	0.17	0.64
Subriso		0.50	2.00	4.02	0.37	0.7	0.71	0.58	0.11	0.65
Nsuekyir	219BU1	0.55	2.84	5.17	0.27	0.7	0.79	0.72	0.11	0.79
Danyease Domeabra	093BU3	0.38	1.32	3.50	0.23	0.7	0.57	0.67	0.26	0.52
Bediadua		0.45	1.92	4.24	0.32	0.6	0.84	0.67	0.08	0.71
Assin Breku (SDA)	102BU3	0.51	2.56	5.05	0.36	0.6	0.79	0.75	0.09	0.80
Assin Breku (Gyidi)	100BU3	0.41	1.60	3.91	0.22	0.7	0.57	0.50	0.19	0.41
Assin Breku		0.52	1.08	2.06	0.33	0.7	0.66	0.50	0.16	0.35

Sample source	Sample ID	SiO_2	HCO_3^-	HCO_3^-/SiO_2	$SiO_2/(Na^++K^+ -Cl^-)$	$Na^++ K^+ -Cl^-/(Na^++K^+ -Cl^- + Ca^{2+})$	$Na^+/(Na^+ +Cl^-)$	$Ca^{2+}/(Ca^{2+}+SO_4^{2-})$	$Cl/\sum anions$	$HCO_3/\sum anions$
Kwame Ankra	411BU2	0.38	0.64	1.68	0.39	0.8	0.76	0.34	0.09	0.26
Techiman No. 1	396BU2	0.43	0.52	1.22	0.29	0.8	0.55	0.31	0.21	0.18
Ninkyiso		0.55	2.92	5.31	0.24	0.7	0.73	0.55	0.12	0.63
Sabina		0.53	1.96	3.72	0.33	0.6	0.75	0.45	0.09	0.48
Ayitey	094BU3	0.30	1.72	5.81	0.21	0.6	0.67	0.51	0.13	0.52
Gromsa		0.29	1.32	4.49	0.09	0.8	0.52	0.37	0.26	0.25
Atu Kurom		0.46	4.08	8.90	0.33	0.5	0.84	0.57	0.04	0.70
Subreso		0.40	1.32	3.29	0.26	0.6	0.83	0.39	0.07	0.34
Anyinase Ankase	030BU3	0.26	1.28	4.84	0.20	0.7	0.70	0.58	0.14	0.51
Somnyamekordur	138BU1	0.46	4.56	9.86	0.10	0.5	0.44	0.95	0.32	0.64
Somnyamekordur	033BU3	0.51	1.94	3.82	0.41	0.4	0.58	0.70	0.13	0.53
Breman	260BU2	0.69	3.08	4.47	0.22	0.7	0.63	0.47	0.17	0.49
Breman		0.51	2.44	4.81	0.38	0.5	0.71	0.58	0.09	0.59
Twifo Agona	236BU2	0.44	3.36	7.55	0.20	0.6	0.69	0.60	0.10	0.61
Zion Camp	014BU3	0.34	4.08	12.17	0.01	0.8	0.34	0.51	0.59	0.12
Twifo Mampong		0.35	1.00	2.84	0.24	0.7	0.83	0.26	0.06	0.22
Twifo Mampong		0.42	0.88	2.11	0.26	0.7	0.79	0.33	0.07	0.19
Akwa Yaw		0.39	2.44	6.32	0.27	0.6	0.84	0.67	0.07	0.74
Mampong		0.36	3.64	10.17	0.05	0.7	0.53	0.60	0.34	0.40
Essamang		0.34	0.56	1.66	0.28	0.8	0.63	0.37	0.15	0.22
Mamponso	24-B-85-1	0.28	0.68	2.44	0.18	0.7	0.46	0.49	0.28	0.23
Sienchem	24/B/32/1	0.33	2.38	7.16	0.05	0.8	0.55	0.66	0.46	0.36
Sienchem	24/B/32/1	0.37	1.76	4.76	0.11	0.7	0.45	0.50	0.29	0.30

All parameters are in meq/L, except, SiO_2 (mmol/L).

Cation-exchange reactions therefore, partly explain the observed excess of Na^+ over Cl^- in groundwater within the basin.

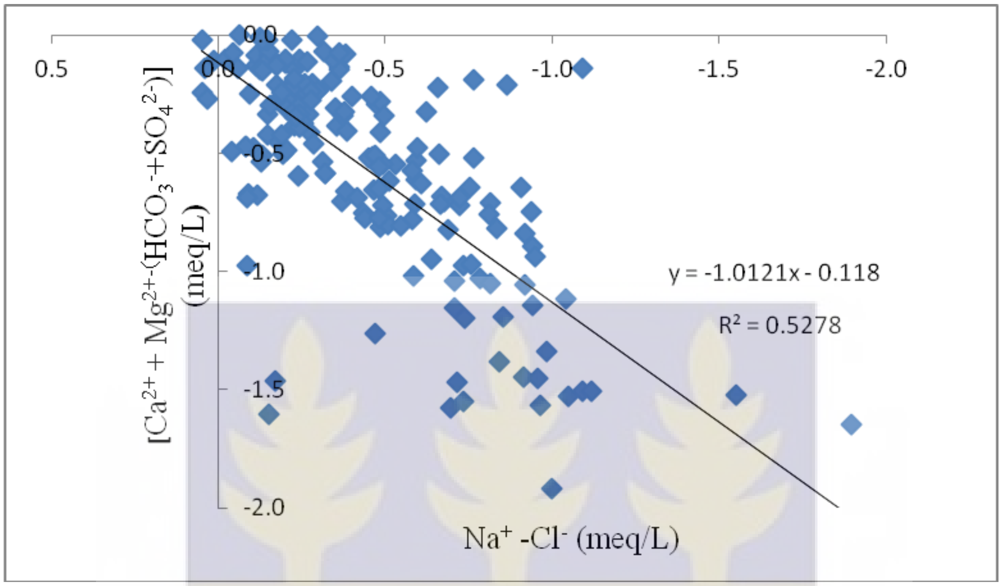


Figure 5-16: Relationship between Na^+- Cl^- vs Ca^{2+} + Mg^{2+}- (HCO_3^- +SO_4^{2-}) for groundwater within the Lower Pra Basin.

Indices of Base Exchange in groundwater within the Lower Pra Basin

Variations in chemical composition of groundwater along its flow-path can be explicitly understood by investigating the Chloro-Alkaline Indices (CAI) (Schoeller 1965, 1977). Ion-exchange between groundwater and its host environment during residence time or in movement process are the essential controlling factors for groundwater composition (Schoeller 1965, 1977). Schoeller (1965, 1977) proposed that, two Chloro-Alkaline Indices, CAI_1 and CAI_2 are essential for the interpretation of ion- exchange between groundwater and its host environment. The Chloro-Alkaline Indices are calculated from Equations 5-18 and 5-19 Schoeller (1965, 1977):

$$CAI_1 = [Cl^- - (Na^+ + K^-)]/Cl^- \qquad 5\text{-}18$$

$$CAI_2 = [Cl^- - (Na^+ + K^+)]/ (SO_4^{2-} + HCO_3^- + CO_3^- + NO_3^-) \qquad 5\text{-}19$$

where, a positive Chloro-Alkaline index denotes an exchange of Na^+ and K^+ from the water with Mg^{2+} and Ca^{2+} in the rocks and, a negative Chloro-Alkaline index denotes an exchange of Mg^{2+} and Ca^{2+} from the water with Na^+ and K^+ in the rocks (Nagaraju *et al.*, 2006). This has been widely accepted and cited by previous authors (i.e Zhu *et al.*, 2007; Ashwani and Abhay, 2014).

To investigate cation-exchange reactions which seem to be one of the dominant hydrogeochemical process influencing groundwater within the basin as suggested by the computed Na^+/ (Na^+ + Cl^-) ratios and presented graphically as in Figure 5-16, the Chloro-Alkaline Indices as suggested by Schoeller (1965, 1977) were computed. Results show that, CAI_1 indices ranged -6.14 to 0.39 with a mean value of -1.63, while, CAI_2 indices ranged -0.65 to 0.67 with a mean value of -0.25 (Table 5-14). Majority of the computed CAI_1 and CAI_2 indices are negative suggesting an exchange of Mg^{2+} and Ca^{2+} from groundwater within the basin with Na^+ and K^+ in the rocks. Thus, the computed Chloro-Alkaline Indices suggests the Na^+/ (Na^+ + Cl^-) ratios and therefore, indicates that, cation-exchange reactions are predominantly, taking place in groundwater within the basin in which case, Ca^{2+} and Mg^{2+} are being exchanged with Na^+ and K^+ in the rocks.

Groundwater with a base-exchange reaction in which alkaline earths are exchanged for Na^+ (HCO_3^- > Ca^{2+} + Mg^{2+}) may be regarded as base-exchanged softened water, and those in which Na^+ are exchanged for the alkaline earths (Ca^{2+} + Mg^{2+} > HCO_3^-) may be regarded as base- exchange hardened water (Ashwani and Abhay, 2014). Additionally, in the Lower Pra Basin, 91.0 % of groundwater had higher HCO_3^- than alkaline earths (i.e. HCO_3^- > Ca^{2+} + Mg^{2+}) suggesting exchange of alkaline earths for Na^+ and K^+.

Thus, groundwater within the basin may be regarded as base- exchange softened water. During this process the host lithology is the primary source of dissolved solids in the groundwater.

Table 5-14: Chloro-Alkaline Indices for Base Exchange in groundwater within the Lower Pra Basin

Sample source	BHID	Na^+	K^+	Na^++K^+	Cl^-	Cl-(Na+K)	CAI_1	HCO_3^-	SO_4^{2-}	NO_3^-	$(HCO_3+SO_4+NO_3)$	CAI_2
Sabina		1.46	0.13	1.59	0.53	-1.05	-1.98	1.82	0.91	0.01	2.74	-0.39
Ayitey	094BU3	1.08	0.14	1.22	0.34	-0.89	-2.65	1.69	0.72	0.01	2.42	-0.37
Nkrafo	098BU3	1.37	0.21	1.59	0.34	-1.25	-3.73	1.79	0.70	0.01	2.50	-0.50
Nkrafo	096BU3	1.98	0.14	2.13	1.07	-1.06	-0.99	5.69	0.92	0.00	6.61	-0.16
Obirikwaku	099BU3	1.20	0.32	1.52	0.39	-1.13	-2.90	2.93	0.38	0.00	3.31	-0.34
Odumase Camp	405BU2	1.33	0.22	1.55	0.29	-1.26	-4.38	1.24	0.70	0.00	1.94	-0.65
Odumase Camp	407BU2	1.46	0.14	1.60	1.03	-0.58	-0.56	2.35	1.08	0.00	3.44	-0.17
Obobakokrowa	246JBU1	0.92	0.11	1.03	1.20	0.17	0.14	0.71	0.87	0.00	1.58	0.11
Dwedaama		1.78	0.19	1.97	0.30	-1.67	-5.48	3.32	1.22	0.00	4.53	-0.37
Dwedaama		0.80	0.13	0.93	0.37	-0.56	-1.51	1.41	0.50	0.00	1.92	-0.29
WoraKesse Habitat	097BU3	0.30	0.10	0.40	0.34	-0.06	-0.19	0.66	0.22	0.00	0.89	-0.07
Brofoyedru Habitat	101BU3	0.25	0.06	0.31	0.34	0.02	0.07	1.43	0.35	0.00	1.79	0.01
Assin Nyankomase		2.11	1.10	3.21	1.77	-1.44	-0.81	1.69	1.10	0.03	2.81	-0.51
Assin Nyankomase		1.23	0.25	1.47	0.49	-0.98	-1.98	1.10	0.38	0.02	1.50	-0.65
Assin Nyankomase		0.79	0.17	0.97	0.42	-0.54	-1.28	0.62	0.46	0.02	1.11	-0.49
Akonfude		1.03	0.43	1.46	1.40	-0.06	-0.04	1.56	0.55	0.01	2.12	-0.03
Akonfude		1.51	0.15	1.66	1.62	-0.03	-0.02	1.57	0.57	0.01	2.15	-0.02
Assin Breku (SDA)	100BU3	0.56	0.11	0.67	0.56	-0.12	-0.21	1.05	0.07	0.01	1.12	-0.10
Assin Breku (Gyidi)	102BU3	1.01	0.12	1.14	0.25	-0.89	-3.53	3.18	0.88	0.01	4.07	-0.22
Assin Breku		1.06	0.17	1.24	1.21	-0.03	-0.02	1.61	0.11	0.01	1.73	-0.02
Techiman No.1	396BU2	0.43	0.13	0.56	0.22	-0.33	-1.49	0.53	0.32	0.01	0.85	-0.39
Kwame Ankra	411BU2	0.84	0.14	0.98	0.46	-0.52	-1.12	0.97	0.24	0.01	1.22	-0.43
Ninkyiso		1.03	0.16	1.19	0.65	-0.54	-0.82	1.06	0.29	0.01	1.36	-0.39
Amoakokrom	337BU3	1.20	0.11	1.31	0.93	-0.38	-0.41	0.89	0.48	0.00	1.36	-0.28
Nyamebekyere	339BU3	0.74	0.13	0.86	0.55	-0.31	-0.57	1.07	0.07	0.01	1.15	-0.27
Jerusalem	339BU3	0.42	0.13	0.55	0.21	-0.34	-1.61	0.48	0.17	0.01	0.65	-0.52
Antoabasa	0502B1/01/09701	1.10	0.12	1.22	0.53	-0.69	-1.29	0.87	0.69	0.01	1.57	-0.44
Antoabasa		1.61	0.10	1.71	0.91	-0.80	-0.87	1.07	0.48	0.01	1.55	-0.51

Sample source	BHID	Na^+	K^+	Na^++K^+	Cl^-	Cl-(Na+K)	CAI_1	HCO_3^-	SO_4^{2-}	NO_3^-	$(HCO_3 + SO_4 + NO_3)$	CAI_2
Bediadua		1.16	0.04	1.20	0.23	-0.97	-4.21	1.96	0.35	0.00	2.31	-0.42
Anum		1.27	0.08	1.35	0.46	-0.89	-1.95	1.82	0.19	0.00	2.01	-0.44
Kyeikurom	086BU3	0.92	0.18	1.10	0.45	-0.64	-1.42	1.35	1.03	0.00	2.38	-0.27
Subrisu		1.58	0.10	1.68	0.79	-0.90	-1.14	1.22	0.70	0.01	1.92	-0.47
Adukrom	088BU3	0.93	0.16	1.09	0.40	-0.68	-1.69	2.13	0.51	0.00	2.64	-0.26
Subriso		1.53	0.16	1.69	0.40	-1.29	-3.20	2.88	0.29	0.00	3.17	-0.41
Nsuekyir	219BU1	0.95	0.09	1.04	0.69	-0.35	-0.50	1.45	0.36	0.00	1.81	-0.19
Denyease Domeabra	093BU3	1.27	0.07	1.34	0.35	-0.99	-2.86	0.94	1.65	0.01	2.60	-0.38
Twifo Mampong		1.27	0.07	1.33	0.37	-0.96	-2.58	1.64	1.57	0.01	3.22	-0.30
Twifo Mampong		1.07	0.07	1.14	0.22	-0.92	-4.19	2.48	0.47	0.01	2.95	-0.31
Akwa Yaw		1.74	0.34	2.08	1.05	-1.03	-0.98	3.09	1.62	0.02	4.73	-0.22
Bremamg	260BU2	0.93	0.09	1.01	0.37	-0.64	-1.74	2.46	0.94	0.00	3.40	-0.19
Bremamg		1.31	0.39	1.70	0.57	-1.13	-1.98	3.44	1.16	0.00	4.61	-0.24
Twifo Agona	236BU2	10.27	1.73	11.99	19.52	7.53	0.39	3.96	7.35	0.01	11.32	0.67
Zion Camp	014BU3	1.84	0.33	2.17	2.30	0.13	0.06	4.55	0.24	0.00	4.80	0.03
Somnyamekordur	138BU1	0.70	0.09	0.79	0.48	-0.31	-0.65	1.96	0.82	0.00	2.77	-0.11
Somnyamekordur	033BU3	1.66	0.41	2.07	0.29	-1.78	-6.14	4.12	1.21	0.01	5.34	-0.33
Atu Kurom		1.23	0.07	1.31	0.26	-1.05	-4.03	1.33	1.30	0.00	2.64	-0.40
Subreso		1.49	0.31	1.80	1.40	-0.40	-0.29	1.36	1.48	0.01	2.85	-0.14
Gromsa	032BU3	0.86	0.10	0.96	0.37	-0.59	-1.58	1.29	0.50	0.03	1.82	-0.32
Anyinase Ankase	030BU3	0.80	0.32	1.11	0.66	-0.45	-0.69	0.69	0.63	0.03	1.35	-0.34
Sienkyem	24/B/32/1	2.71	0.34	3.05	2.12	-0.93	-0.44	1.97	1.07	0.06	3.09	-0.30
Sienkyem	24/B/32/1	0.60	0.07	0.67	0.32	-0.35	-1.10	0.54	0.71	0.07	1.33	-0.26
Mamponso	24-B-85-1	0.36	0.02	0.38	0.18	-0.20	-1.14	0.51	0.04	0.01	0.56	-0.36
Essamang		2.88	0.27	3.15	4.35	1.20	0.28	1.35	1.52	0.05	2.92	0.41

CAI_1 = Chloro-Alkaline index 1, CAI_2 = Chloro-Alkaline index 2

Sources of HCO_3^-, SO_4^{2-} and Cl^- in groundwater within the Lower Pra Basin

Principal sources of HCO_3^- in groundwater are carbonate and silicate weathering by CO_2 – charged water (Hounslow, 1995). However, saturation indices as calculated for calcite and dolomite minerals for the two most productive minerals responsible for the bulk alkalinity for the neutralization of acidity generated as a result of mining (Nilsen and Grammeltvedt, 1993) in groundwater within the Lower Pra Basin using Phreeqc for Windows shows that groundwaters have come from environments where, calcite and dolomite are impoverished. Carbonate weathering by carbon dioxide charged water to release HCO_3^- is therefore unlikely. This leaves silicate/aluminosilicate weathering by carbon dioxide charged water as the weathering process significantly responsible for the HCO_3^- concentrations in groundwater within the basin.

This is consistent with the Gibbs (1970) diagram (see Figure 5-7). SO_4^{2-} concentrations in groundwater within the basin is possibly due to the application of chemical products such as ammonium sulphate fertilizers via agricultural activities. Cl^- concentrations is possibly due to sea aerosol spray as a result of the maritime climate which is prevalent along the coast where, the study area is located.

5.13.2.2 Sources of minor ions

The concentrations of NO_2-N, NO_3-N, NH_4-N, PO_4-P and F^- were either very low or below detection and therefore pose no threat to groundwater within the basin. This suggests that, even though agricultural activities are taking place within the study area where, a minimum of two crops are cultivated annually and additionally inorganic fertilizers are being used, these activities do not seem to have significant influence on groundwater resources.

5.13.3. Using stable isotopes to determine the origin of groundwater within the Lower Pra Basin.

The mean values of stable isotopes in groundwater from previous studies in Ghana are presented alongside results from this study in Table 5-15. From Table 5-15, the mean values for $\delta^{18}O$ ranged from -2.12 ‰ to -3.80 ‰. Thus, a mean isotopic composition of groundwater within the Lower Pra Basin of -2.49 ‰ for $\delta^{18}O$ is consistent with the isotopic compositions of groundwater in Ghana.

Table 5-15: Mean values of stable isotopes ($\delta^{18}O$) in groundwater from previous studies in Ghana alongside the results from this study

Locality	Mean value ‰ ($\delta^{18}O$)	Reference
Accra Plains	-2.80	Akiti (1980)
Afram Plains	-3.00	Acheampong (1996)
Northern and Upper Regions	-3.80	Kortatsi and Sekpey (1993)
Tarkwa-Prestea area	-2.12	Kortatsi (2004)
Pra Basin	-2.49	This Study (2012)

Results of $\delta^{2}H$ ‰ and $\delta^{18}O$ ‰ analyses of forty one (41) boreholes, seven (7) streams and Pra River sampled at Twifo Praso and Beposo within the Lower Pra Basin are presented in Table 5-16 , while, Table 5-17 presents the statistical summary of $\delta^{2}H$ ‰ and $\delta^{18}O$ ‰ for ground and surface water. The data indicates variation in $\delta^{18}O$ from -3.24 ‰ to -0.95 ‰ with mean and median values of -2.49 ‰ and -2.53 ‰ respectively and $\delta^{2}H$ from -15.25 ‰ to -1.67 ‰ with mean and median values of -10.45 ‰ and -10.35 ‰ respectively for boreholes.

The stream water show variation in $\delta^{18}O$ from -2.34 ‰ to -3.22 ‰ with mean and median values of -2.65 ‰ and -2.55 ‰ and $\delta^{2}H$ from -9.44 ‰ to -17.10 ‰ with mean and median values of -11.86 ‰ and -10.71 ‰ respectively.

Table 5-16: Stable isotopes ($\delta^{2}H$ ‰ and $\delta^{18}O$‰) and physical parameters for boreholes, streams and river Pra within the Lower Pra Basin

Sample Source	GPS Co-ordinates	Sample ID	SWL(m)	T°C	pH	EC(μS/cm)	$\delta^{18}O$ ‰	$\delta^{2}H$‰
Sabina	N05.86974',W001.27172'		2.7	29.2	6.28	269	-2.88	-12.81
Ayitey	N05.88353',W001.25584'	094BU3	4.61	28.5	5.96	209	-2.8	-12.11
Nkrafo	N05.87813',W001.23365'	098BU3	11.52	28.1	6.71	374	-3.09	-14.23
Nkrafo	N05.88086',W001.23863'	096BU3	2.47	29.3	7.01	469	-2.81	-12.49
Obirikwaku	N05.91570',W001.23361'	099BU3	6.63	29.1	6.07	495	-2.79	-11.98
Odumasi Camp	N05.82454',W001.19149'	405BU2	1.38	30.5	66.2	269	-2.38	-9.80
Obobakokrowa	N05.80277',W001.17656'	246JBU1	15.03	28.7	5.64	135.9	-2.27	-7.81
Odumasi Camp	N05.19421',W001.19421'	407BU2	2.72	28.1	6.14	295	-2.68	-10.90
Dwendaama	N05.80162',W001.20490'		7.16	28	6.12	246	-2.88	-12.87
Dwendaama	N05.80159',W001.20572'		7.1	28.2	6.47	90.4	-2.86	-12.81
WoraKesse Habitat	N05.76445',W001.23152'	097BU3	7.28	27.2	5.33	76.2	-3.1	-14.65
Brofoyedru Habitat	N05.78437',W001.28443'	101BU3	15.61	26.3	5.59	119.2	-2.62	-10.35
Assin Nyankumase	N05.75829',W001.28643'		5.37	26.9	5.24	846	-2.28	-9.18
Assin Nyankumase	N05.75762',W001.29058'		4.72	27.6	5.64	178.4	-2.41	-8.63
Assin Nyankumase	N05.75729',W001.29082'		6.66	27.1	4.80	180.1	-2.15	-8.56
Akonfude	N05.82614',W001.30953'		14.91	25.7	6.87	295	-2.32	-8.13
Akonfude	N05.82945',W001.31011'		6.32	26.2	5.31	533	-1.72	-7.10
Assin Breku (SDA)	N05.86625',W001.33689'	100BU3	5.9	25.6	5.76	132.5	-3.13	-15.06
Assin Breku (Gyidi)	N05.87056',W001.33793'	102BU3	5.34	28.6	6.55	336	-2.87	-12.42
Assin Breku	N05.86808',W001.34099'		0.63	26.9	5.54	291	-2.52	-9.63
Techiman No.1	N05.80440',W001.36794'	396BU2	6.16	26.7	5.36	57.8	-3.01	-13.92
Kwame Ankra	N05.81540',W001.38197'	411BU2	2.89	26.5	5.31	125.7	-2.62	-10.84
Ninkyiso	N05.812119',W001.39917'		9.54	28.2	4.82	216	-2.82	-12.23
Amoakokrom	N05.78654' , W001.34582'	337BU3	4.61	28.8	4.94	329	-2.24	-9.32
Nyamebekyere	N05.76558' , W001.34666'	339BU3	11.72	29.2	5.56	151.6	-3.24	-15.25
Jerusalem	N05.75216' , W001.44366'	0502B1/01/0901	13.12	28.8	5.16	70.5	-2.79	-12.13
Antoabasa	N05.77203' , W001.46879'		8.03	30.4	5.61	168	-2.61	-10.48

Sample Source	GPS Co-ordinates	Sample ID	SWL(m)	T°C	pH	EC(µS/cm)	δ ^{18}O ‰	δ^{2}H‰
Antoabasa	N05.77018' , W001.46949'		7.08	29.2	5.59	220	-2.65	-10.93
Anum	N05.78218' , W001.50222'	086BU3	3.42	28.3	6.1	273	-2.53	-10.31
Kyeikurom	N05.82504' , W001.52242'		2.68	31.6	5.7	145.6	-2.96	-13.84
Adukrom	N05.84924' , W001.52394'	088BU3	3.0	27	5.52	135.8	-3.14	-15.09
Subrisu	N05.82474' , W001.54799'		-	27.1	5.7	245	-2.49	-9.74
Nsuekyir	N05.77244' , W001.50221'	219BU1	1.54	26.5	5.66	169.8	-1.86	-5.34
Denyease Domeabra	N05.74806' , W001.53606'	093BU3	3.01	26.8	5.78	222	-2.41	-8.94
Twifo Mampong	N05.52361' , W001.55671'		2.6	27.4	5.32	279	-1.39	-1.67
Twifo Mampong	N05.52316' , W001.55452'		2.66	26.8	5.73	1140	-0.95	-5.67
Akwa Yaw	N05. 44168' ,W001.48580'		6.7	28.9	5.28	107.7	-2.08	-8.14
Bremang	N05.70882' , W001.60273'	260BU2	0.4	28.5	6.15	308	-1.96	-8.02
Bremang	N05.70720', W001.50387’		6.53	29.8	6.27	216	-1.79	-7.34
Twifo Agona	N05.74540' , W001.50387'	236BU2	7.93	29.9	6.06	1797	-1.75	-7.14
Zion Camp	N05.87221' , W001.64609'	014BU3	5.89	30.7	5.88	265	-2.24	-9.24
Somnyamekordur	N05.66454' , W001.58470'	138BU1	21.83	29.2	6.41	799	-3.02	-14.20
Somnyamekordur	N05.66044' , W001.58376'	033BU3	1.25	29.5	5.47	57.1	-2.31	-9.06
Atu Kurom	N05.60612' , W001.67843'		8.15	28.1	5.29	330	-2.32	-9.45
Subreso	N05.65596' , W001.67676'		-	28.6	6.06	236	-3.13	-15.11
Gromsa	N05.59000' , W001.60611'	032BU3	3.18	28	5.75	171.3	-2.48	-9.89
Amoakokrom	N05.78604' , W001.34668'	Bupa		28.1	6	161.9	-2.60	-11.17
Odumase Camp	N05.82402' , W001.19105'	Esuodom		29.1	6.5	80.0	-3.22	-17.10
Assin Nkukuase	N05.86473',W001.19748'	Fumsuo		27.7	6.09	90.1	-2.75	-11.96
WoraKesse Habitat	N05.76974’,W001.23320’	Frodor		24.5	5.35	80.2	-2.34	-9.44
Twifo Praso	N05.61055',W001.55632'	Pra River		28.3	6.44	100.0	-2.51	-9.99
Bremang	N.05.71210',W001.60150'	Apakamba		27.3	6.07	70.0	-2.55	-10.76
Atu Kurom	N05.63660',W001.67900'	Osini		25.0	5.59	70.0	-2.37	-9.80
Essamang	N.05.36059',W001.67924'	Esuosham		25.0	5.93	60.0	-2.63	-10.96
Beposo	N.05.12278',W001.61845'	Pra River		27.5	6.91	90.0	-2.64	-11.58

SWL – Static water level

Table 5-17: Statistical summary of stable isotope data for boreholes and streams within the Lower Pra Basin

Water Source	δ^2H ‰ Min	δ^2H ‰ Max	δ^2H ‰Mean	δ^2H ‰ Median	$\delta^{18}O$‰ Min	$\delta^{18}O$‰ Max	$\delta^{18}O$‰ Mean	$\delta^{18}O$‰ Median
Borehole	-15.25	-1.67	-10.45	-10.35	-3.24	-0.95	-2.49	-2.53
Stream	-17.10	-9.44	-11.86	-10.76	-3.22	-2.34	-2.65	-2.55
River	-11.58	-9.99	-	-	-2.64	-2.51	-	-

River Pra show variation in $\delta^{18}O$ from -2.62 ‰ to -2.52 ‰ and δ^2H from -11.58 ‰ to -9.99 ‰. Figure 5-17 presents the plot of δ^2H vs $\delta^{18}O$ with the best fit regression line of δ^2H ‰ = 7.2 $\delta^{18}O$ ‰ + 7.8, and a coefficient (r^2) value of 0.92 and a d-excess (δ^2H -7.2 $\delta^{18}O$) of 7.8.

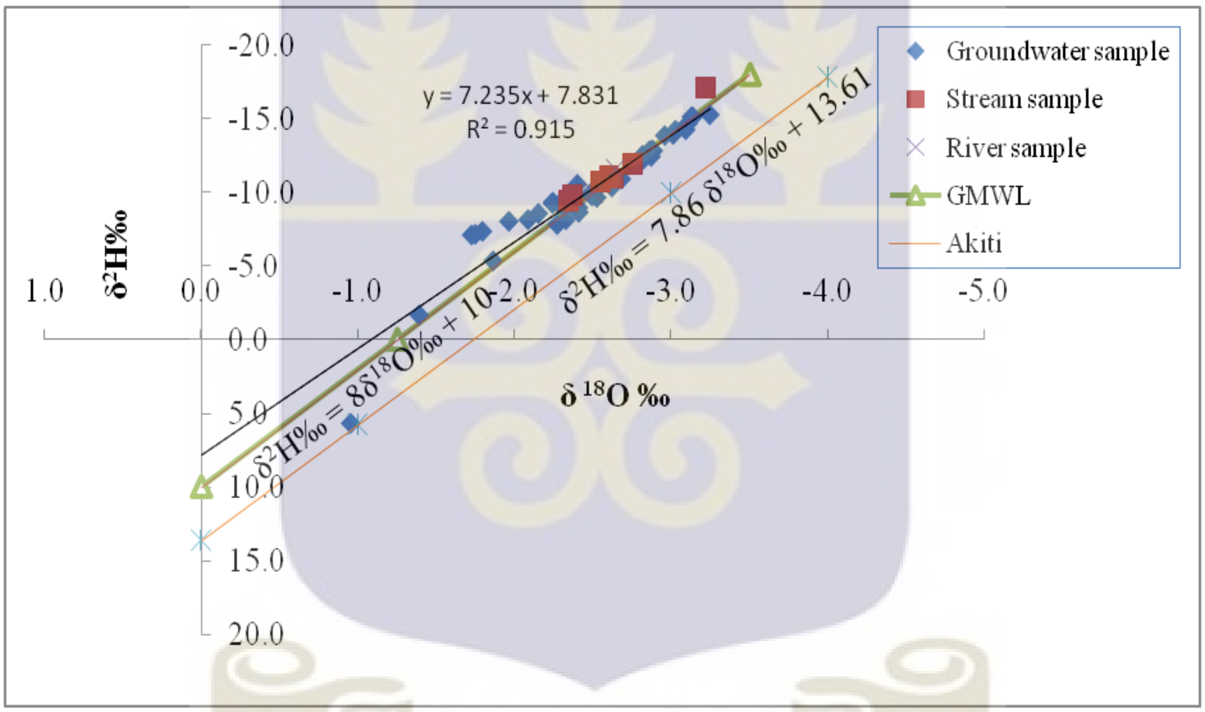


Figure 5-17: Stable isotopes (δ^2H ‰ and $\delta^{18}O$‰) composition of boreholes, streams and rivers within the Lower Pra Basin.

The Global Meteoric Water Line (GMWL) which generally describes the meteoric relationship between the stable isotopes and is a convenient reference line for the explicit understanding and tracing of local groundwater movement and origin is shown for reference (Craig, 1961).

The Local Meteoric Water Line (LMWL) for the Accra Plains (Akiti, 1986) is also shown for comparison with the best fit regression line for this study. The best fit regression line is only slightly deviated from the GMWL and therefore is in conformity with meteoric waters. However, the best fit regression line for this study is strongly deviated from the LMWL by Akiti (1986), and perhaps indicates evaporation on the surface or in the unsaturated zone before recharge.

Literature indicates the non-existence of stable isotope data for rain water for the Lower Pra Basin area. Thus, it is very difficult to establish the local meteoric water line for this study. However, according to IAEA (1983) majority of groundwater will normally plot close to the local meteoric water line unless influenced through isotopic modifications by evaporation, geothermal rock-water reaction or gaseous exchange.

The plot of $\delta^{18}O$ ‰ vs $\delta^{2}H$ ‰ (Figure 5-17) for groundwaters within the Lower Pra Basin show that, majority of the groundwaters (93.0 %) clustered along (either fall on or close to) the global meteoric water line (GMWL). This result suggest that, groundwater within the basin is apparently not influenced by evaporation, geothermal rock-water reaction, or gaseous exchange (see Figure 2-1) and is consistent with result by IAEA (1983) that, groundwater will normally plot close to the local meteoric water line unless influenced by evaporation, geothermal rock-water reaction or gaseous exchange and therefore, almost identical to the GMWL. Thus, Figure 5-17 is similar to the plot of $\delta^{2}H$ ‰ vs $\delta^{18}O$ ‰ in global meteoric water by Craig (1961). $\delta^{2}H$ ‰ and $\delta^{18}O$ ‰ values of groundwater within the basin are therefore, closely clustered along the global meteoric water line ($\delta^{2}H = 8\ \delta^{18}O + 10$) (Craig, 1961), suggesting an integrative, rapid and smooth recharge from meteoric origin.

Similarly, the $\delta^{18}O$ ‰ and $\delta^{2}H$ ‰ values for River Pra at Twifo Praso and Beposo and all stream water, except, the stream water at Odumase Camp (-3.22, -17.10) community fall either on or close to the GMWL also suggesting that, they are also of meteoric origin. From Figure 5-17, the surface waters were observed to be relatively lighter (more negative) in $\delta^{18}O$ ‰ and $\delta^{2}H$ ‰ concentrations perhaps, due to the relatively low evaporation losses than in some groundwaters which were relatively enriched in the heavy isotopes. This suggests that, these groundwaters are rapidly recharged by the streams and River Pra due to the relatively low evaporation losses. This is consistent with results by Craig (1961) that, water containing heavier isotopes $\delta^{18}O$ ‰ and $\delta^{2}H$ ‰ evaporates and condenses at slightly different fractional rates due to mass differences.

The plot of $\delta^{18}O$ ‰ vs $\delta^{2}H$ ‰ (Figure 5-17) for surface and groundwaters within the Lower Pra Basin also show that, all the surface and groundwaters clustered above the Local meteoric water line for the Accra Plains by Akiti (1986). This result is in sharp contrast with the comparison with the GMWL and suggests evidence of isotopic enrichment by evaporation on the surface or in the unsaturated zone before recharge into the groundwater system.

Comparison between stable isotopes of $\delta^{2}H$ and $\delta^{18}O$ from the present study and previous studies carried out in other parts of Ghana at the; Southern Voltaian Sedimentary Basin (Acheampong, 1996); Upper Region of Ghana (Kortatsi and Sekpey, 1993) and the Keta Basin (Jorgensen and Banoeng-Yakubu, 2001) showed that, the isotopes of $\delta^{2}H$ and $\delta^{18}O$ in groundwater follows one trend, that is, they all cluster along the GMWL, suggesting rapid recharge with little or no isotopic evaporation.

Armah (2002) conducted similar environmental stable isotope studies in the Gomoa, Enyan, Mfantsiman and Awutu-Senya Districts of the Central Region. The study also showed a close correlation of the isotopic results to the GMWL points. Armah (2002) concluded that, the origin of groundwater in the study area is meteoric and not marine.

In conclusion, recharge to the aquifer system within the basin is primarily meteoric water with little or no isotopic modifications.

5.14 Hierarchical Cluster Analysis (HCA) of groundwater within the Lower Pra Basin.

5.14.1 Variables and data transformation

In this study, pH, EC, TDS, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, SO_4^{2-}, Cl^{-}, HCO_3^{-}, NO_3-N and SiO_2 in sixty eight (68) water samples and two (2) streams representing all the water sources sampled during the reconnaissance sampling trip were used as input variables in the agglomerative hierarchical cluster analysis (AHC) to classify waters within the basin into groups and subgroups.

A Microsoft-Excel® add-in module XLSTAT 4.04 (statistiXL 2011) was used to conduct the AHC. Both ground- and surface water samples were used in the cluster analysis in order to examine the relationship between the groups (Gűler *et al.*, 2002). As a result, all parameters are skewed positively, except pH (Gűler *et al.*, 2002). The data was transformed or standardized prior to performing multivariate statistical analysis to ensure; data normality, changes in the weights of different species or variables as well as removing the effect of measurement units (Noy-Meir, 1973; Romesburg, 1984; Thyne *et al.*, 2004; Singh *et al.*, 2009). HCA is a kind of multivariate statistical method which accumulates an entity based on its similarity with various other entities (Gűler *et al.*, 2002).

Thus, similarity between groups of samples can be attained using agglomerative cluster analysis (Gűler *et al.*, 2002). To improve normality of the variables, all variables, except pH, were log-transformed (Gűler *et al.*, 2002). Subsequently, all 11 variables were standardized to their standard scores (z-scores) according to Equation 5-20:

$$Z_i = \frac{X_i - \mu}{S} \qquad 5\text{-}20$$

where, Z_i is the standard score of the sample i, X_I is the value of the sample i, μ is the mean, and S defines the standard deviation. The standardization process assigns each variable equal weight in the multivariate statistical analysis in order to prevent the variable with the greatest magnitude from strongly influencing the Euclidean distances (Gűler *et al.*, 2002). The Q-mode clustering of the sixty eight (68) sampling sites and two (2) streams were clustered into four major water characteristics. The four major groups and subgroups are presented in Table 5-18.

Table 5-18: Clustering of groundwater within the Basin into groups and subgroups

Group 1	Subgroup1		Group 2	Subgroup 2			Group 3	Group 4
	1A	1B		2A	2B	2C		
BH1	BH15	BH1	BH3	BH7	BH3	BH4	BH41	BH46
BH2	BH16	BH2	BH4	BH8	BH21	BH5	BH61	
BH6	BH17	BH6	BH5	BH12	BH22	BH11	BH62	
BH9	BH18	BH9	BH7	BH24	BH25	BH14		
BH10	BH32	BH13	BH8	BH34	BH26	BH20		
BH13	BH50	BH19	BH11	BH38	BH28	BH30		
BH15	BH66	BH23	BH12	BH41	BH29	BH37		
BH16		BH27	BH14	BH43	BH42	BH52		
BH17		BH31	BH20	BH51	BH44	BH53		
BH18		BH33	BH21	BH56	BH49	BH54		
BH19		BH35	BH22	BH59	BH58	BH67		
BH23		BH36	BH24	BH60		BH68		
BH27		BH39	BH25	BH63				
BH31		BH40	BH26					
BH32		BH47	BH28					
BH33		BH48	BH29					
BH35		BH55	BH30					
BH36		BH57	BH34					
BH39		BH64	BH37					
BH40		BH65	BH38					
BH47		ST1	BH42					
BH48		ST2	BH43					
BH50			BH44					
BH55			BH45					
BH57			BH49					
BH64			BH51					
BH65			BH52					
BH66			BH53					
ST1			BH54					
ST2			BH56					
			BH58					
			BH59					
			BH60					
			BH63					
			BH67					
			BH68					

The mean of the four major groups and subgroups is presented in Table 5-19 and the dendrogram of the four major groups and subgroups is presented in Figure 5-18.

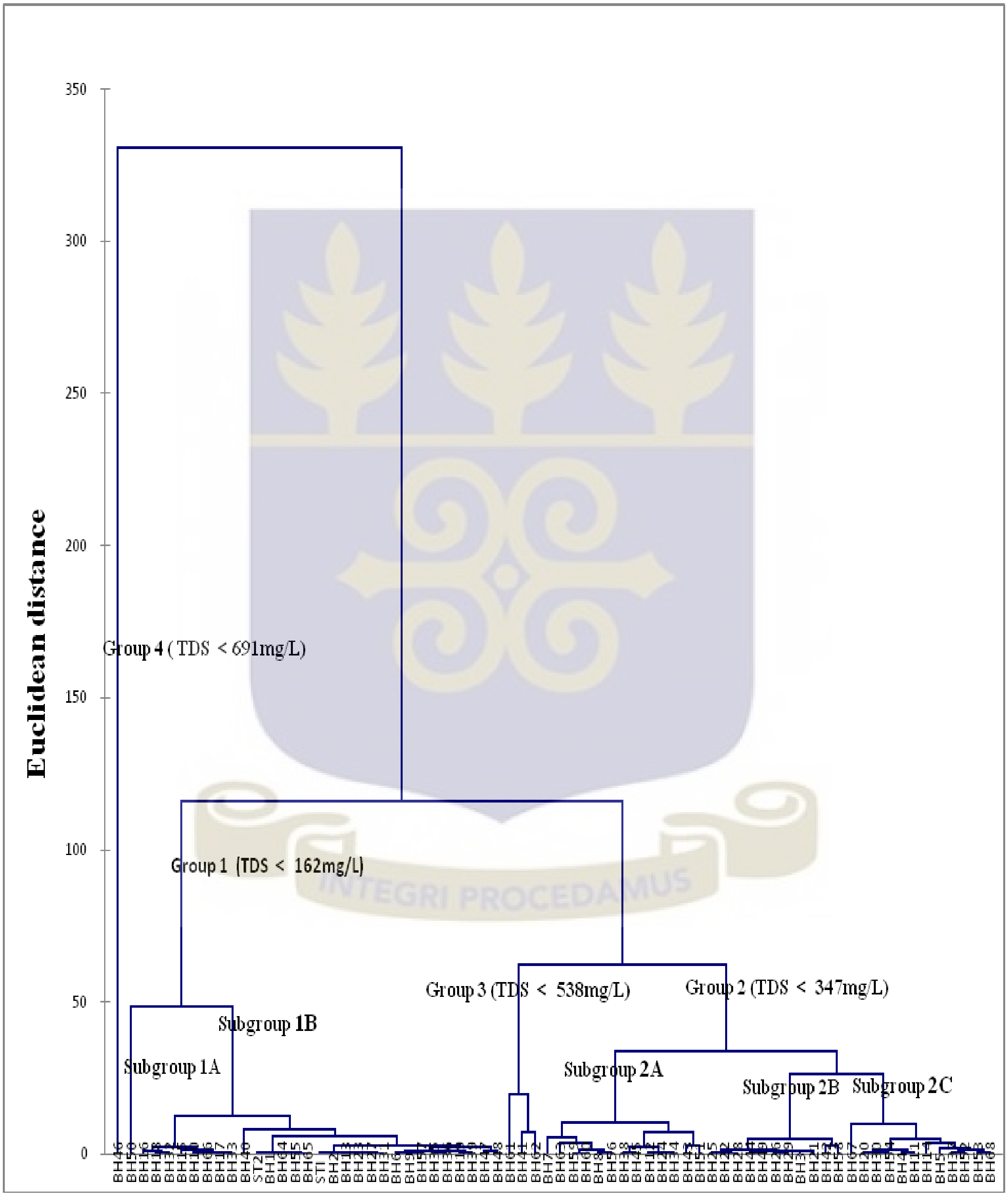


Figure 5-18 : Dendrogram of Q-mode AHC for borehole and stream samples within the Lower Pra Basin.

Table 5-19: Mean hydrochemical data for water groups and subgroups defined by HCA.

Group	Subgroup	n	pH	EC	TDS	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2
Group 1 (GW[1] + SW[2])		30	5.9	155.4	85.4	12.8	8.1	20.5	3.9	17.3	64.8	0.5	40.1	20.9
	Subgroup 1A (GW1)	8	5.6	168.2	92.5	11.3	7.8	18.7	4.0	22.2	40.0	0.5	43.0	19.2
	Subgroup 1B (GW[1] + SW[2])	22	6.0	144.5	79.4	12.9	8.1	21.1	3.8	14.3	74.1	0.3	36.3	21.7
Subgroup 2 (GW[1])		36	7.3	333.6	174.8	28.5	14.6	32.6	7.2	31.3	160.7	0.3	43.5	25.9
	Subgroup 2A (GW1)	13	6.5	356.1	195.9	36.7	18.3	34.8	8.3	25.3	221.2	0.3	49.4	25.8
	Subgroup 2B (GW1)	11	6.4	211.7	116.4	19.5	10.0	23.1	3.7	13.2	129.6	0.1	25.6	28.4
	Subgroup 2C (GW1)	12	6.0	431.2	214.6	25.4	13.9	36.8	8.6	52.7	105.7	0.2	49.4	22.0
Group 3 (GW[1])		3	6.3	884.0	485.8	60.3	23.2	68.2	18.9	115.8	189.8	0.3	120.1	24.6
Group 4 (GW[1])		1	6.3	1201.0	661.0	160.9	104.6	226	69.5	689.9	248.9	0.4	371.2	20.1

[1]Groundwater [2]Surfacewater n- number of samples

The most distinguishing characteristics between the major groups are the decreasing trend of both physical (except, pH) and chemical (except, HCO_3^-, NO_3-N and SiO_2) parameters. The relative abundance of both physical and chemical parameters is in the order: GP4 > GP3 > GP2 > GP1 (Table 5-19).

5.14.2 Partitioning of the study area

The Lower Pra Basin falls under three different Districts namely; the Assin South District within which the Assin Fosu area falls, the Twifo/Heman/Lower Denkyira District within which the Twifo Praso area falls and the Mpohor/Wassa East District within which the Daboase area falls. For the purposes of this study, the Lower Pra Basin has been partitioned into three (3) zones (Assin Fosu area-Zone 1, Twifo Praso area- Zone 2 and Daboase area- Zone 3). The communities within the districts have also been categorized into areas as indicated under Zones 1, 2 and 3 in order to delineate the spatial distribution of the water groups and subgroups defined by HCA as well as identify the groundwater recharge and discharge zones within the Lower Pra Basin. The partitioning has been presented in Table 5-20.

5.14.3 Characteristics of the Water groups

5.14.3.1 Group 1 waters

The waters that clustered in Group 1 consist of 42.6 % of the groundwaters as well as the two stream samples. Results show that, waters in Group 1 have the lowest mean pH (5.6 pH units), mean EC (≤ 155 µS/cm), mean TDS (85 mg/L) as well as mean major ions (Table 5-19). The low mineralized groundwater, reflected by the low mean EC and mean TDS, is indicative of short residence time in the aquifer and/or contact with relatively insoluble silicate minerals (Freeze and Cherry, 1979). According to Freeze and Cherry (1979), due to the longer residence time and

Table 5-20: Partitioning of the Lower Pra Basin into Zones for spatial distribution of water groups.

Zone 1 (Assin Fosu)	Zone 2 (Twifo Praso)	Zone 3 (Daboase)
Assin Fosu Area	**Twifo Mampong Area**	**Daboase Area**
Assin Nyankomase	Akwa Yaw	Sienkyem
Assin Breku	Twifo Mampong	Mamponso
		Essamang
		Mampong
Akonfude Area	**Zion Camp Area**	
Akonfude	Bremang	
Brofoyedru Habitat	Somnyamekordur	
WoraKesse Habitat	Twifo Agona	
Odumase Camp	Zion Camp	
Obobakokrowa		
Dwedaama	**Anyinase Area**	
Obirikwaku	Anyinase Ankase	
Nkrafo	Gromsa	
Sabina	Atu kurom	
Ayitey	Subreso	
Breku Area		
Ninkyiso		
Kwame Ankra		
Techiman No.1		
Senkyem Area		
Amoakokrom		
Nyamebekyere		
Jerusalem		
Antoabasa		
Bediadua		
Anum		
Adukurom		
Kyeikurom		
Subriso		
Nsuekyir		
Danyeasi Domeabra		

prolonged contact time with the aquifer matrix, groundwater at the discharge zones tend to have higher mineral concentration (TDS) compared to that at the recharge zones. This suggests that, waters in Group 1 are mainly fresh (TDS < 500). Waters in Group 1 are therefore; principally bicarbonate dominated with sodium and calcium as dominating cations.

They are characterized by Na-HCO_3, Ca-Mg-HCO_3, Na-Cl and Ca-Mg-Cl type waters (see Figure 5-20). Numerous groundwater geochemical evolution studies have showed that, the Ca-Mg-HCO_3 water type is often regarded as recharge area waters at their early stage of geochemical evolution and are rapidly circulating groundwaters which have not undergone pronounced water-rock interaction (Plummer *et al.*, 1990; Edmunds and Smedley, 2000; Adams *et al.*, 2001). The waters that are characterized by Na-HCO_3 type waters are reminiscent of aggressive recharging alkali carbonate waters perhaps, originating from water-Na-silicate rocks (such as albite, hornblende) interaction. Other possible processes that can result to Na-HCO_3 type waters include; cation-exchange, anaerobic degradation of organic matter and proton exchange.

Waters characterized by Na-Cl type waters may be due to the influence of local rain and illustrate the importance of local recharge conditions within the basin. The Ca-Mg-Cl type water which also characterized the Group 1 waters is mixed type waters where, there is no dominant cation. The Ca-Mg-HCO_3/ Na-HCO_3/ Na-Cl/ Ca-Mg-Cl type waters found in Group 1, suggests that areas where, Group 1 waters are found within the basin are transitional zones, where, primarily, ion-exchange reactions may be taking place to evolve into the different water types.

Group 1 waters are therefore, transitional waters or waters that changed their chemical character through mixing with waters of geochemically different ionic signatures (Frazee, 1982). Based on the map of the study area (see Figure 3-1) waters in Group 1 are found in the North-Eastern parts-Breku, Akonfude and Senkyem in the Assin Fosu area- Zone 1 and the Central parts- Anyinase and Twifo Mampong in the Twifo Praso area- Zone 1 (all in the Central Region) within the basin.

5.14.3.2 Group 2 waters

The waters that clustered in Group 2 consist of 52.9 % of the groundwaters. These waters are characterized by the highest mean pH (7.5 pH units) relatively higher mean EC (≤ 334 μS/cm) and higher mean TDS (175 mg/L) values as well as higher mean cation and anion values compared to waters in Group 1 (Table 5-19). Waters in Group 2 are principally dominated by bicarbonate with sodium and calcium as dominating cations.

Waters in Group 2 may be localized in the transitional zone between recharge and discharge areas within the basin due to their intermediate TDS values, though fresh (TDS < 500). Group 2 waters are also regarded as transitional waters or waters that changed their chemical character through mixing with waters of geochemically different ionic signatures (Frazee, 1982). They are characterized by Na-HCO_3, Ca-Mg-HCO_3, Na-Cl and Ca-Mg-Cl type waters and therefore, have similar chemical characteristics as Group 1 waters (see Figure 5-20). It is thus, evident that, categorization into groups cannot be used to explicitly differentiate Groups 1 and 2 waters. This may be due to the similar groundwater evolution trend amongst the two groups, suggesting more or less the same hydrogeochemical processes (perhaps ion- exchange reactions) along the groundwater flow-path.

Waters in Group 2 are mostly found in the north-eastern parts- Breku, Akonfude and Senkyem in the Assin Fosu area- Zone 1, the central parts- Anyinase in the Twifo Praso area- Zone 2, all in the Central Region and the southern parts- Sienchem in the Daboase area- Zone 3.

5.14.3.3 Group 3 waters

The waters that clustered in Group 3 consist of 4.0 % of the groundwaters. These waters are characterized by intermediary mean pH values (6.6 pH units) and relatively higher mean EC (884 μS/cm), higher mean TDS (486 mg/L) and higher mean major ion values compared to Groups 1 and

2 waters (Table 5-19). Group 3 waters are characterized either by high Mg and relatively lower Ca or high Ca and relatively lower Mg with high Cl in either cases and therefore, may represent mixed waters where no cation dominates. They represent Ca-Mg-Cl type waters (see Figure 5-20). Waters in Group 3 are mostly found in the central parts- Somnyamekordur in the Twifo Praso area- Zone 2, and the Southern parts-Mampong in the Daboase area-Zone 3.

5.14.3.4 Group 4 waters

The waters that clustered in Group 4 consist of only 1.5 % of the groundwaters. These waters are characterized by intermediary mean pH values (6.3 pH units), and highest mean EC (1201µS/cm), highest mean TDS (661 mg/L) and highest mean major ions compared to Groups 1, 2 and 3 waters (Table 5-19). Group 4 waters are characterized by high Na and relatively lower Ca and high Cl and relatively lower SO_4. These waters represent Na-Cl type waters (see Figure 5-20). These water types represent the influence of local rain and illustrate the importance of local recharge conditions within the basin.

Waters in Group 4 are mostly found in the northern parts- Zion Camp in the Twifo Praso area- Zone 2. The relatively high mineralized groundwater, reflected by the high EC and TDS, is indicative of long residence time in the aquifer (Freeze and Cherry, 1979) and/or contact with relatively soluble minerals. This suggests that, areas where Group 4 waters are found may be potentially serving as discharge areas to groundwater within the basin (Freeze and Cherry, 1979). Groups 2 and 3 waters are therefore localized in the transitional recharge (Group 1) and discharge (Group 4) areas. Based on the agglomerative hierarchical clustering, Groups 1, 2 and 3 waters primarily occur in Cape Coast Granitoids.

5.14.4 Characteristics of the water subgroups

The water subgroups (1A, 1B, 2A, 2B and 2C) define the chemical differences of the different type waters in an area and the geochemical changes they undergo along the groundwater flow-path.

5.14.4.1 Subgroups 1A and 1B

The waters which clustered in Subgroup 1A are characterized by low TDS (35.7-162.0 mg/L). These subgroups represent Ca-Mg-Cl and Na-Cl water types (see Figure 5-20). Subgroup 1A waters therefore, represent the influence of local rain (Na-Cl type waters) and illustrate the importance of local recharge conditions as well as temporally hard waters where, no cation dominates (Ca-Mg-Cl type waters). Subgroup 1A waters are located in Breku (37.5 % of waters), Akonfude (25.0 % of waters) and Senkyem (12.5 % of waters) in the Assin Fosu Zone in the Central Region and the Daboase Zone (25.0 % of waters) in the Western Region.

The waters which clustered in Subgroup 1B are characterized by relatively lower TDS (32.5-154.0 mg/L) as compared to the Subgroup 1A waters (Table 5-21). They are largely characterized by Na-HCO_3 and Ca-Mg-HCO_3 type waters with a few Na-Cl type waters (see Figure 5-20). Subgroup IB waters therefore, represent recharge area waters at their early stage of geochemical evolution and are rapidly circulating groundwaters which have not undergone pronounced water-rock interaction and waters that are reminiscent of aggressive recharging waters. Minimal influence of local rain, illustrating local recharge conditions within the basin also characterize Subgroup 1B waters.

Subgroup 1B waters may therefore be regarded as the evolution indictors that define the hydrogeochemical processes influencing groundwater within the basin. These water subgroups can be found in Breku (9.5 % of waters), Akonfude (33.3 % of waters) and Senkyem (9.5 % of waters) in the Assin Fosu Zone and the central parts- Anyinase (9.5 %) and Twifo Mampong (9.5 %) in the

Twifo Praso Zone of the basin (all in the Central Region) and Sienkyem (28.7 % of waters) of the Western Region.

The stream waters, ST1 (in the Senkyem area) and ST2 (in the Akonfude area) which both clustered in subgroup IB with low TDS (47.7 - 52.2 mg/L) are characterized by high Na and relatively low Ca and high HCO_3 relatively lower SO_4 and represents Na-HCO_3 type waters. These streams are reminiscent of aggressive recharging waters that may be potentially serving as recharge reservoirs to groundwater within the basin. This is consistent with the stable isotopes results that, some groundwaters within the basin are rapidly recharged by the streams and River Pra due to the more enriched $\delta^{18}O$ ‰ and $\delta^{2}H$ ‰ values in these surface waters.

5.14.4.2 Subgroups 2A, 2B and 2C

The waters which clustered in Subgroup 2A are characterized by low TDS (131.0 - 347.0 mg/L) (Table 5-19). This subgroup represents Na-HCO_3 and Ca-Mg-HCO_3 type waters (see Figure 5-20). Subgroup 2A waters represent intermediate or transitional (i.e. they are undergoing geochemical evolution) rock-water interactions and groundwater residence time and may be regarded as recharge area waters at their early stage of geochemical evolution and are rapidly circulating groundwaters which have not undergone pronounced water-rock interactions. Subgroup 2A waters are located in Breku (7.7 % of groundwaters), Akonfude (23.1 % of groundwaters) and Senkyem (7.7 % of groundwaters) in the Assin Fosu zone and the central parts- Anyinase (7.7 % of groundwaters) and northern part- Zion Camp (15.4 % of groundwaters) in the Twifo Praso area- Zone 2 of the basin (all in the Central Region) and Sienchem (38.4 % of groundwaters) in the Daboase area- Zone 3 in the Western Region.

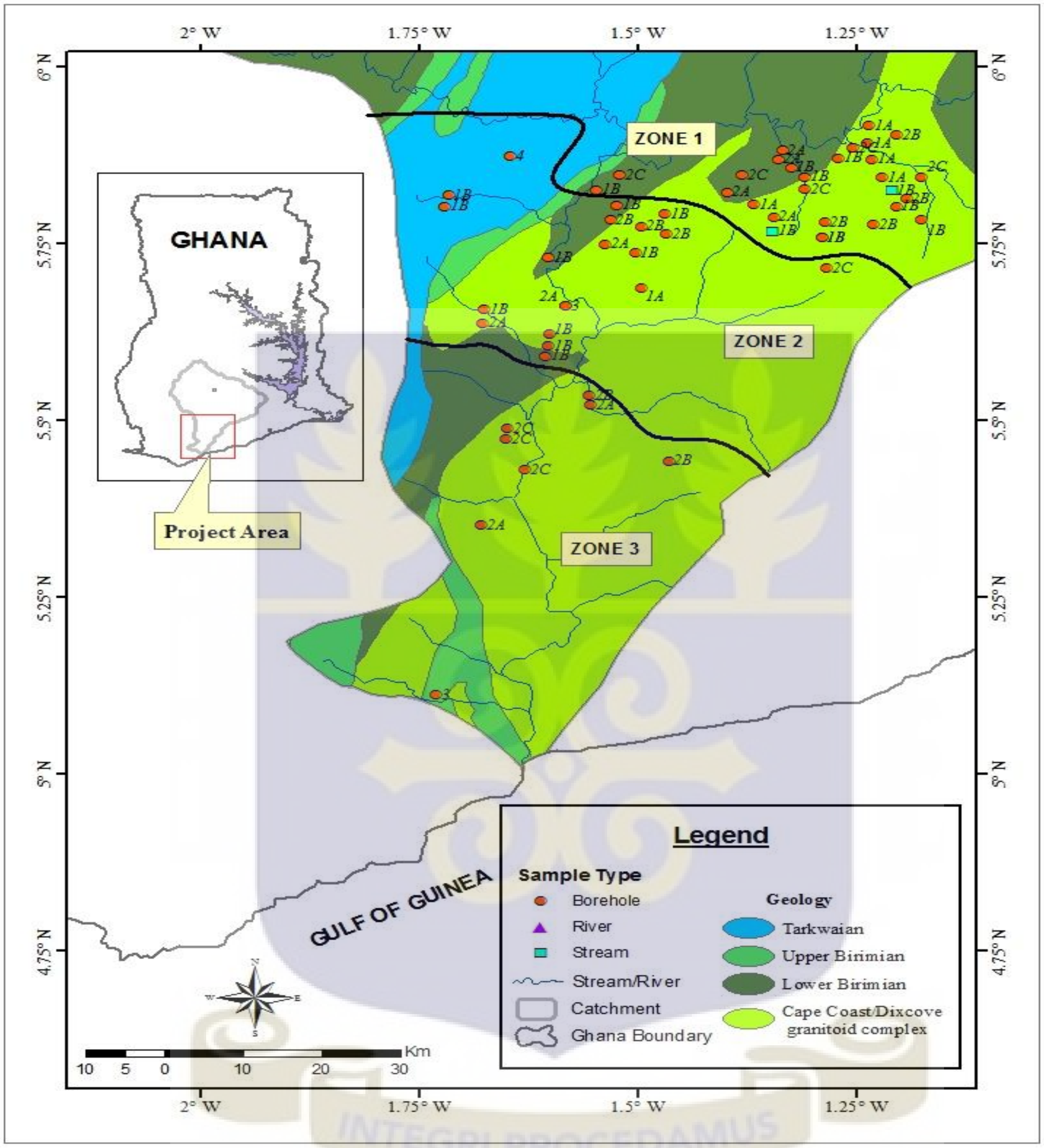
The waters which clustered in Subgroup 2B are characterized by relatively lower TDS (47.7-

194.0 mg/L) compared to Subgroup 2A waters (Table 5-19). This Subgroup is also characterized by Na-HCO_3 and Ca-Mg-HCO_3 type waters and represent a relatively higher (than waters in subgroups 2A and 2C) intermediate rock-water interactions and groundwater residence time and may also be regarded as recharge area waters at their early stage of geochemical evolution and are rapidly circulating groundwaters which have not undergone pronounced water-rock interactions. They are located in Breku (9.1 % of groundwaters), Akonfude (9.1 % of groundwaters) and Senkyem (45.5 % of groundwaters) in the Assin Fosu area- Zone 1 and the central parts- Twifo Mampong (9.1 % of groundwaters) and northern parts- Zion Camp (18.2 % of groundwaters) in the Twifo Praso area- Zone 2 within the basin (all in the Central Region) and Sienchem (9.1 % of groundwaters) in the Daboase area- Zone 1 in the Western Region.

The waters which clustered in Subgroup 2C are characterized by intermediary TDS (127.0 - 329.0 mg/L) and represent Na-HCO_3, Ca-Mg-HCO_3, Na-Cl and Ca-Mg-Cl type waters (Figure 5-20). It is thus evident that, Subgroup 2C waters are localized in the transitional zone between recharge and discharge areas and explicitly indicates groundwater geochemical evolution along the groundwater flow-path through mixing with waters of geochemically different ionic signatures (Frazee, 1982), within the basin. Subgroup 2C waters may also be regarded as the evolution indictors that define the hydrogeochemical processes influencing groundwater within the basin. This subgroup are located in Breku (16.7 % of groundwaters), Akonfude (25.0 % of groundwaters) and Senkyem (8.3 % of groundwaters) in the Assin Fosu area- Zone 1 and the central parts- Anyinase (8.3 % of groundwaters) in the Twifo Praso area- Zone 2 of the basin (all in the Central Region) and Mamponso (41.7 % of groundwaters) in the Daboase area- Zone 3 in the Western Region.

5.14.5 Spatial distribution of water groups and subgroups

The spatial distribution (zonation) of the water groups and subgroups defined by hierarchical cluster analysis (HCA) is presented in Figure 5-19.



(Modified after Geological Survey Department, 2009)

Figure 5-19: Spatial distribution of the water groups and subgroups defined by Hierarchical Cluster Analysis (HCA).

From Figure 5-19, the Assin Fosu area (Zone 1) has the highest number of subgroup 1A (75.0 %, with characteristic Na-Cl and Ca-Mg-Cl water types), 2C (50.0 %, with characteristic, Na-HCO_3, Ca-Mg-HCO_3, Na-Cl and Ca-Mg-Cl water types) and 2B (44.0 %, with characteristic Na-HCO_3 and

Ca-Mg-HCO_3 water types) and therefore, a transition zone between aggressive recharging fresh waters (Na-HCO_3 water type)/fresh waters which have not undergone prolong contact with the minerals (Ca-Mg-HCO_3 water types)/ limited recharging local rain (Na-Cl water type)/mixed water (Ca-Mg-Cl water type).

The Twifo Praso area (Zone 2) has the highest number of subgroup 1B (59.0 %, with characteristic Na-HCO_3, Ca-Mg-HCO_3 and Na-Cl water types), with relatively lower number of subgroups 2A and 2B each with 33.0 %, with characteristic Na-HCO_3 and Ca-Mg-HCO_3 water types) lower numbers of subgroups 1A (12.5 %) and 2C (12.5 %). The Twifo Praso area (Zone 2) therefore, principally represents recharge area within the basin. The Daboase area (Zone 3) has the least number of 2A and 2B subgroups with relatively higher (than Zone 2) 2C subgroup. The Daboase area also represents transition zone between aggressive recharging fresh waters (Na-HCO_3 water type)/fresh waters which have not undergone prolong contact with the minerals (Ca-Mg-HCO_3 water types)/limited recharging local rain (Na-Cl water type)/mixed water (Ca-Mg-Cl water type).

Group 3 waters represent permanent hard water (Ca-Mg-Cl water type) and are found in Zone 3. Group 4 waters represent the influence of local rain and are found in Zone 2.

Results from the sources of major ions (see Section 5.13.2.1) show that, ion-exchange is one of the principal hydrogeochemical processes influencing groundwater within the basin. Consistent with the Chadha plot (see Figure 5-20), the different water subgroups have common water types perhaps due to ion-exchange reactions along the flow-paths. Thus, Zones 1, 2 and 3 all represents transition zones between fresh waters which have not undergone prolong contact with the minerals/aggressive recharging fresh waters/and limited recharging local rain/permanent hard water. Thus, the waters in Zones 1, 2 and 3 evolves from the mixing of waters with geochemically different ionic signatures (Frazee, 1982). The five subgroups are therefore, separated geographically, as well as physiographically with significant correlation between spatial locations and the HCA results.

Spatially, groundwaters that belong to the same subgroup are located in close proximity to one another suggesting more or less the same hydrogeochemical processes along the flow-paths. The high degree of spatial and statistical coherence also suggests that, the changes between the principal hydrochemical facies define the hydrochemical evolution of groundwater within the basin. The spatial distribution of the water groups and subgroups as defined by hierarchical cluster analysis is presented in Table 5-21.

Table 5-21: Spatial distribution of the water groups and subgroups defined by HCA

Sample Source	ID	Longitude	Latitude	Group	Subgroup
Assin Nyakomase	BH1	5.75724	-1.29063	1	1B
Assin Nyakomase	BH2	5.75719	-1.29084	1	1B
Assin Nyakomase	BH3	5.75897	-1.28652	2	2B
Brofoyedru Habitat	BH4	5.73346	-1.28457	2	2C
Akonfude	BH5	5.82570	-1.30988	2	2C
Akonfude	BH6	5.82950	-1.31011	1	1B
Assin Breku	BH7	5.86801	-1.34094	1	2A
Assin Breku (Gyidi)	BH8	5.87059	-1.33603	2	2A
Assin Breku (SDA)	BH9	5.86625	-1.33603	1	1B
Techiman No. 1	BH10	5.80432	-1.36792	1	1A
Kwame Ankra	BH11	5.81542	-1.38199	2	2C
Ninkyiso	BH12	5.82117	-1.39912	2	2A
Sabina	BH13	5.86974	-1.27172	1	1B
Ayitey	BH14	5.88353	-1.25584	2	2C
Nkrafo	BH15	5.87809	-1.23364	1	1A
Nkrafo	BH16	5.88087	-1.23862	1	1A
Obirikwaku	BH17	5.91571	-1.23661	1	1A
Odumase Camp	BH18	5.82454	-1.19147	1	1A
Obobakokrowa	BH19	5.82490	-1.17768	1	1B
Obobakokrowa	BH20	5.83276	-1.17653	2	2C
Odumase Camp	BH21	5.82181	-1.19419	2	2B
Dwedaama	BH22	5.90170	-1.20496	2	2B
Dwedaama	BH23	5.80159	-1.20575	1	1B
Amoakokrom	BH24	5.85972	-1.25611	2	2A
WoraKesse Habitat	BH25	5.76443	-1.13154	2	2B
Antoabasa	BH26	5.77196	-1.46878	2	2B
Antoabasa	BH27	5.7702	-1.46948	1	1B
Bediadua	BH28	5.77278	-1.49722	2	2B
Anum	BH29	5.78219	-1.50224	2	2B

Sample Source	ID	Longitude	Latitude	Group	Subgroup
Kyeikurom	BH30	5.82504	-1.52242	2	2C
Adukurom	BH31	5.82278	-1.52444	1	1B
Nsuekyir	BH32	5.68667	-1.49722	1	1A
Subriso	BH33	5.82474	-1.54799	1	1B
Danyiase Domeabra	BH34	5.74806	-1.53806	2	2A
Anyinase Ankase	BH35	5.59446	-1.60279	1	1B
Gromsa	BH36	5.58991	-1.60607	1	1B
Somnyamekodur	BH37	5.66046	-1.58376	3	
Somnyamekordur	BH38	5.66046	-1.58376	2	2A
Twifo Agona	BH39	5.74595	-1.50398	1	1B
Nyamebekyere	BH40	5.80139	-1.72139	1	1B
Jerusalem	BH41	5.81667	-1.71750	1	1B
Akwa Yaw	BH42	5.44157	-1.46580	2	2B
Twifo Mampong	BH43	5.52016	-1.55449	2	2A
Twifo Mampong	BH44	5.52359	-1.55681	2	2B
Atu Kurom	BH45	5.63657	-1.67850	2	2A
Subreso	BH46	5.65596	-1.67676	1	1B
Bremang	BH47	5.70878	-1.60277	1	1B
Bremang	BH48	5.70720	-1.60261	1	1B
Zion Camp	BH49	5.87217	-1.64602	4	
Mampong	BH50	5.11147	-1.73174	3	
Essamang	BH51	5.05042	-1.67979	2	2A
Mamponso	BH52	5.42906	-1.63002	2	2C
Sienchem	BH53	5.47123	-1.65053	2	2C
Sienchem	BH54	5.47246	-1.65156	2	2C
Amoakokrom	ST1	5.78604	-1.34668	1	1B
Odumase Camp	ST2	5.82402	-1.19105	1	1B

Longitude (N), Latitude (W)

5.14.6 Hydrochemical characteristics of the HCA subgroups

Water quality data for subgroups 1A, 1B, 2A, 2B and 2C were analysed using statistical distribution diagram proposed by Chadha (1999) to understand the chemical differences between the subgroups and geochemical changes along the groundwater flow-path. Chadha (1999) proposed a new way of expressing hydrogeochemical classification of water. The rectangular plot proposed by Chadha (1999) describes the primary character of water including temporary and permanent hardness. The rectangular field is divided into eight sub-fields (Figure 5-20), each of which represents a water type and hardness domain as follows:

1. Alkaline earth metals(Ca and Mg) exceeds alkali metals (Na and K)
2. Alkali metals (Na and K) exceeds alkaline earths metals (Ca and Mg)
3. Weak acidic anions (HCO_3) exceed strong acidic anions (Cl and SO_4)
4. Strong acidic anions (Cl and SO_4) exceed weak acidic anions (HCO_3)

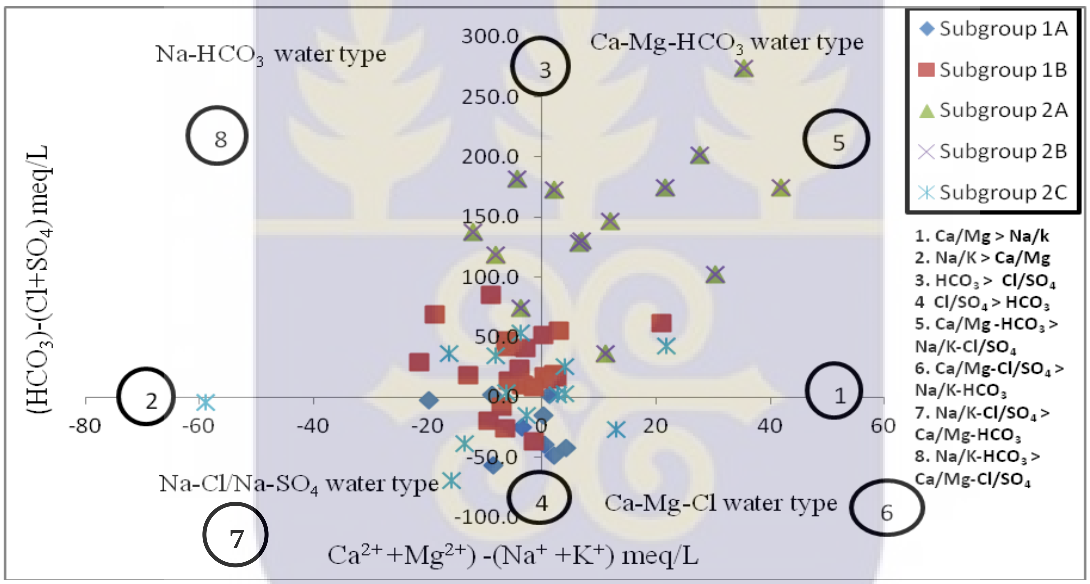


Figure 5-20: Plot of (Ca^{2+}+Mg^{2+})-(Na^{+}+K^{+}) vs (HCO_3^-)-(SO_4^{2-}+Cl^-) for geochemical classification of water quality parameters and hardness for groundwater within the Lower Pra Basin.

5. Alkaline earths metals (Ca and Mg) and weak acidic anions (HCO_3) exceed both alkali metals (Na and K) and strong acidic anions (Cl and SO_4) respectively. Such water has temporary hardness. The samples plotting in this domain represents Ca-Mg-HCO_3 water type.
6. Alkaline earths metals (Ca and Mg) exceed alkali metals (Na and K) and strong acidic anions (Cl and SO_4) exceed weak acidic anions (HCO_3). Such water has permanent

hardness. Residual sodium carbonate is low. The samples plotting in this domain represents Ca-Mg-Cl water type.

7. Alkali metals (Na and K) exceed alkaline earths metals (Ca and Mg) and strong acidic anions (Cl and SO_4) exceed weak acidic anions (HCO_3). These waters are characterized by salinity problems. The waters are Na-Cl and Na-SO_4 type.
8. Alkali metals (Na and K) exceed alkaline earths metals (Ca and Mg) and weak acidic anions (HCO_3) exceed strong acidic anions (Cl and SO_4). The samples plotting in this domain represents Na-HCO_3 water type.

From Figure 5-20, the subgroup 1A waters evolved from alkaline earths (Ca and Mg) and strong acidic anions (Cl and SO_4); Ca-Mg-Cl water type and alkali metals (Na and K) and strong acidic anions (Cl and SO_4); Na-Cl and Na-SO_4 type while, subgroup 1B waters evolved from alkali metals (Na and K) and weak acidic anions (HCO_3); Na- HCO_3 water type, alkaline earths (Ca and Mg) and weak acidic anions (HCO_3), with characteristic temporary hardness; Ca-Mg- HCO_3 water type and alkali metals (Na and K) and strong acidic anions (Cl and SO_4); Na-Cl and Na-SO_4 water types.

Group 1 waters found in the North-Eastern parts- Breku, Akonfude and Senkyem in the Assin Fosu area and the Central parts- Anyinase and Twifo Mampong in the Twifo Praso areas (all in the Central Region) of the basin which are clustered with the stream water samples therefore, represent a transition zone between Na-Cl/ Ca-Mg-Cl /Na-SO_4 water types and Ca-Mg-HCO_3/NaHCO_3 water types through mixing with waters of geochemically different ionic signatures (Frazee, 1982).

Subgroup 2A are largely alkali metals (Na and K) and weak acidic anions (HCO_3); Na-HCO_3 water type and alkaline earths (Ca and Mg) and weak acidic anions (HCO_3); Ca-Mg-HCO_3 water type. Similarly, Subgroup 2B are also largely alkali metals (Na and K) and weak acidic anions (HCO_3); Na-HCO_3 water type and alkaline earths (Ca and Mg) and weak acidic anions (HCO_3); Ca-Mg-HCO_3 water type.

Subgroup 2C waters are mixed Ca-Mg-Cl/Na-Cl/Na-SO_4/ Ca-Mg-HCO_3/NaHCO_3 water types with no dominant cation or anion. These waters represent transition stage waters between subgroups 1A, 1B, 2A and 2B waters.

5.14.7 Groundwater chemistry evolution

In order to investigate the groundwater chemistry evolution within the basin, the mean saturation indices of the water subgroups with respect to the various mineral phases were calculated (Table 5-22). From Table 5-22, groundwater within the basin is generally subsaturated with respect to anhydrite, calcite, dolomite, amorphous silica, melantherite, ferric-hydroxide and generally supersaturated with respect to goethite.

Table 5-22: Mean saturation indices of the water subgroups with respect to various mineral phases

Phase	Stoichiometry	1A	1B	2A	2B	2C
Anhydrite	$CaSO_4$	-0.4	-0.6	-0.5	-0.4	-0.4
Calcite	$CaCO_3$	-0.5	-0.7	-0.5	-0.4	-0.8
Dolomite	$CaMg(HCO)_3$	-1.5	-1.4	-1.1	-1.0	-1.0
Ferric-hydroxide	$Fe (OH)_3$	-1.2	-2.1	-2.0	-1.9	-2.4
Goethite	FeOOH	4.6	3.8	2.9	3.7	4.6
Melantherite	$FeSO_4.7H_2O$	-3.1	-2.5	-3.2	-2.4	-0.9
SiO_2 (a)	SiO_2	-1.0	-0.8	-1.1	-0.9	-0.8

This suggests that anhydrite, calcite, dolomite, melantherite and ferric-hydroxide if present, would continue to dissolve, while, goethite would continue to precipitate in the groundwater within the basin until equilibrium conditions are established. However, there is no petrographic evidence to suggest the existence of the minerals; calcite and dolomite in the area. Thus, if indeed these minerals contribute to the evolution of groundwater within the basin then, they are masked by other processes such as incongruent silicate/aluminosilicate weathering.

Groundwater which clustered in subgroup 1B is chemically the least evolved of the groundwaters investigated (Table 5-19). Subgroup 1B, with predominantly, Na-HCO_3/Ca-Mg-

HCO_3 type water evolves into subgroup 1A, with Ca-Mg-Cl/ Na-Cl/ Na-SO_4 type water through mixing with waters of geochemically different ionic signatures (Frazee, 1982). As the waters infiltrates and moves down gradient, the different chemical constituents of waters of geochemically different ionic signatures are exchanged through ion-exchange and the groundwater modifies and evolves to the different water types depending upon its flow-path and the host lithology. From Subgroup 1B to 1A, parameters generally, increased (Table 5-19). Typically, the total dissolved solids of groundwater will increase with depth and prolong residence time due to chemical interactions with aquifer materials and possible mixing with older mineralized water along flow-paths (Helstrup *et al.*, 2007).

The plot of the relationship between Na^+ and Cl^- contents in Figure 5-21a shows that, the groundwaters fit well with a conservative mixing line between the groundwater subgroups belonging to the different water types. Figure 5-21a shows that, most of the groundwaters in the entire subgroups plot above the mixing line, indicating a surplus of Na^+. Figure 5-21b also shows some degree of deficiency of Ca^{2+} in the groundwater in all the subgroups as some groundwaters belonging to the different subgroups plot below the 1:1 line. A surplus of Na^+ is an indication of refreshing, while, a surplus of Ca^{2+} indicates saline-water intrusion (Appelo and Postma, 1994).

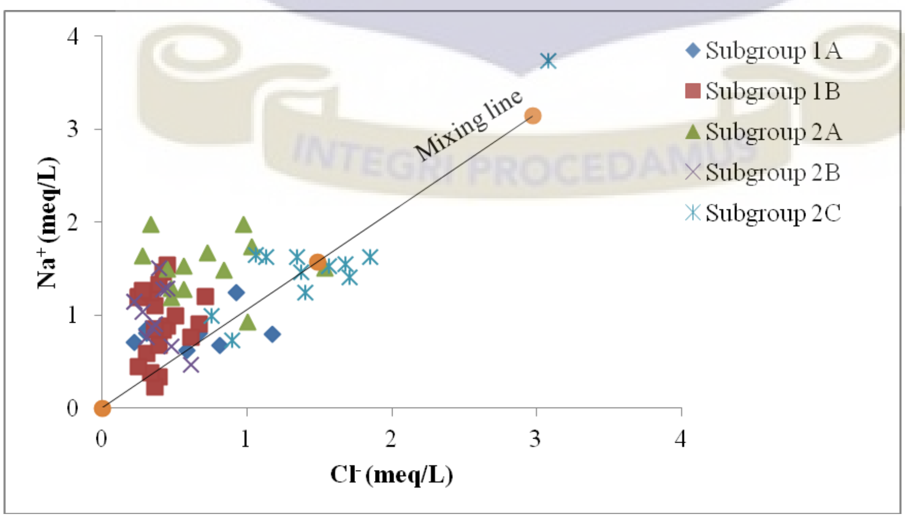


Figure 5-21a: A plot showing the mixing of Na^+ and Cl^- in the groundwater subgroups

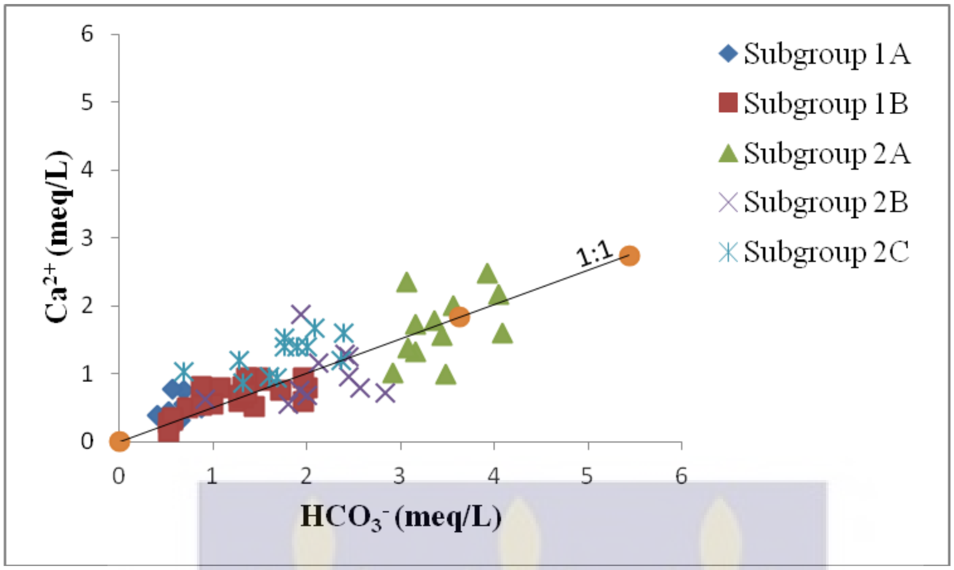


Figure 5-21b: A plot showing the degree of deficiency of Ca^{2+} in the groundwater subgroups

Figures 5-21 (a-b): Relationship between (a) Na^+ and Cl^-, (b) Ca^{2+} and HCO_3^- contents in the groundwater subgroup

NB: The inserted mixing line has been calculated based on the arithmetic means of Na^+ and Cl^- concentrations in the groundwater subgroups.

This result suggests that, groundwater within the basin is primarily undergoing recharge processes (mixing with waters of geochemically different ionic signatures i.e., Ca-Mg-HCO_3/Na-HCO_3 type waters) (Frazee, 1982), than processes involving saline-water intrusion (mixing of fresh and old waters- i.e. Ca-Mg-HCO_3/Na-HCO_3 and Na-Cl). Cation-exchange processes are likely to be responsible for the observations in Figures 5-21 a and b. The cation-exchange effects observed in groundwater belonging to the different subgroups indicates evolution (changes) in the water chemistry along the groundwater flow-path.

Figures 5-21 a and b respectively shows the effects of limited mixing with local rain (as only a few of the subgroups plot close to or on the mixing line) and limited dissolved carbonate equilibria (as only a few of the subgroups plot close to or on the 1:1 line) and are important controls on the hydrochemical evolution of groundwater within the basin. Subgroup 2C represents a less evolved groundwater than subgroups 2A and 2B. From Figure 5-20, it is clear that subgroup 2A and 2B, with Ca-Mg-HCO_3/Na-HCO_3 type water evolves into Subgroup 2C with Ca-Mg-Cl/Na-Cl/Na-SO_4 water type through mixing with waters of geochemically different ionic signatures (Frazee, 1982). As the waters of subgroups 2A and 2B (Ca-Mg-HCO_3/Na-HCO_3 types waters) infiltrates and moves down gradient, they modify and evolves into subgroup 2C (Mg-Cl/Na-Cl/Na-SO_4) water types depending upon its flow-path and the host lithology. Unlike groundwater, the evolution of surface water within the basin was observed to be uncomplicated as all the streams evolved as Na–HCO_3 water type emanating from water-Na-silicate rocks perhaps, due to short residence time during water–rock interaction and short route to flow.

Based on the geographical locations of the water groups and subgroups (see Figure 5-19), the mean water chemistry (see Table 5-19) and the hydrogeology of the water groups and subgroups, groundwater within the basin perhaps, evolves from Ca-Mg-HCO_3 type water (often regarded as recharge area waters at their early stage of geochemical evolution and are rapidly circulating groundwaters which have not undergone pronounced water-rock interaction into Na-HCO_3 type water (reminiscent of aggressive recharging waters) into Ca-Mg-Cl type water (permanent hard water where, no cation dominates) and finally into Na-Cl type water (due to the influence of limited local rain and illustrate the importance of local recharge conditions within the basin) along its flow-path through mixing with waters of geochemically different ionic signatures (Frazee, 1982).

5.15 Application of Multivariate Statistical Technique for Hydrogeochemical Assessment of groundwater within the Lower Pra Basin.

5.15.1 Statistical Analysis

In this study, Spearman's correlation matrix was generated to determine any relationship between the observed parameters in order to explain factor loadings during PCA. In order to ensure normality of the data all hydrochemical data (except pH) were log-transformed prior to statistical analyses. The hydrochemical data was also auto-scaled by calculating the standard scores (z scores) and ensuring that all z scores are < ± 2.5 (Acero *et al.*, 2013).

Spearman's correlation matrix and PCA were performed using Statistical Programme for Social Sciences (SPSS) version 16.0 for windows in order to establish the possible connections and interdependence between the different chemical constituents as well as define the main controls on groundwater chemistry within the basin. High correlation coefficient value (i.e. -1 or 1) predicts a good relation between two variables and correlation coefficient value around zero (0) predicts no relationship between the two variables at a significant level of $P < 0.05$. Parameters showing $r > 0.7$ are considered to be strongly correlated, whereas r between 0.4 and 0.7 shows moderate correlation and $r < 0.4$ shows low to no correlation. A probability value of $P < 0.05$ was considered as statistically significant in this study.

5.15.2 Data analysis using correlation matrix

The stoichiometric relations of the dissolved ions have been assessed in order to identify the main hydrogeochemical processes occurring within the aquifer. The Spearman's correlation matrix generated is presented in Table 5-23. The correlation matrix generated show that, pH show low to moderate correlation (except K^+) with all major and minor ions. The correlation matrix also shows that, HCO_3^- had relatively high correlation (0.53) compared to other major ions. According to Hounslow (1995), essentially, in silicate weathering reactions bicarbonate is produced, suggesting that HCO_3^- perhaps, originates primarily from silicate weathering reactions in groundwater within the basin.

Total Dissolved Solids (TDS) show strong correlation with, Ca^{2+}($r = 0.78$; $p < 0.05$), Mg^{2+}($r = 0.71$; $p < 0.05$) , Na^+ ($r = 0.71$; $p < 0.05$), K^+ ($r = 0.62$; $p < 0.05$), Cl^-($r = 0.74$; $p < 0.05$) and SO_4^{2-} ($r = 0.64$; $p < 0.05$) (Table-5-23) suggesting that, these major ions contributes positively to the total

Table 5-23: Spearman's Correlation Matrix for groundwater within the Lower Pra Basin.

	pH	EC	TDS	TH	Ca	Mg	Na	K	Cl	HCO_3	NO_3-N	SO_4	Cu	Mn	Zn	Cd	Pb	Fe	Al	As	Hg	Se
pH	1.00																					
EC	0.26	1.00																				
TDS	0.30	**0.96**	1.00																			
TH	0.40	**0.82**	**0.83**	1.00																		
Ca	0.42	**0.85**	**0.78**	**0.86**	1.00																	
Mg	0.23	**0.83**	**0.71**	**0.71**	**0.83**	1.00																
Na	0.16	**0.82**	**0.71**	**0.55**	**0.79**	**0.87**	1.00															
K	-0.04	**0.70**	**0.62**	0.47	**0.65**	**0.72**	**0.79**	1.00														
Cl	0.15	**0.85**	**0.74**	**0.66**	**0.84**	**0.94**	**0.93**	**0.78**	1.00													
HCO_3	**0.53**	0.58	**0.58**	**0.64**	**0.72**	0.48	0.48	0.36	0.37	1.00												
NO_3-N	-0.27	0.01	0.08	-0.07	-0.09	-0.02	0.06	0.10	0.04	-0.28	1.00											
SO_4	0.10	**0.76**	**0.64**	**0.59**	**0.78**	**0.93**	**0.91**	**0.81**	**0.92**	0.39	0.10	1.00										
Cu	-0.13	0.12	0.20	0.09	0.04	0.01	0.14	0.13	0.04	0.03	0.39	0.16	1.00									
Mn	-0.03	0.13	0.14	0.09	0.08	0.04	0.09	0.17	0.08	-0.04	0.31	0.15	0.26	1.00								
Zn	-0.07	0.13	0.20	0.09	0.03	0.00	0.15	0.07	0.03	0.07	0.35	0.15	**0.93**	0.24	1.00							
Cd	0.01	-0.06	-0.07	-0.06	-0.07	-0.04	-0.02	-0.05	-0.03	-0.10	-0.02	0.00	-0.03	-0.05	0.26	1.00						
Pb	-0.24	0.01	0.01	-0.06	-0.05	0.03	0.07	0.16	0.04	-0.08	0.21	0.02	-0.03	-0.06	-0.13	-0.09	1.00					
Fe	-0.03	-0.25	-0.21	-0.22	-0.22	-0.25	-0.20	-0.07	-0.20	-0.19	-0.08	-0.25	-0.10	-0.19	-0.18	-0.21	0.40	1.00				
Al	-0.27	-0.17	-0.17	-0.13	-0.21	-0.20	-0.09	-0.11	-0.10	-0.29	0.01	-0.14	-0.07	-0.16	-0.03	0.04	-0.17	-0.05	1.00			
As	-0.10	0.09	0.03	0.09	0.12	0.14	0.11	0.13	0.03	0.35	0.05	0.18	0.01	0.11	0.11	-0.03	-0.11	-0.23	-0.10	1.00		
Hg	0.26	0.13	0.13	-0.01	0.04	-0.01	0.16	0.11	0.09	0.13	-0.20	-0.05	-0.17	-0.20	-0.17	-0.08	0.14	0.17	0.17	-0.17	1.00	
Se	-0.34	0.04	0.06	-0.12	-0.08	-0.05	0.11	0.45	0.00	-0.01	0.10	0.03	0.03	-0.05	-0.05	0.00	0.44	0.18	0.02	-0.06	0.12	1.00

Bold values indicate high correlation (at significant level of $P < 0.05$) and shows evidence of observed water composition dissolved solids of the groundwater and can be accounted for by a major geochemical process, perhaps aluminosilicate weathering and also originating from the same source (Subba Rao, 2002).

Correlation analysis of major ions revealed expected processes- based relationships between $Mg^{2+}$and Ca^{2+}($r = 0.83$; $p < 0.05$), Ca^{2+} and Na^{+} (r =0.0.79; $p < 0.05$), Ca^{2+} and K^{+} ($r = 0.65$; $p < 0.05$), Ca^{2+} and Cl^{-}($r = 0.84$; $p < 0.05$), Ca^{2+} and SO_4^{2-} ($r = 0.78$; $p < 0.05$), $Mg^{2+}$and Na^{+} ($r = 0.87$; $p < 0.05$), $Mg^{2+}$and K^{+} ($r = 0.72$; $p < 0.05$), $Mg^{2+}$and Cl^{-}($r = 0.94$; $p < 0.05$), $Mg^{2+}$and SO_4^{2-} ($r = 0.93$; $p < 0.05$), Na^{+} and K^{+} ($r = 0.79$; $p < 0.05$), Na^{+} and Cl^{-} ($r = 0.93$; $p < 0.05$), Na^{+} and SO_4^{2-} ($r = 0.91$; $p < 0.05$), K^{+} and Cl^{-} ($r = 0.78$; $p < 0.05$), K^{+} and SO_4^{2-} ($r = 0.81$; $p < 0.05$) and Cl^{-} and SO_4^{2} ($r = 0.92$; $p < 0.05$), derived mainly from the geochemical processes such as ion-exchange and silicate/aluminosilicate weathering within the aquifer. These process-based relationships between the observed parameters may be due to mineralogical influence which would be explicitly explained by factor loadings during principal component analysis (PCA) in the ensuing section.

The correlation between $Cu^{2+}$and Zn^{2+}($r = 0.93$; $p < 0.05$), reveals the possible existence of a process-based (biochemical) relationship between the two metals. Zinc is one of the earliest known trace metal and a common environmental pollutant which is widely distributed in the aquatic environment, while, copper is intimately related to the aerobic degradation of organic matter (Das & Notling, 1993). Aerobic degradation of organic matter in groundwater within the basin may therefore, be responsible for the strong correlation between Cu^{2+} and Zn^{2+}.

5.15.3 Data analysis using Principal Component Analysis (PCA)

PCA using varimax with Kaiser Normalization rotation has resulted in the extraction of three main principal components, which have accounted for approximately 79.0 % of the total variance in the hydrochemistry. Table 5-24 presents the rotated component matrix of the main physico-chemical parameters; while, Table 5-25 presents the determined initial principal component and its

Table 5-24: Rotated component matrix of the main physico-chemical parameters

Chemical parameter	Component		
	1	2	3
Na^+	**0.969**	0.092	0.038
Cl^-	**0.960**	0.005	-0.068
Mg^{2+}	**0.936**	0.152	-0.052
SO_4^{2-}	**0.923**	0.073	-0.012
K^+	**0.870**	-0.021	0.022
Ca^{2+}	**0.864**	0.349	0.079
TDS	**0.832**	0.097	0.348
EC	**0.831**	0.109	0.354
SiO_2	-0.147	**0.757**	-0.021
pH	0.267	**0.720**	0.065
HCO_3^-	0.413	**0.712**	0.111
NO_3-N	0.109	-0.560	**0.708**
PO_4-P	-0.008	-0.430	**-0.677**

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

eigenvalues and percent of variance contributed in each principal component. Component 1 explains nearly 51.9 % of the total variance (Table 5-25) and has high positive loadings (> 0.7) for EC, TDS, Mg^{2+}, Ca^{2+}, Na^+, K^+, Cl^- and SO_4^{2-} (Table 5-24) suggesting that, these major ions contribute positively to the total dissolved solids of the groundwater and can be accounted for by major geochemical processes within the aquifer. By their definitions, TDS is the total dissolved solids, while, EC is the total ions in solution. Generally, a plot of TDS against EC shows a linear relationship with slope (m), and TDS-Conductivity factor (r^2). The general equation for this linear graph can be represented as KA = S, where, K is the EC (µS/cm), S is the TDS (mg/L), and A is a

Table 5-25 : Total Variance Explained

Component	Initial Eigen values			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	7.090	54.538	54.538	7.090	54.538	54.538	6.752	51.941	51.941
2	2.038	15.677	70.214	2.038	15.677	70.214	2.278	17.525	69.467
3	1.141	8.778	78.992	1.141	8.778	78.992	1.238	9.526	78.992
4	0.804	6.186	85.179						
5	0.697	5.363	90.541						
6	0.390	2.997	93.538						
7	0.328	2.521	96.059						
8	0.271	2.086	98.145						
9	0.134	1.034	99.179						
10	0.059	0.454	99.633						
11	0.036	0.277	99.910						
12	0.008	0.060	99.970						
13	0.004	0.030	100.000						

Extraction Method: Principal Component Analysis.

constant which defines whether a particular water type is high in HCO_3^-, SO_4^{2-} or Cl^- (Clark and Fritz, 1997). Tay *et al.*, (2014) reported that, a correlation of the TDS against EC showed that, the TDS-Conductivity factor (r^2) which is the coefficient of determination was 0.95 for groundwater within the basin and probably reflects the role of the dominant ions that may be associated with the mineralogy.

This is also consistent with the TDS-EC correlation in the correlation Table (Table 5-23), where TDS show strong correlation with EC ($r = 0.96$; $p < 0.05$). Thus, the high positive loadings of the major ions together with EC and TDS in Component 1 are expected and suggest their contribution to major geochemical processes through mineralogical influence.

Component 2 explains approximately 17.5 % of the total variance (Table 5-25) and has high positive loadings for pH, SiO_2 and HCO_3^- (Table 5-24) reflecting a common source. This suggests silicate/aluminosilicate weathering by carbon dioxide charged water. Clark and Fritz (1977) documented that, in the linear equation for conductivity and TDS (i.e. KA = S), A, defines whether a particular water type is high in bicarbonate, sulphate or chloride.

According to Clark and Fritz (1977), A = 0.55 shows waters high in bicarbonate, A = 0.75 shows waters high in sulphate and A = 0.9 shows waters high in chloride. Tay *et al.*, (2014) showed that, A, ranged 0.45 – 0.69, and 72.4 % of groundwater within the basin had A = 0.55, suggesting that, groundwater within the basin is high in bicarbonate perhaps, due principally to silicate or aluminosilicate weathering. This results is also consistent with the scatter plot of TDS vs. Na^+/ (Na^+ + Ca^{2+}) showing rock dominance weathering (Figure 5-9). It is thus, most probable that the high positive loadings for dissolved silica, bicarbonate and pH in Component 2 originates from the chemical breakdown of silicates/aluminosilicates during weathering processes.

Component 3 explains approximately 9.5 % of the total variance (Table 5-25) and has high positive loading for NO_3-N and moderate negative loading for PO_4-P (Table 5-24). Component 3 reflects a common source of pollution possibly from human induced activities such as inorganic fertilizer. The economic activity within the basin is primarily, farming where, food crops such as yam, plantain, banana, vegetables, fruits and cash crops such as cocoa, oil palm and coffee are grown. Land degradation as a result of poor farming practices where, indiscriminate use of nitrogen and phosphorus based fertilizers may be widespread and in some cases agrochemicals are used, are some of the human induced activities which are most likely to have anthropogenic impact on the water resources within the basin. Component 3 though reflects a common source of pollution, it also shows how NO_3-N and PO_4-P relates, i.e. where, NO_3-N concentration is high, PO_4-P concentration is low. The component plot in rotated space is presented in Figure 5-22. Figure 5-22 further shows the three main principal component matrix of the main physico-chemical parameters and therefore, consistent with the rotated component matrix extracted in Table 5-24.

Thus, from the PCA, it can be deduced that, Component 1 delineates the main natural processes (water-soil-rock interactions) through which groundwater within the basin acquires its chemical characteristics, Component 2 delineates the incongruent dissolution of silicates or aluminosilicates, while, Component 3 delineates anthropogenic pollution principally from agricultural inputs.

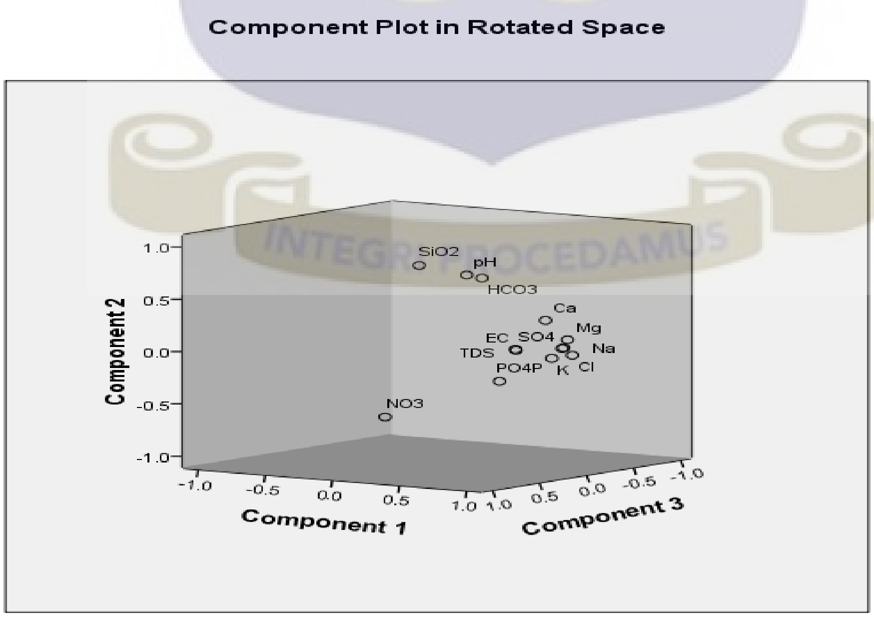


Figure 5-22: Component plot in rotated space for groundwater within the Lower Pra Basin.

5.16 Trace metal levels in groundwater within the Lower Pra Basin

With respect to trace metals with concentrations below their detection limits, one-half (½) of the value of their corresponding detection limit was substituted and used in statistical analyses in this study. The value of the ratio of the mean and the WHO guideline limit (Mean / WHO guideline limit) of the various trace metals which gives the quotient of the mean trace metal concentration to the WHO guideline limit expressing how many times each metal concentration is above or below the WHO guideline limit is given in Table 5-26.

5.16.1 Iron (Fe)

Iron (Fe^{2+}) concentrations in groundwater within the basin ranged 0.005 – 2.53 mg/L, with a mean value and standard deviation of 0.34 (± 0.46) mg/L. The WHO (2004) guideline limit for iron in drinking water is 0.3 mg/L (Table 5-26). Results show that, 21.6 % of boreholes had iron concentrations above the WHO (2004) guideline limit for drinking water. The high content of Fe^{2+} found in 21.6 % of groundwater (boreholes with Fe^{2+} above 0.3 mg/L) within the basin cannot be attributed to the presence of pyrite and arsenopyrite in the rock matrix of the Birimian rocks which is associated with some portion of the geology of the Lower Pra Basin (Kesse, 1985). Generally, the oxidation of pyrite and arsenopyrite by oxygen through proton production is expected to be a significant source of Fe^{2+} and SO_4^{2-} in groundwater (Kortatsi, 2004). Equations 5-3 and 5-8 (see Section 5.3.3) presents the reaction equations of the oxidation of pyrite and arsenopyrite by oxygen through proton production respectively.

Ideally, these reactions produce high sulphate concentrations, low pH and Fe^{2+}/SO_4^{2-} molar ratios of 0.5 (for pyrite oxidation) and 1.0 (for arsenopyrite oxidation) (Kortatsi, 2004). On the contrary, the generally very low SO_4^{2-} concentration of 0.04 - 0.95 $mmolL^{-1}$ (except Zion Camp with a sulphate concentration of 3.68 $mmolL^{-1}$) coupled with the fact that, no groundwater satisfied the Fe^{2+}/ SO_4^{2-}

Table 5-26 : Summary statistics for trace metal levels in groundwater within the Lower Pra Basin and guideline Limits for trace metal constituents in drinking water (n =250).

Parameter	Groundwater within the Lower Pra Basin				WHO (2004) Guideline limit
	Range of value	Mean value	Std Dev	Mean /WHO	
Iron $_{total}$ (Fe)*	0.005 – 2.53	0.32	0.46	1.07	0.3
Copper (Cu)	0.015 – 0.395	0.028	0.05	0.014	2.0
Manganese (Mn)	0.003- 2.28	0.162	0.34	0.405	0.4
Cadmium (Cd)	0.001 – 0.003	0.001	0.00	0.33	0.003
Zinc (Zn)*	0.003 – 0.395	0.021	0.02	0.007	3.0
Lead (Pb)	0.003 – 0.062	0.017	0.02	1.7	0.01
Selenium (Se)	0.001 – 0.01	0.005	0.001	0.5	0.01
Aluminium (Al)	0.005- 0.727	0.136	0.17	0.68	0.2
Arsenic (As)	0.001 - 0.019	0.005	0.002	0.5	0.01 (p)
Mercury (Hg) total	0.001 - 0.01	0.003	0.002	3.0	0.001 (p)

All units in mg/L, *constituents in drinking water which although not necessarily harmful to health, may give rise to consumers complaints when in excess, (p) provisional guideline value, Std Dev- Standard deviation, n = number of samples, Mean/WHO = quotient of the mean trace metal concentration to the WHO guideline limit expressing how many times each metal concentration is above or below the WHO guideline limit.

molar ratios of 0.5 and 1.0 for the stoichiometry of pyrite and arsenopyrite oxidation respectively (Table 5-27) suggest that, pyrite and arsenopyrite oxidation processes in groundwater within the basin are not exclusively responsible for the concentration of iron in the boreholes.

The stability of iron species for the groundwater system under the existing pE/pH condition (at 25^{o}C and 1 atmosphere) within the Lower Pra Basin is presented in Figure 5-23. From Figure 5-23, clearly, the groundwaters plot in the Fe^{2+}/ Fe $(OH)_3$ field suggesting that, amorphous $Fe(OH)_3$ significantly controls the concentration of iron in groundwater within the Lower Pra basin. This is consistent with the results from acid mine drainage investigation in Section 5.2.2.2 that, possible acid mine drainage reactions in groundwater within the basin produces principally $Fe(OH)_3$, which is, perhaps, a secondary source of iron in groundwater within the basin.

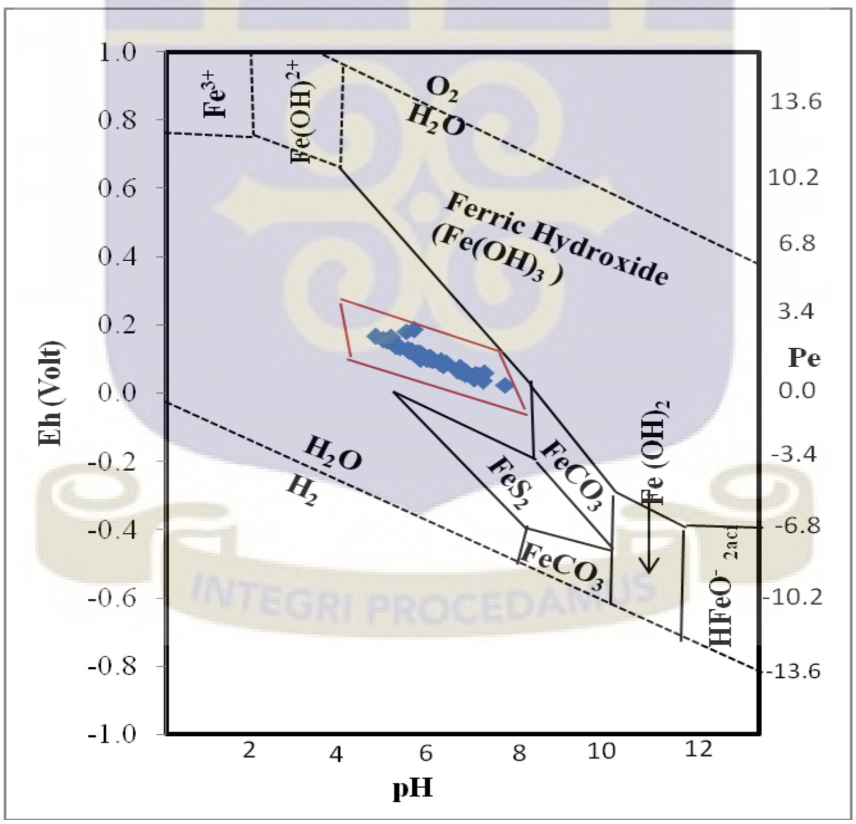


Figure 5-23: Stability diagram for iron species in groundwater within the Lower Pra Basin.

NB: Boundaries valid at 25^{o}C, 1 atmosphere total pressure, total iron activity of dissolved species 10^{-6}. Groundwaters from the Lower Pra Basin are as shown. (After Garrels and Christ, 1965).

Table 5-27: Fe^{2+} /SO_4^{2-} molar ratios for groundwater within the Lower Pra Basin.

Sample Source	BHID	Fe^{2+}(mg/L)	Fe^{2+}(mmol/L)	SO_4^{2-}(mg/L)	SO_4^{2-} (mmol/L)	Fe^{2+}/SO_4^{2-}
Sabina	380 BU1	0.526	0.01	18.8	0.20	0.05
Ayitey	094 BU3	0.160	0.00	8.9	0.09	0.03
Nkrafo	098 BU3	0.576	0.01	4.7	0.05	0.21
Nkrafo	096 BU3	0.075	0.00	10.9	0.11	0.01
Obirikwaku	099 BU3	0.465	0.01	18.4	0.19	0.04
Odumase Camp	405 BU2	0.714	0.01	11.8	0.12	0.10
Obobakokrowa		0.492	0.01	14.1	0.15	0.06
Odumase Camp	407 BU2	0.472	0.01	31.7	0.33	0.03
Dwedaama		0.156	0.00	35.0	0.36	0.01
Dwedaama		0.087	0.00	14.0	0.15	0.01
WoraKesse Habitat	097 BU3	0.044	0.00	7.4	0.08	0.01
Brofoyedru Habitat	101 BU3	0.042	0.00	17.9	0.19	0.00
Assin Nyakomase		0.042	0.00	55.6	0.58	0.00
Assin Nyakomase		0.186	0.00	18.1	0.19	0.02
Assin Nyakomase		0.068	0.00	18.7	0.19	0.01
Akonfude		0.040	0.00	17.9	0.19	0.00
Akonfude		0.088	0.00	31.2	0.32	0.00
Assin Breku (SDA)	100 BU3	2.130	0.04	25.3	0.26	0.14
Assin Breku (Gyidi)	102 BU3	0.249	0.00	4.0	0.04	0.11
Assin Breku		0.068	0.00	43.4	0.45	0.00
Techiman No. 1	396 BU3	0.047	0.00	6.2	0.06	0.01
Kwame Ankra	411 BU3	0.106	0.00	13.0	0.14	0.01
Ninkyiso		0.409	0.01	9.3	0.10	0.08
Amoakokrom	337 BU3	0.121	0.00	12.6	0.13	0.02
Nyamebekyere	339 BU3	0.108	0.00	24.1	0.25	0.01
Jerusalem	0502B1/6/09701	0.010	0.00	3.6	0.04	0.00
Antoabasa		0.476	0.01	7.5	0.08	0.11
Antoabasa		0.178	0.00	31.8	0.33	0.01

Sample Source	BHID	Fe^{2+}(mg/L)	Fe^{2+}(mmol/L)	SO_4^{2-}(mg/L)	SO_4^{2-} (mmol/L)	Fe^{2+}/SO_4^{2-}
Bediadua		0.038	0.00	21.9	0.23	0.00
Anum	086 BU3	0.368	0.01	18.3	0.19	0.03
Kyeikurom	090 BU3	0.045	0.00	10.3	0.11	0.01
Adukurom	088 BU3	0.101	0.00	16.7	0.17	0.01
Subriso		0.101	0.00	3.6	0.04	0.05
Nsuekyir	219 BU1	0.924	0.02	24.2	0.25	0.07
Danyiase Domeabra	092 BU3	0.010	0.00	22.2	0.23	0.00
Twifo Mampong		0.178	0.00	22.2	0.23	0.01
Twifo Mampong		0.081	0.00	77.8	0.81	0.00
Akwa Yaw		0.078	0.00	76.8	0.80	0.00
Breman	260 BU2	0.181	0.00	23.8	0.25	0.01
Breman		0.514	0.01	75.7	0.79	0.01
Twifo Agona	263 BU2	0.220	0.00	44.9	0.47	0.01
Zion Camp	014 BU3	0.103	0.00	353.2	3.68	0.00
Somnyamekordur	048D033 BU3	0.441	0.01	22.6	0.24	0.03
Somnyamekordur		0.150	0.00	13.6	0.14	0.02
Atu Kurom		0.186	0.00	10.4	0.11	0.03
Subreso	048D035 BU3	0.010	0.00	58.7	0.61	0.00
Gromsa	032 BU3	2.430	0.04	62.1	0.65	0.07
Anyinase Ankase	030 BU3	0.103	0.00	23.8	0.25	0.01
Sienchem	24/B/32-1	0.108	0.00	9.9	0.10	0.02
Sienchem	24/B/32-2	0.105	0.00	91.0	0.95	0.00
Mamponso	24/B/85-1	0.068	0.00	31.9	0.33	0.00
Essamang		0.170	0.00	32.2	0.34	0.01
Mampong	22/D/73-1	0.125	0.00	75.9	0.79	0.00

Additionally, the groundwaters are generally subsaturated with respect to melantherite ($FeSO_4.7H_2O$), amorphous $Fe(OH)_3$ and siderite ($FeCO_3$) (see Table 5-10) and therefore, capable of dissolving more melantherite, amorphous $Fe(OH)_3$ and siderite depending on equilibrium or pE-pH conditions. The groundwaters are also generally supersaturated with respect to goethite (FeOOH) and hematite (Fe_2O_3) (see Table 5-10) and therefore capable of precipitating these minerals depending on equilibrium or pE-pH conditions. Supersaturation of these minerals means that, the groundwaters might have reacted with these minerals long enough to attain equilibrium and therefore, no more capable of dissolving more of these minerals (Kortatsi, 2004). Thus, the groundwaters are capable of precipitating these iron minerals to reduce Fe^{2+}/SO_4^{2-} ratio (Kortatsi, 2004). The reduction of Fe^{2+}/SO_4^{2-} ratios due to the continuous precipitation of goethite and hematite is therefore, possible. Iron in groundwater within the Lower Pra Basin thus, may have been derived significantly from continuous dissolution of amorphous $Fe(OH)_3$, melantherite and siderite in the presence of organic matter until the water has attained equilibrium with these minerals.

Though, the organic matter content in the soil zone of the boreholes were not measured in this study, the brown colouration of streams and rivers within the basin throughout the year (See Plates 1-3 and 1-4) is an indication of the presence of organic matter in the soil zone (Kortatsi, 2004). Additionally, iron in groundwater within the basin may have been derived from leaching of minerals such as actinolite, chlorite, ankerite, hornblende, mica and biotite present in the rock matrices of the Lower Pra Basin (see Table 4-1) as a result of attack on these minerals by aggressive carbon dioxide (CO_2) charged groundwaters. Figure 5-24a presents the spatial distribution of Fe^{2+} in groundwater within the basin.

5.16.2 Copper (Cu)

Copper is closely related to the aerobic degradation of organic matter (Das and Notling, 1993). It has been shown to cause acute gastrointestinal discomfort and nausea at concentrations above 3 mg/L

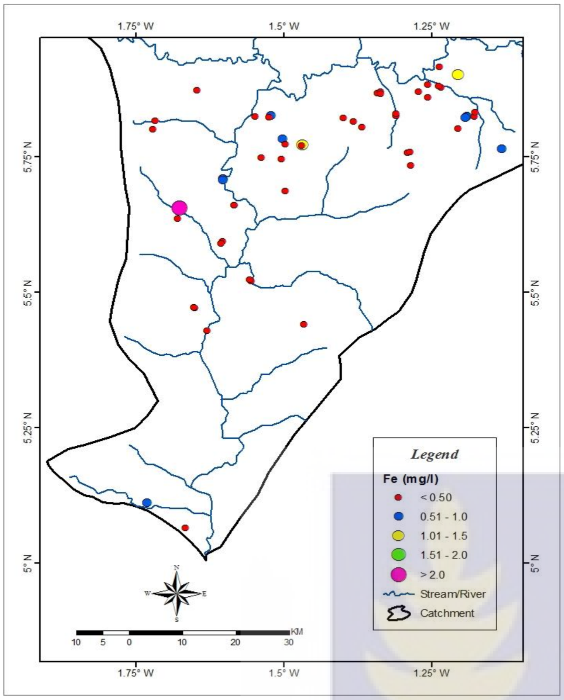


Figure 5-24 (a): Spatial distribution of Fe^{2+}

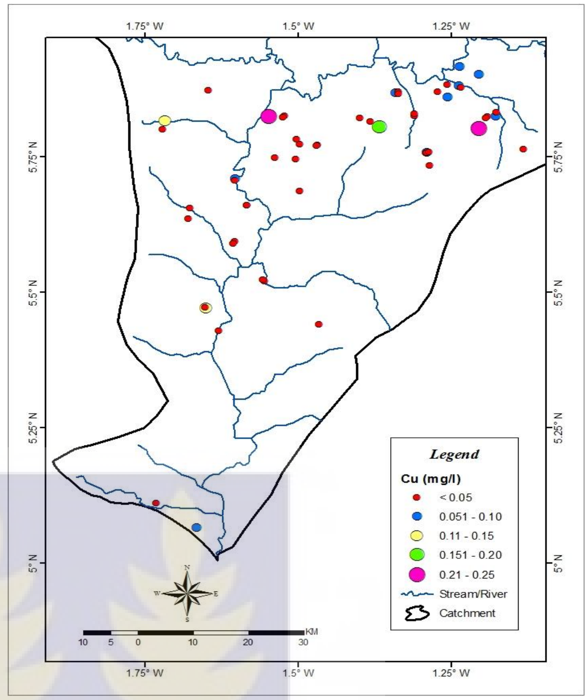


Figure 5-24 (b): Spatial distribution of Cu^{2+}

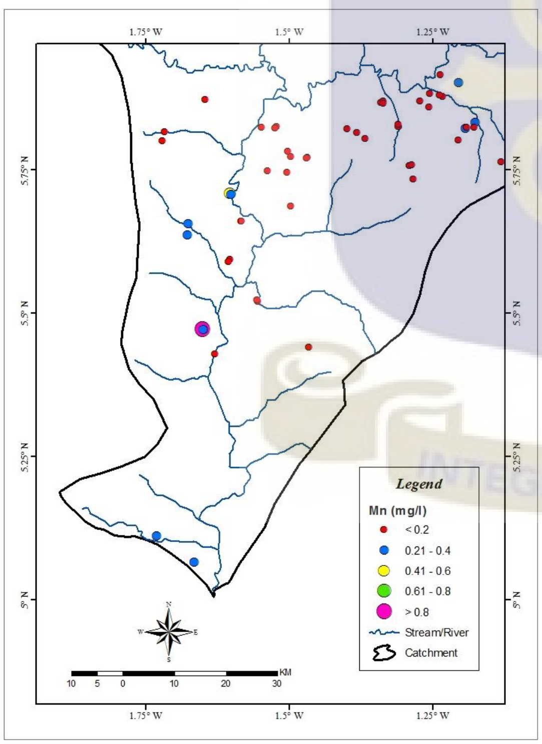


Figure 5-24 (c): Spatial distribution of Mn^{2+}

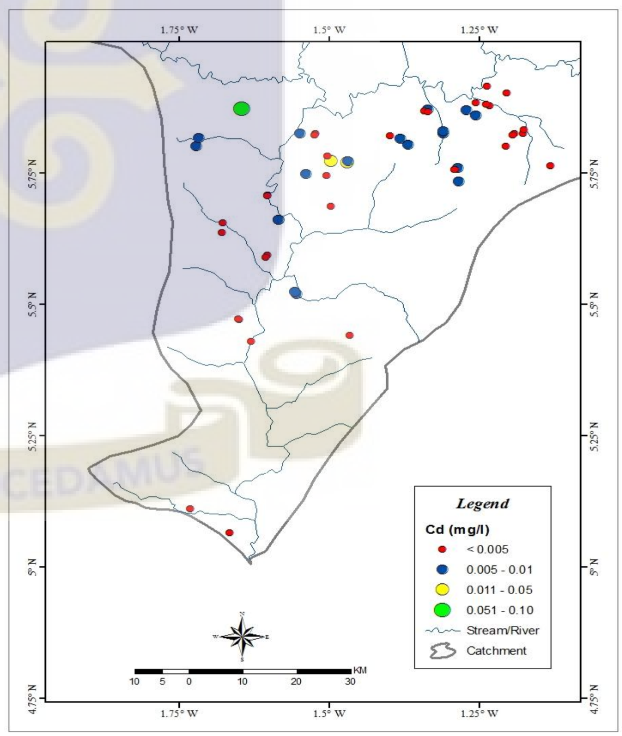


Figure 5-24 (d): Spatial distribution of Cd^{2+}

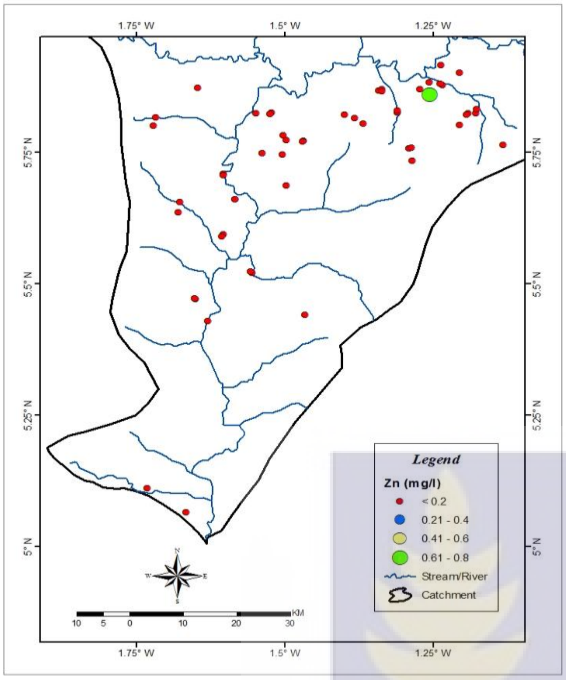


Figure 5-24 (e): Spatial distribution of Zn^{2+}

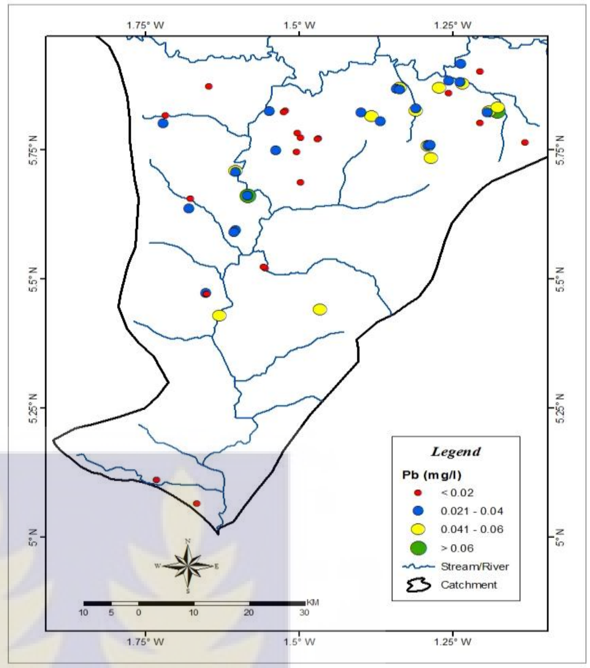


Figure 5-24 (f): Spatial distribution of Pb^{2+}

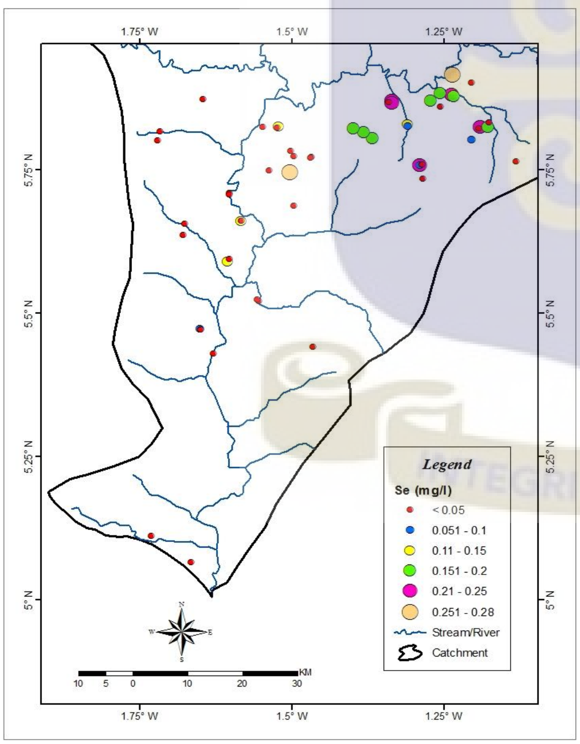


Figure 5-24 (g): Spatial distribution of Se^{2+}

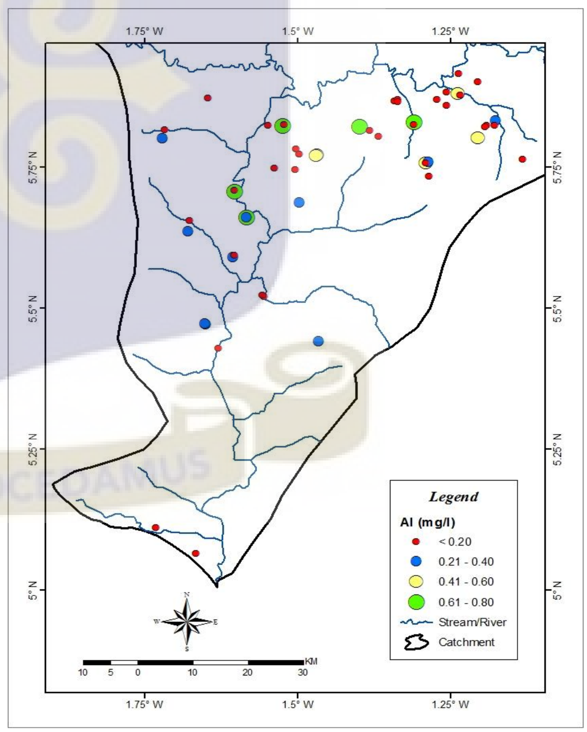


Figure 5-24(h): Spatial distribution of Al^{3+}

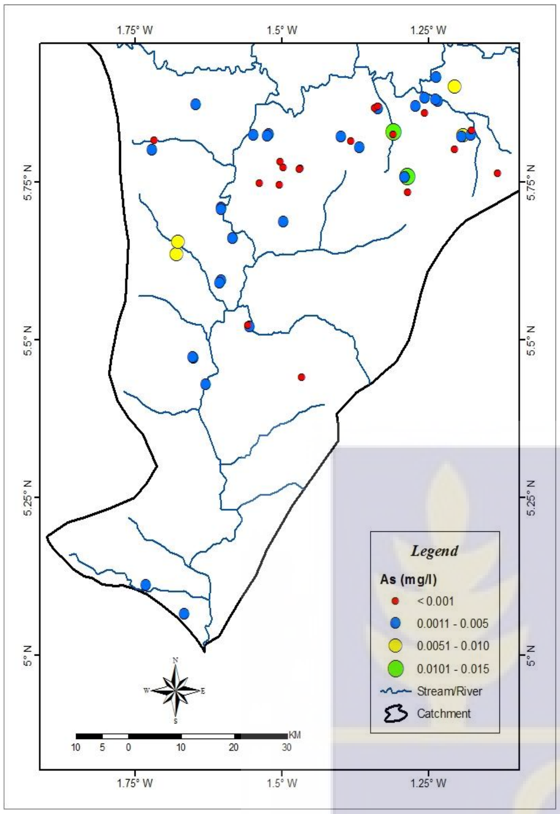


Figure 5-24 (i): Spatial distribution of As^{2+}

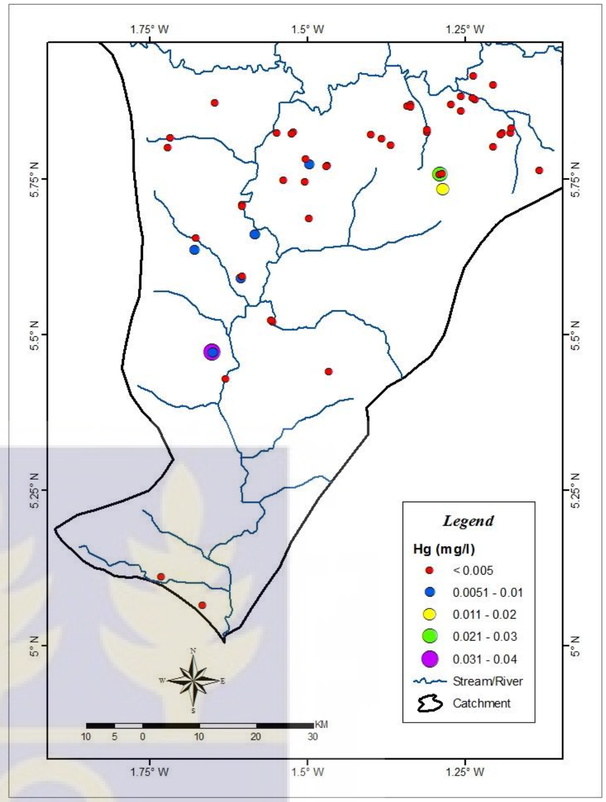


Figure 5-24 (j): Spatial distribution of Hg^{2+}

Figures 5-24 (a-j): Map of the spatial distribution of trace metals in groundwater within the Lower Pra Basin.

(WHO, 2004). Cu^{2+} concentrations in groundwater within the basin ranged 0.015 – 0.395 mg/L, with a mean value and standard deviation of 0.028 (± 0.05) mg/L. Results from this study have shown that, majority of the boreholes had Cu concentrations below detection limits. The WHO (2004) guideline limit of copper in drinking water is 2.0 mg/L (Table 5-26). Cu concentrations in groundwater within the basin do not possess physiological or aesthetic problems based on the WHO (2004) guideline. Cu^{2+} concentrations in groundwater within the basin could be attributed to the presence of oxygen and organic matter, thereby, enhancing the process of aerobic degradation of organic matter which, invariably, is closely related to the deposition of Cu^{2+} (Das and Notling, 1993). A principal source of Cu in groundwater within the basin is perhaps, corrosion of interior copper plumbing (IPCS, 1998; US NRC, 2000). The spatial distribution of copper in groundwater within the basin is presented in Figure 5-24b.

5.16.3 Manganese (Mn)

According to Evans *et al*., (1977), manganese is an element of low toxicity with considerable biological significance and, one of the most biogeochemical and active transition metals in aquatic environment. Manganese is usually found in manganese-containing minerals such as biotite and hornblende in igneous rocks and manganese oxides and hydroxides in some other rocks (Klusman and Edwards, 1977). According to Hounslow (1995), in oxidising environments, the most widespread of the minerals species containing manganese is pyrolusite (MnO_2). Manganese occurs in groundwater within the Lower Pra Basin mainly as manganese and manganiferrous oxides particularly in areas underlain by Birimian rocks (Junner *et al.*, 1942; Kesse, 1985). Saturation indices of manganese species as calculated using Phreeqc for Windows (Parkhurst and Appelo, 1999) as presented in Table 5-28 have shown that, groundwater within the Lower Pra Basin is generally subsaturated with respect to all common manganese oxides and hydroxides such as; hausmannite (Mn_3O_4), manganite (MnOOH), pyrochroite [$Mn(OH_2)$], pyrolusite (MnO_2) and rhodochrosite ($MnCO_3$).

Subsaturation occurs when: (1) the rock is depleted with respect to the mineral concerned, (2) the water has limited contact time with the rock to react to equilibrium, and (3) the ions exist in other forms in water (Kortatsi, 2004). However, petrographic evidence exists for the presence of manganese and manganiferrous oxides within the rocks of the basin and therefore, subsaturation due to depletion of the minerals in the rock is not probable. Chemical reactions involving iron are very similar to those involving manganese (Kortatsi, 2004). Therefore, if the contact time for groundwater to be supersaturated with respect to majority of the iron oxides is adequate, as is the case of groundwater within the Lower Pra Basin, then, the contact time for groundwater to be supersaturated with respect to manganese oxides and hydroxides should similarly be adequate (Kortatsi, 2004). Subsaturation with respect to the common manganese oxides and hydroxides thus, suggests that, manganese exists in other forms, possibly, insoluble manganese complexes formed with other chemical constituents different from the common oxides and hydroxides (Kortatsi, 2004).

Under mildly reducing conditions, manganese dissolves to produce mobile divalent manganous ion (Mn^{2+}) (Griffin, 1960; Wolfe, 1960). When exposed to air, the manganous ion is oxidised to hydrated oxides to form black colouration and stain on plumbing fixtures and laundry textiles (Griffin, 1960; Wolfe, 1960). Manganese is an important micro-nutrient for both plants and animals (WHO, 2004). However, when taken in very large doses can cause disease and liver damage (WHO, 2004). Exposure to manganese at levels common in groundwater is associated with intellectual impairment in children (Bouchard *et al*, 2011). As is the case of iron, the sensory effect that it produces results to the rejection and abandoning of boreholes (WHO, 2004). The WHO (2004) guideline limit for manganese in drinking water is 0.4 mg/L (Table 5-26). Manganese concentrations in groundwater within the basin ranged 0.003 - 2.28 mg/L, with a mean value and standard deviation of 0.162 (± 0.34) mg/L. Results show that, 5.6 % of boreholes had manganese concentrations above the WHO (2004) guideline limit for drinking water. The spatial distribution of manganese in groundwater within the basin is presented in Figure 5-24c. Boreholes with manganese concentration above the WHO (2004) guideline limit have the tendency of being abandoned in spite of the high cost of drilling. There is therefore, the need to treat these boreholes by reducing the levels of manganese.

In view of this it is recommended that, iron removal compartment should be constructed and attached to these boreholes as a possible solution since most of the boreholes with high iron

Table 5-28: Saturation indices for manganese species in groundwater within the Lower Pra Basin.

Sample Source	BHID	T°C	pH	Hausmannite (SI)	Manganite (SI)	Pyrochroite (SI)	Pyrolusite (SI)	Rhodochrosite (SI)
Assin Nyankomase		28.6	5.1	-26.8	-11.1	-10.0	-17.7	-1.3
Assin Nyankomase		27.6	5.6	-22.7	-9.5	-9.0	-15.7	-0.5
Assin Nyankomase		29.6	6.1	-21.3	-8.9	-8.9	-14.9	-0.9
Sabina	094BU3	28.5	6.1	-27.0	-10.9	-10.3	-17.4	-1.9
Ayitey	098BU3	27.6	6.1	-24.5	-10.1	-9.2	-16.9	-0.6
Nkrafo	096BU3	27.1	6.1	-24.6	-10.2	-9.3	-16.5	-0.6
Nkrafo	099BU3	27.5	7.0	-24.2	-10.2	-9.5	-16.1	-0.9
Obirikwaku	405BU2	27.9	6.2	-26.2	-10.7	-9.8	-17.5	-0.9
Odumase Camp	407BU2	28.1	6.0	-27.4	-11.1	-10.0	-18.1	-1.6
Odumase Camp	246JBU1	27.8	5.9	-20.1	-8.7	-8.7	-14.4	-0.9
Obobakokrowa		29.4	5.5	-23.1	-9.6	-9.2	-15.7	-0.9
Dwedaama		27.5	6.4	-23.4	-9.9	-9.8	-15.8	-0.9
Dwedaama	097BU3	26.5	5.6	-23.3	-9.8	-9.2	-16.0	-0.5
WoraKesse Habitat	101BU3	27.5	5.5	-20.6	-8.8	-8.8	-14.4	-0.2
Brofoyedru Habitat		26.4	5.9	-27.9	-11.5	-10.5	-17.9	-1.5
Akonfude		26.7	5.8	-18.8	-8.4	-8.0	-13.9	-0.4
Akonfude		27.9	5.4	-23.0	-9.9	-9.1	-16.0	-0.3
Assin Breku (SDA)	100BU3	27.9	6.1	-17.0	-7.8	-7.8	-12.9	-0.3
Assin Breku (Gyidi)	102BU3	26.2	6.9	-20.0	-9.1	-8.5	-15.0	-0.1
Assin Breku		27.6	6.2	-25.8	-10.9	-9.3	-17.8	-0.9
Techiman No.1	396BU2	26.7	5.5	-24.8	-10.5	-9.4	-17.1	-0.4
Kwame Ankra	411BU2	26.5	5.5	-18.7	-8.2	-7.9	-13.9	-0.2
Ninkyiso		27.6	5.1	-19.8	-8.3	-8.5	-13.7	-0.7
Amoakokrom	337BU3	28.4	5.3	-20.0	-8.8	-8.5	-14.2	-0.2
Nyamebekyere	339BU3	26.9	5.8	-19.7	-8.6	-8.5	-13.8	-0.3
Jerusalem	339BU3	26.5	5.4	-20.4	-8.9	-8.5	-14.5	-0.1
Antoabasa	0502B1/01/097-01	27.5	5.8	-25.7	-10.7	-10.1	-16.6	-1.4
Antoabasa		27.8	5.6	-23.4	-10.3	-9.3	-16.2	-0.4

Sample Source	BHID	T°C	pH	Hausmannite $_{(SI)}$	Manganite $_{(SI)}$	Pyrochroite $_{(SI)}$	Pyrolusite $_{(SI)}$	Rhodochrosite $_{(SI)}$
Bediadua		28.1	6.5	-24.0	-10.0	-9.6	-15.8	-1.2
Anum		26.9	5.9	-20.0	-8.8	-8.5	-14.3	-0.1
Kyeikurom	086BU3	27.3	5.8	-20.5	-8.7	-8.4	-14.7	-0.1
Adukrom	088BU3	26.8	6.4	-22.4	-9.5	-8.9	-15.6	-0.2
Subriso		26.8	6.8	-20.4	-8.7	-8.4	-14.1	-0.6
Nsuekyir	219BU1	28.0	6.0	-21.3	-9.0	-8.5	-15.1	-0.1
Denyease Domeabra	093BU3	27.1	6.7	-23.8	-10.2	-9.5	-16.1	-0.7
Twifo Mampong		27.4	6.0	-22.5	-9.7	-8.9	-15.8	-0.1
Twifo Mampong		27.9	6.2	-24.2	-10.0	-8.4	-16.4	-0.6
Akwa Yaw		26.5	6.2	-24.6	-10.1	-9.7	-16.1	-1.3
Breman	260BU2	27.4	6.7	-19.0	-8.2	-8.2	-13.9	-0.2
Breman		27.9	6.6	-24.6	-10.5	-9.4	-16.9	-0.3
Twifo Agona	236BU2	26.8	5.9	-26.9	-11.1	-10.3	-17.4	-1.3
Zion Camp	014BU3	26.4	6.8	-27.8	-11.4	-10.6	-17.7	-1.8
Somnyamekordur	138BU1	27.7	6.7	-24.9	-10.5	-9.6	-16.8	-0.5
Somnyamekordur	033BU3	27.3	5.8	-20.7	-8.9	-8.5	-14.7	-0.1
Atu Kurom		28.3	5.6	-22.1	-9.4	-8.9	-15.3	-0.3
Subreso		26.4	6.5	-20.2	-8.8	-8.5	-14.4	-0.1
Gromsa	032BU3	27.5	6.4	-14.8	-6.7	-7.1	-11.6	-0.5
Anyinase Ankase	030BU3	27.3	5.9	-19.1	-8.4	-7.8	-14.3	-0.6
Sienkyem	24/B/32/1	26.6	5.4	-18.2	-7.7	-7.9	-13.3	-0.1
Sienkyem	24/B/32/1	26.4	5.5	-18.3	-7.8	-8.0	-13.2	-0.2
Mamponso	24-B-85-1	27.2	5.8	-19.9	-8.5	-7.9	-14.9	-0.7
Essamang		26.8	5.3	-14.2	-6.4	-6.4	-12.3	-1.6
Mampong	22/D/73-1	27.8	5.5	-25.8	-10.8	-9.9	-17.2	-0.8

content coincidentally had high manganese content. Ferric hydroxide [$Fe(OH)_3$], which may be produced in the iron removal plant during aeration has the tendency to absorb manganous ions, and therefore, the dual removal ability of both iron and manganese (Kortatsi, 2004).

5.16.4 Cadmium (Cd)

Cadmium is one of the most toxic elements with widespread carcinogenic effects in humans, and is widely distributed in the aquatic environment (Goering *et al*., 1994). Cd occurs naturally in the form of CdS or $CdCO_3$ and is recovered as a by-product from the mining of sulphide ores of lead, zinc and copper (Goering *et al*., 1994). The form of cadmium present in an environment depends on the solution and soil chemistry as well as treatment of the waste prior to disposal (Smith *et al*., 1995). The most widespread forms of cadmium include; Cd^{2+}, cadmium-cyanide complexes such as $[Cd (Cn)_4]^{2-}$ and $Cd(OH)_2$ solid sludge (Smith *et al*., 1995). At high pH, the hydroxide ($Cd(OH)_2$) and carbonate ($CdCO_3$) forms of cadmium are common, whereas at lower pH (< 8), Cd^{2+} and aqueous sulphate species are the common forms of cadmium (Smith *et al*., 1995). In the presence of sulphur under reducing conditions, the stable solid $CdS_{(s)}$ is formed (Smith *et al*., 1995). Cadmium is also capable of precipitating in the presence of phosphate, arsenate, chromate and other anions, although, its solubility varies with pH and other chemical factors (Smith *et al*., 1995).

In surface and groundwater systems, Cd is relatively mobile and exists commonly as hydrated ions or as complexes with humic acids and other organic ligands (Callahan *et al*., 1979). Under acidic conditions, cadmium may also form complexes with chloride and sulphate (Callahan *et al*., 1979). Health effects of cadmium contaminated water include kidney damage (Callahan *et al*., 1979). Cadmium concentration in groundwater within the Lower Pra Basin ranged 0.001 – 0.003 mg/L, with a mean and standard deviation value of 0.001 (± 0.0) mg/L. Based on results from this study, approximately 18.0 % of groundwater within the basin had cadmium concentrations in excess of WHO (2004) guideline limit for drinking water of 0.003 mg/L (Table 5-26).

Common sources of cadmium contamination include plating operations and the disposal of cadmium-containing wastes (Smith *et al*., 1995). Other sources of cadmium in drinking water are corrosion of galvanized pipes, erosion of natural deposits, discharge from metal refineries, runoff from waste batteries and paints (Smith *et al*., 1995). However, there are no metal refineries and runoffs from waste batteries and paints are rare within the basin. This leaves corrosion of galvanized fittings used for the construction of boreholes as one of the probable sources through which cadmium can be released in significant quantities into groundwater within the basin. Consumers living in the communities where cadmium concentrations are in excess of the WHO (2004) may be potentially at risk of Cd-related infections such as kidney damage. The spatial distribution of cadmium in groundwater within the basin is presented in Figure 5-24d.

5.16.5 Zinc (Zn)

One of the earliest known trace metals and a common environmental pollutant is Zn, and is widely distributed in the aquatic environment (Hess and Schmidt, 2002). It has been found to have low toxicity effect in man (Hess and Schmidt, 2002). However, long-term consumption of large doses can result in health complications such as fatigue, dizziness, and neutropenia (Hess and Schmidt, 2002). Zn compounds are found naturally in air, soil, water and food (Hess and Schmidt, 2002). Zinc is present in the earth crust and is commonly found associated with sulphide of other metals (Train, 1979).

Zn occurs as a natural mineral in many drinking waters (Train, 1979). One major source of human exposure to Zn is possibly drinking water containing Zn as a result of soil erosion and corrosion of plumbing fixtures which use zinc-containing materials (WHO, 1980). Zinc is also a vital dietary nutrient and a beneficial element in human metabolism (Vallee, 1957). Insufficient dietary zinc intake may lead to poor growth and development, loss of appetite, birth defects, slow healing of wounds and skin injuries (Vallee, 1957). Long- term injection of zinc compounds at lower doses can lead to copper deficiency by interfering with the body's ability to take in and use copper (Carlos *et al.*, 1997).

The WHO (2004) guideline limit of zinc in drinking water is 3.0 mg/L (Table 5-26). Zinc concentration in groundwater within the Lower Pra Basin ranged 0.003 – 0.395 mg/L, with a mean and standard deviation value of 0.021 (± 0.02) mg/L. Zinc concentrations in groundwater within the Lower Pra Basin therefore, does not pose quality problems for groundwater supply and development within the basin. The spatial distribution of Zinc in groundwater within the basin is presented in Figure 5-24e.

5.16.6 Lead (Pb)

According to the classification by the United States Environmental Protection Agency (USEPA) lead (Pb) is potentially hazardous and toxic to most forms of life (USEPA, 1986). Pb is known to be responsible for a number of ailments in humans such as chronic neurological disorders especially in foetuses and children (WHO, 1980). A concentration of Pb > 0.1 mg/L is detrimental to foetuses and children with possible development of neurological problems (WHO, 1980). High lead concentration results in metabolic poisoning that manifest in symptoms such as tiredness, lassitude, slight abdominal discomfort, irritation and anaemia (WHO, 1980). The WHO (2004) guideline limit for lead in drinking water is 0.01 mg/L.

Lead concentration in groundwater within the Lower Pra Basin ranged 0.003 – 0.062 mg/L, with a mean and standard deviation value of 0.017 (± 0.02) mg/L. Results show that, approximately 39.6 % of boreholes within the basin had lead levels in excess of WHO (2004) guideline limit of 0.01 mg/L (Table 5-26). The relatively high levels of lead in groundwater occurred in Assin Breku, Assin Nyankomase, Brofoyedru Habitat, Sabina, Somnyamekordur, Nkrafo, Ayitey, Obirikwaku, Obobakokrowa, Akonfude and Mamponso communities which are underlain by Cape Coast/Dixcove granitoids and Birimian rocks. This suggests that consumers living in these communities may be potentially at risk of possible metabolic poisoning as a result of long-term consumption of groundwater particularly, children under five years and pregnant women are at potential risk of elevated lead levels in the blood stream (Moskowitz *et al.*, 1986).

Sources of lead in groundwater within the basin may include anthropogenic sources such as mining and plumbing fixtures. According to Lee *et al.*, (1989), even boreholes in which plastic pipes are used during plumbing, significant levels of lead have been found, primarily from the brass faucet fixtures, which are used in almost all plumbing. The spatial distribution of lead in groundwater within the basin is presented in Figure 5-24f.

5.16.7 Selenium (Se)

Biologically, Se is beneficial to the metabolic requirement of animals when taken in the concentration range of 0.1-10 mg/kg of food (Fairhill, 1941). However, Se can be potentially toxic to man with symptoms characteristically similar to those of arsenic (Fairhill, 1941). Se contamination in drinking water in excess of the maximum contaminant level over many years could result to hair or fingernail losses and numbness in fingers or toes (Fairhill, 1941).

According to Kortatsi (2004), sources of Se contamination include; discharge from petroleum and metal refineries; erosion of natural deposits and discharge from mines. However, there are no petroluem and metal refineries within the Lower Pra basin. This leaves discharge from mines (small-scale mining activities- *"galamsey"*) through which Se can be released in significant quantities into groundwater within the basin.

The concentration of Se in groundwater within the basin ranged 0.001 – 0.01 mg/L, with a mean and standard deviation value of 0.005 (± 0.001) mg /L. The WHO (2004) guideline limit of Se in drinking-water is 0.01 mg/L (Table 5-26). This shows that, approximately 18.4 % of boreholes within the basin had Se levels above the WHO (2004) guideline limit. Communities with Se concentrations in excess of the WHO (2004) in groundwater are potentially prone to hair and fingernail losses as well as numbness in fingers and toes after a prolong intake of drinking water. Se could therefore, pose a serious threat to groundwater management and development in these communities. The spatial distribution of Se in groundwater within the basin is presented in Figure 5-24g.

5.16.8 Aluminium (Al)

Al concentration in water is controlled by pH, the type and concentration of complexing agents that may be present, the oxidation state of the mineral components, and the redox potential of the system (WHO, 1984). According to Parkhurst and Appelo (1999), Al speciation using Phreeqc for windows suggests a phenomenon of Al^{3+} as the thermodynamically favoured under the prevailing pH/Eh conditions. Generally, aluminium (Al^{3+}) appears to have only little detrimental effect on human (Moskowitz *et al.*, 1986). However, Al toxicity has been associated with central nervous system disorders including Alzheimer's disease and dialysis dementia (Moskowitz *et al.*, 1986). Al concentrations in groundwater within the Lower Pra basin ranged 0.005- 0.727 mg/L, with a mean and standard deviation value of 0.136 (± 0.17) mg/L.

According to Ondřej Šráček (2004), a significant impact of acidification is the dissolution of aluminium hydroxide minerals as a result of which toxic aluminium is released. Aluminium concentration is often controlled by the precipitation of amorphous aluminium hydroxide $[Al(OH)]_5$ (Ondřej Šráček, 2004). Thus, water with lower pH (acidic) is often accompanied by high concentration of aluminium (Ondřej Šráček, 2004). As expected, relatively higher Al concentrations are associated with boreholes with lower pH values in some communities even though no distinct pattern was established (Figure 5-25).

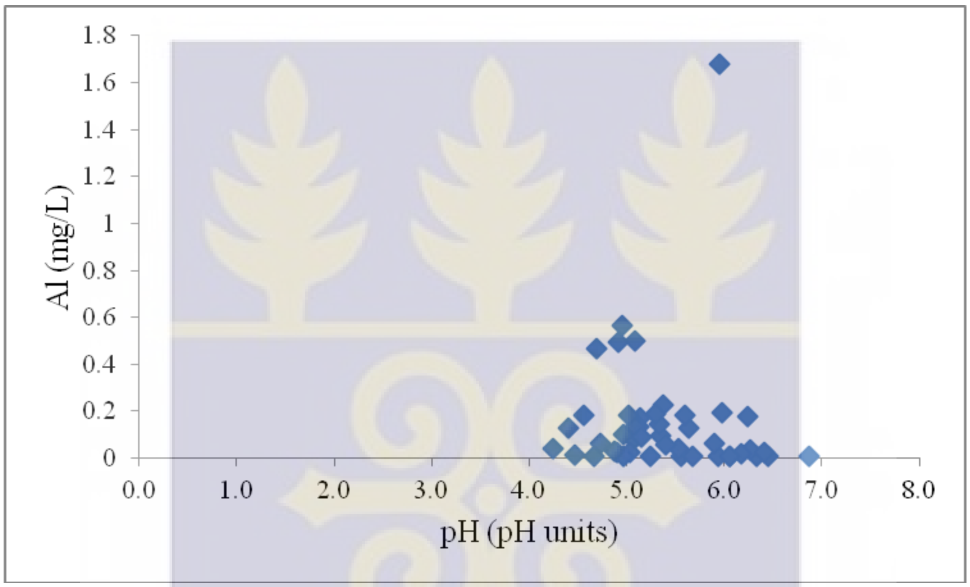


Figure 5-25: Relationship between pH and Aluminium levels in groundwater within the Lower Pra Basin.

The most significant problem associated with Al is the occurrence of discolouration in drinking water and its distribution systems at concentrations exceeding 0.2 mg/L, thereby, rendering the drinking water aesthetically unacceptable (WHO, 1993). On this basis, aluminium concentrations in groundwater within the Lower Pra Basin seem to pose a major quality problem owing to the fact that, approximately, 19.2 % of the boreholes had Al^{3+} concentration exceeding the WHO (2004) guideline limit for drinking water (Table 5-26). The spatial distribution of aluminium in groundwater within the basin is presented in Figure 5-24h.

5.16.9 Arsenic (As)

Groundwater within the Lower Pra Basin generally, had As concentrations which ranged 0.001 - 0.019 mg/L, with a mean and standard deviation value of 0.005 (± 0.002) mg/L. Based on the results, approximately 11.6 % of the shallow boreholes (depths < 100 m) had arsenic concentrations slightly in excess of the WHO (2004) guideline limit of 0.01 (p) mg/L (Table 5-26). Despite the presence of pyrite and arsenopyrite minerals in the rocks within the basin, arsenic concentrations in groundwater within the basin is generally low. This suggest some level of co-precipitation of arsenic with ferrric oxyhydroxide in the solution before possible infiltration into the acquifer (Kortatsi, 2004).

The principal source of arsenic contamination in the environment are metal smelting, chemical manufacturing, pesticides application and coal combusting (Diaz-Barringa *et al.*, 1993). However, coal combusting and pesticides applications are not common within the Lower Pra Basin, while chemical manufacturing is non-existent. This leaves mining and /or smelting of sulphide ores as the only sources that could possibly be responsible for high arsenic concentrations in surface- and ground waters within the basin. Additionally, the widespread low SO_4^{2-} concentration of 0.04 - 0.95 $mmolL^{-1}$ coupled with the fact that, no groundwater satisfied the iron to sulphate (Fe^{2+}/ SO_4^{2-}) molar ratios of 0.5 and 1.0 for the stoichiometry of pyrite and arsenopyrite oxidation respectively (Table 5-27) suggest that, pyrite and arsenopyrite oxidation in groundwater within the basin may not be exclusively responsible for the concentration of arsenic in the groundwater within the basin.

According to Smedley *et al.*, (1995), arsenic occurs in high concentrations when in association with manganese and iron ores especially sulphide minerals and particularly, pyrites. Saturation indices of the iron species melantherite, siderite and amorphous Fe $(OH)_3$ (see Table 5-10) suggests that, the groundwaters are generally subsaturated with respect to these minerals and therefore, will continuously dissolve in solution depending on the Eh/pH conditions. This suggests that, pyrite and arsenopyrite minerals may have undergone oxidation, hydrolysis and co-precipitation of iron and arsenic as Fe^{3+}/ferrihydrite due to the introduction of oxygenated air within the aquifer (Kortatsi, 2004). Furthermore, the generally low levels of arsenic in groundwater within the basin suggest that, mining (surface or underground) has an inconsequential impact on arsenic concentrations in groundwater within the basin.

According to Smedley *et al.*, (1995), the International Agency for Research on cancer, the World Health Organization (WHO) and the US Environmental Protection Agency (USEPA), have classified arsenic as a known carcinogen *(a cancer producing gent)* and a toxin. Arsenic, when taken in large doses, leads to coma and subsequently, death (Carlos *et al.*, 1997). Small oral doses of arsenic can possibly cause gastro-intestinal pains, haemorrhage, nausea, vomiting, diarrhoea, anaemia, and neurological toxicity such as headache, lethargy, confusion, hallucination, seizures, and coma (Carlos *et al.*, 1997). Long-term low-level exposure to arsenic may also result in cardiovascular toxicity, anaemia, liver toxicity, and a pattern of skin changes that includes darkening of the skin and the appearance of small corns or warts (Carlos *et al.*, 1997). Long-term, low- level exposure to arsenic through drinking water has been associated with skin cancer (WHO, 1993). There is evidence to suggest increasing risk of bladder, kidney, liver, and lung tumours when exposed to arsenic (WHO, 1993).

The WHO (2004), restricted the level of arsenic in drinking water based on its carcinogenicity and potential nutrient requirement considerations provisionally to 0.01 mg/L. Thus, the 11.6 % of boreholes with arsenic slightly in excess of the WHO (2004) guidline limit located in Odumase Camp, Dwendaama, Sienchem, Akonfude and Atu Kurom posses potential diseases associated with long-term low- level exposure to consumers in these communities. Nevertheless, in terms of morbidity, Wang and Huang (1994) noted that, no morbidity cases were found where, arsenic concentrations in drinking water were less than, 0.1 mg/L but morbidity increased exponentially as aqueous arsenic increased and indeed, mild arsenic poisoning was observed in the range 0.1 – 0.2 mg/l. Since no borehole within the Lower Pra Basin had arsenic concentration exceeding 0.1 mg/L, it suggets that, though, the concentrations were sightly in excess of the WHO (2004) guideline limit, no morbidity is expected. The spatial distribution of arsenic in groundwater within the basin is presented in Figure 5-24i.

5.16.10 Mercury (Hg)

Hg sources in the environment include; natural degassing of earth crust and industrial activities such as cement manufacturing, mining and smelting as well as waste disposal (Wershaw, 1970; Voege, 1971; WHO, 1980). Hg can also enter the soil through direct application of mercury-containing fertilizers, lime and fungicides (Wershaw, 1970). The occurrence of Hg in water is due mainly to leaching from rocks and sometimes from release into water in the form of wastewater effluents from industrial plants that use Hg (Holden, 1995). The most widespread species of Hg in most surface waters are mercuric hydroxide and chloride (WHO, 1980).

Hg is commonly used in batteries, thermometers, fungicides, antiseptics and dental fillings (WHO, 1980). The consumption of food contaminated with Hg, usually fish or shellfish as well as the Hg vapour released from dental fillings are mainly the result of human exposure to Hg (Voege, 1971; WHO,1980). The form of mercury found in fish and shellfish is organic or carbon-containing mercury (Voege, 1971; WHO,1980). The form of Hg found in dental fillings is metallic mercury (Carlos *et al.*, 1997). The form of mercury associated with rocks as well as mining and smelting is inorganic or non-carbon-containing mercury (Carlos *et al.*, 1997).

Inorganic Hg in the environment can be transformed to organic mercury by micro-organisms (Carlos *et al.*, 1997). The most widespread form of organic mercury, methyl mercury, can accummulate in some types of fish to very high concentrations (Carlos *et al.*, 1997). Human exposure to methyl mercury occurs when contaminated fish or shellfish are consumed (Carlos *et al.*, 1997). Methyl mercury is most likely to cause nervous system toxicity than inorganic mercury (WHO,1980). Both short- and long-term oral exposure to inorganic mercury salts can lead to kidney damage, including kidney failure (Carlos *et al.*, 1997). When orally ingested, inorganic mercury can rapidly accummulate in the kidney and could become very irritating to the gastrointestinal tract and cause nausea, vomiting, pain, ulceration and diarrhorea (WHO,1980). Toxicity to the brian and nervous system has been reported following large doses of inorganic mercury taken medicinally (WHO, 1980).

Groundwater within the Lower Pra Basin generally, had Hg concentrations which ranged 0.001 - 0.01 mg/L, with a mean and standard deviation value of 0.003 (± 0.002) mg/L. Based on the results approximately 42.0 % of the shallow boreholes (depths < 100 m) had Hg concentrations significantly in excess of the WHO (2004) guideline limit of 0.001 (p) mg/L (Table 5-25). However, there is no petrographic evidence of Hg in the rocks within the basin, neither are there industrial activities within the basin apart from small-scale mining activities (*"galamsey"*) that can release mercury in significant quantities into groundwater. The temporal variation of Hg in groundwater within the basin is presented in Figure 5-26.

Figure 5-26 shows a trend which suggests that, the concentrations of Hg in the boreholes are significantly in excess of the WHO (2004) guideline limit of 0.001 mg/L for drinking water during the rainy (wet) seasons (June - October). However, the concentrations of Hg becomes < 0.0 mg/L or below detection limit during the dry seasons (January – March). This observation suggest that, Hg concentrations in groundwater within the basin increases during the rainy season.

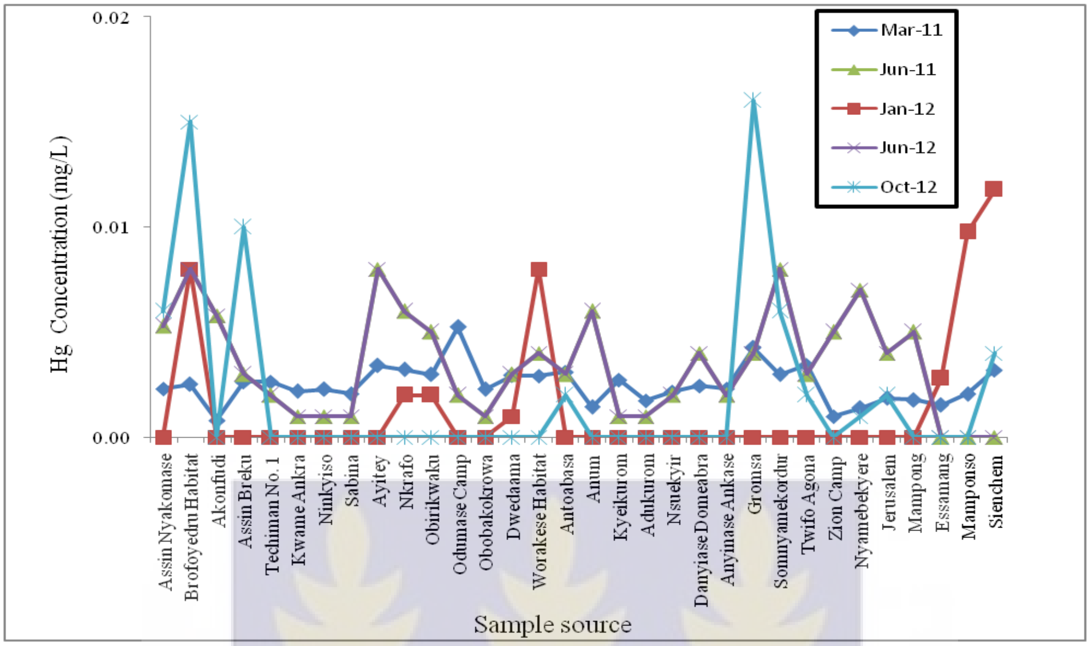


Figure 5-26: Temporal variation in Hg concentration in groundwater within the Lower Pra Basin.

Assuming that, Hg concentrations in groundwater within the basin is attributable to the rocks, ideally, a uniform and even distribution in Hg concentrations within the basin regardless of the season (whether wet or dry) all year round would have been expected (Kortatsi, 2004). However, a careful investigation of the relationship between recharge regimes of polluted groundwater and Hg concentrations (Figure 5-26) suggests a trend, in which case, during the rainy season surface water resources polluted with Hg as a result of the small-scale mining *('Galamsey')* activities recharge groundwater through infiltration subsequently, reaching the water-table (Kortatsi, 2004).

Consequently, groundwater within the basin is potentially under threats of Hg contamination due to contaminated surface water resources, possibly as a result of the indiscriminate use of Hg amalgamation through small-scale mining activities. The implication of the significantly higher Hg concentrations mainly during the wet season is that, consumers in the affected communities within the basin are potentially at risk from mercury poisoning and its associated health hazards such as kidney failure, brain and nervous breakdown, gastrointestinal tract irritation, ulceration and diarrhoea (WHO, 1980). The spatial distribution of mercury in groundwater within the basin is presented in Figure 5-24j.

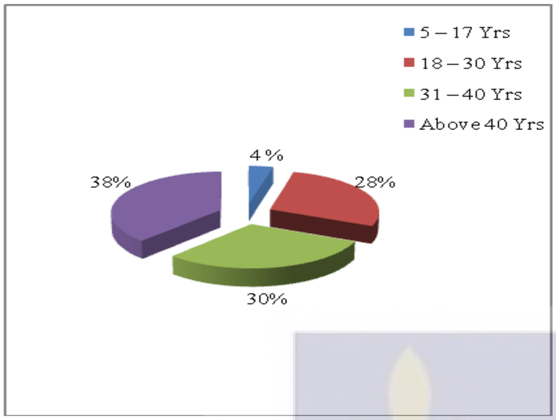
5.17 Socio-demographic characteristics of respondents

Table 5-29 presents the demographic information of three hundred (300) respondents interviewed during questionnaire administration. The ages of the respondents varied from 5 years to above 40 years, with majority (96.1 %) of females and majority (82.0 %) of males with ages varying between 18 and above 40 years.

Table 5-29 : Socio- Demographic characteristics of respondents within the Lower Pra Basin

Gender	Number of Respondents	
	Female Total: 234	**Male** Total : 66
Age		
5 – 17	9	12
18 - 30	65	11
31 -40	71	43
Above 40	89	-
Literacy		
No education	33	-
1st Cycle	186	57
2nd Cycle	15	6
3rd Cycle	-	3
Occupation		
Farming	130	55
Trading	71	-
Mining	-	9
Others	33	2
Marital Status		
Single	80	9
Married	139	47
Divorced	15	10

The percentage age of respondents for females and males are presented in Figures 5-27 a and b respectively.



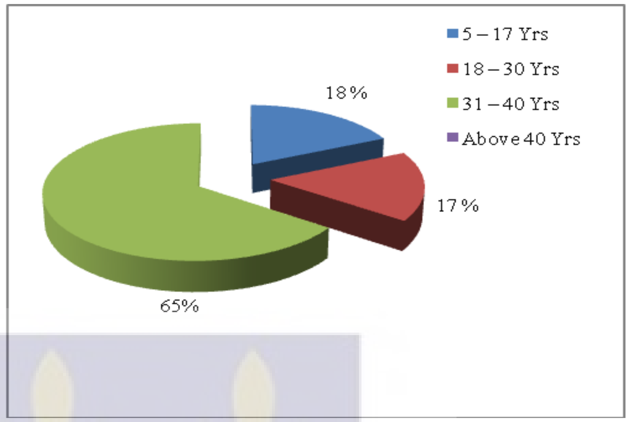
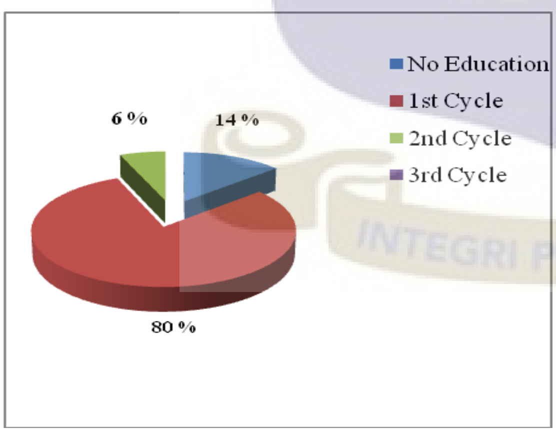


Figure 5-27 (a): Female Respondents **Figure 5-27 (b): Male Respondents**

Figures 5-27(a-b): Percentage age of Respondents; (a) - Female and (b) – Male

The percentage literacy of the respondents for females and males are presented in Figures 5-28 a and b respectively. Figures 5-28 a and b shows that, there is high illiteracy rate amongst the respondents as 80.0 % of females and 86.0 % of males attained only 1st Cycle education (Primary, Middle and JHS).



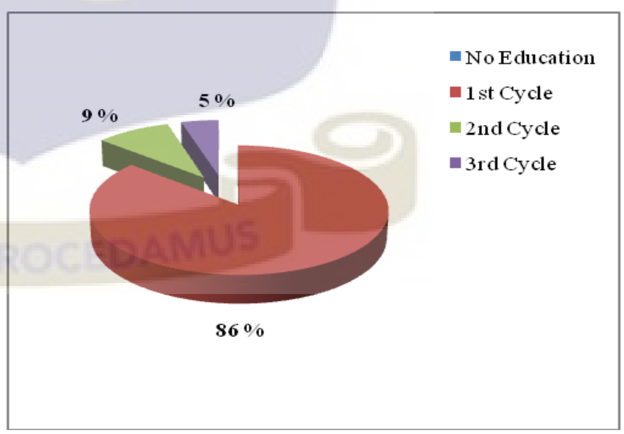


Figure 5-28 (a): Female Respondents **Figure 5-28 (b): Male Respondents**

Figures 5-28 (a-b): Percentage literacy of Respondents; (a)- Female and (b)- Male

Figures 5-29 a and b presents the percentage occupation of the respondents for females and males respectively. Figures 5-29 a and b shows that, the occupation of the respondents is predominantly farming. Of the 234 female respondents 54.0 % are farmers, 30.0 % are traders and 16.0 % do other jobs such as seamstress, hairdressing, nursing, teaching and others. Of the 66 respondents who are males, 83.0 % are farmers, 14.0 % are miners, while, 4.0 % do other jobs such as teaching, driving, mechanics and others. Of the 234 female respondents, 59.4 % are married, 34.2 % are single while, 6.4 % are divorced. Of the 66 male respondents, 13.6 % are married, 71.2 % are single, while, 15.2 % are divorced (Table 5-30).

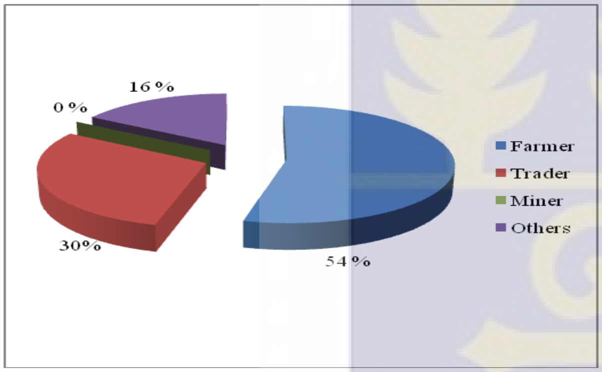


Figure 5-29(a): Female Respodents

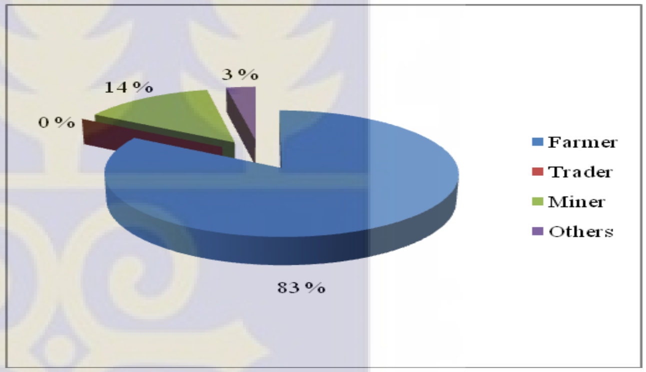


Figure 5-29 (b): Male Respondents

Figures 5-29 (a-b): Percentage occupation of Respondents; (a)- Female and (b)- Male

Responses were also sought on how long the respondents had lived in the community. Figures 5-30 a and b presents the number of years the respondents had lived in the community.

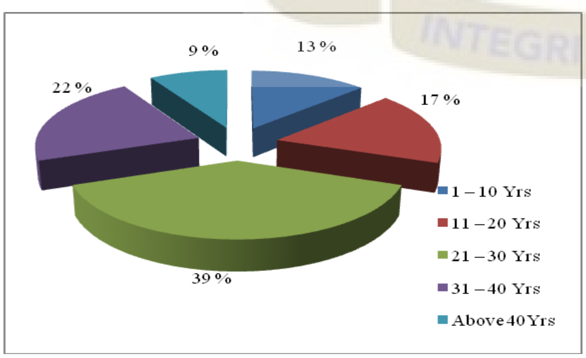


Figure 5-30 (a): Female Respondentds

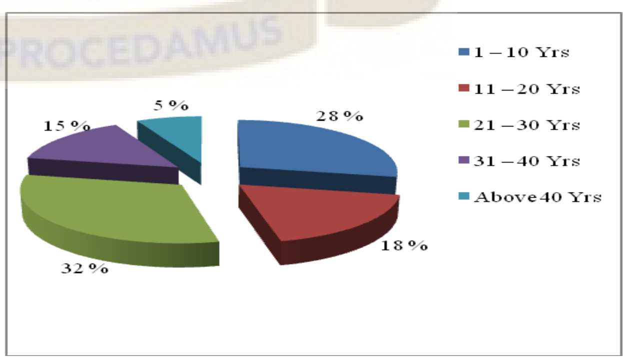


Figure 5-30 (b): Male Respondents

Figures 5-30(a-b): Number of years Respondents lived in the community; (a) -Female and (b)-Male

From Figures 5-30 a and b, majority of the respondents, 52.0 % of the males and 70.0 % of the females respectively have lived in the community between 21- 40 years and therefore, are familiar with the water resources available in the community as well as the anthropogenic activities which have the tendency of impacting on the quality of water resources within the study area.

The survey also shows that, most of the communities have a minimum of two water sources which are boreholes and streams. All (100 %) the respondents said that the main drinking water sources in their communities are the boreholes and that, water from the borehole is used predominantly for all domestic purposes (i.e., drinking, washing, bathing and cooking). Of the 300 respondents, 54.0 % said they drink raw water from the stream without treatment, while, 46.0 % asserted that, they do not drink raw water from the stream. Of the respondents who said that they drink raw water from the stream, 23.0 % of them said that, they are not aware of the health implications of drinking raw water from the stream, while, 77.0 % of them said that, they are aware of the health implications. Of the 300 respondents, 58.0 % said that, their choice of drinking water source is due to the water quality, 26.0 % said it is due to availability, 11.0 % said it is due to the only source, 3.0 % said it is due to distance from home and 2.0 % said it is due to poverty. 93.0 %, 4.0 % and 3.0 % of the 300 respondents have also said that the level of usage of borehole water in their communities is very high, moderately high and high respectively.

In terms of income spent on water needs of the households, 68.0 % of the respondents said that they pay for the water they abstract from the boreholes, while, 32.0 % said that they do not pay for the water they abstract from the boreholes. The cost of water from boreholes within the basin ranges from ten to twenty Ghana Pesewas per average bucket. In some communities within the basin, payment is made every month and the cost ranges from GH ¢ 1.00 to 5.00. Responses were also sought on whether respondents consider the cost of water to be high, 53.0 % of respondents said NO, while 47.0 % of respondents said YES.

The survey further sought to establish whether the availability of other water sources such as rivers and streams could affect the level of patronage of borehole water. 86.0 % of respondents said that they will continue to patronize borehole water due principally to the quality (taste) of borehole water, while, 14.0 % of respondents said they would patronize rivers and streams. Of the category which said they would patronize rivers and streams, when asked why? 40.0 % said it is due to the high cost, while, 60.0 % said it is due to the quality (taste) of borehole water.

In order to assess possible borehole water contamination through improper solid waste disposal and on-site or on-plot sanitation systems, such as pit latrines or open defecation, responses were also sought on how solid waste is disposed off in the area they lived and how far away their disposal site is from the wellhead. Of the 300 respondents, 38.0 % said their solid waste is disposed off at a public disposal site over 100 metres away from the wellhead, 19.0 % said their solid waste is disposed off at a public disposal site about 100 metres away from the wellhead, 2.0 % said their solid waste is disposed off at a public disposal site about 80 metres away from the wellhead, 2.5 % said their solid waste is disposed off at a disposal site about 60 metres away from the wellhead, 3.6 % said their solid waste is used as fertilizer under cocoanut and plantain trees about 40 metres away from the wellhead, 2.5 % said their solid waste is disposed of at the outskirts of their compound about 20 metres away from the wellhead. 25.0 % said their solid waste is disposed off at a public open pit over 100 metres away from the wellhead, 6.4 % said their solid waste is disposed off at a public open pit about 100 metres away from the wellhead, 5.5 % said their solid waste is disposed off at a public open pit about 80 metres away from the wellhead, 3.6 % said their solid waste is disposed off at an open pit 40 metres away from the wellhead, 3.6 % said their solid waste is disposed off at an open pit at the outskirts of their compound 20 metres away from the wellhead and 8.3 % said their solid waste is burnt at a waste disposal site between 80 to 100 metres away from the wellhead.

The Community Water and Sanitation Agency (CWSA) recommend a minimum of 50 metres as the safe distance between a community borehole and a community solid waste disposal site (CWSA Guidelines and Standards, 2010). Based on the CWSA Guidelines and Standards, 13.3 % of groundwater within the basin may become contaminated through solid waste disposal.

Of the 300 respondents interviewed regarding on-site or on-plot sanitation systems, such as pit latrines (KVIP), 46.0 % said they patronize public pit latrines situated over 100 metres away from the wellhead, 23.0 % said they patronize public pit latrines situated about 100 metres away from the wellhead, 6.0 % said they have their own pit latrines situated about 100 metres away from the wellhead, 8.0 % said they patronize public pit latrines situated about 80 metres away from the wellhead, 6.5 % said they have their own pit latrines situated about 80 metres away from the wellhead, 4.5 % said they patronize public pit latrines situated about 60 metres away from the wellhead, 1.0 % said they have their own pit latrines situated about 40 metres away from the wellhead, 1.0 % said they have their own pit latrines situated about 20 metres away from the wellhead and 4.0 % said they have their own water closets.

Similarly, the Community Water and Sanitation Agency (CWSA) recommend a minimum of 50 metres as the safe distance between a community borehole and a community KVIP latrine (CWSA Guidelines and Standards, 2010). Based on the CWSA Guidelines and Standards, 2.0 % of groundwater within the basin may become contaminated through human waste excreta.

The survey further sought to assess the possible impact of farming activities on the rivers/streams within the basin. In this assessment, responses were sought on whether, farming activities takes place along the river/stream and if YES, whether the farmers use agrochemicals. Of the 300 respondents, 81.8 % said that farming activities do take place along the rivers/streams and that, the farmers usually spray their farm produce using agrochemicals, 11.0 % said that even though farming activities do take place along the rivers/streams, the farmers do not usually spray their farm produce using agrochemicals. 7.2 % said that farming activities do not take place along the rivers/streams.

Owing to the fact that, throughout the two-year period of sampling campaign, foot pumps were usually doped with water prior to abstraction when the boreholes are left without being used for long hours (see Plate 6-1), this survey, sought to additionally assess the perception of the respondents regarding the foot pumps. Of the 300 respondents, 59.0 % use foot pumps for groundwater abstraction. Out of the respondents who use the foot pumps, 54.0 % said they do have problems with the foot pumps and 46.0 % said they do not have problems with the foot pumps.

The survey further sought to identify the nature of problems with the foot pumps. Of the respondents who have problems with the foot pumps, 68.6 % said that, the problem with the foot pumps is doping with water for several minutes prior to abstraction if the borehole is left without being used for long hours and therefore, they would prefer hand pumps to the foot pumps. Responses were also sought whether in their opinion, they would need additional boreholes. Of the 300 respondents, 98.3 % said YES.

The survey further sought to assess the impact of drinking water on the health of the consuming public within the basin. Owing to the fact that, assessment of the trace metal levels in groundwater within the basin had revealed that the groundwaters were contaminated with trace metals, the questionnaire was designed to include the possible health effects of long-term consumption of water containing trace metals in concentrations exceeding the WHO (2004) guideline limits for drinking water. The questionnaire sought to find out if, there are medical facilities available in the communities and how far these medical facilities are from their homes. Results show that, medical facilities are within less than 5 km and greater than 10 km from their homes. Responses were sought on whether the respondents or any of their family members have ever visited these medical facilities, 96.0 % of the respondents said YES. A follow- up question for the respondents who said YES, was, what disease were you or your family member diagnosed of?

Figure 5-31 presents the diseases reported by the respondents. Of the 300 respondents, 33.0 % said abdominal discomfort, 25.0 % said numbness in fingers or toes, 24.0 % said diarrhoea, 12.0 % said others (heart disease, body pains, malaria, skin rashes, typhoid, blindness and hypertension), 3.0 % said brain or nervous damage, 1.0 % each said dialysis dementia, kidney damage and loss of hair/finger nails. This result (Figure 5-31) is thus, consistent with the trace metals analytical results which identified the possible diseases likely to be associated with the long-term use of groundwater as potable water within the basin.

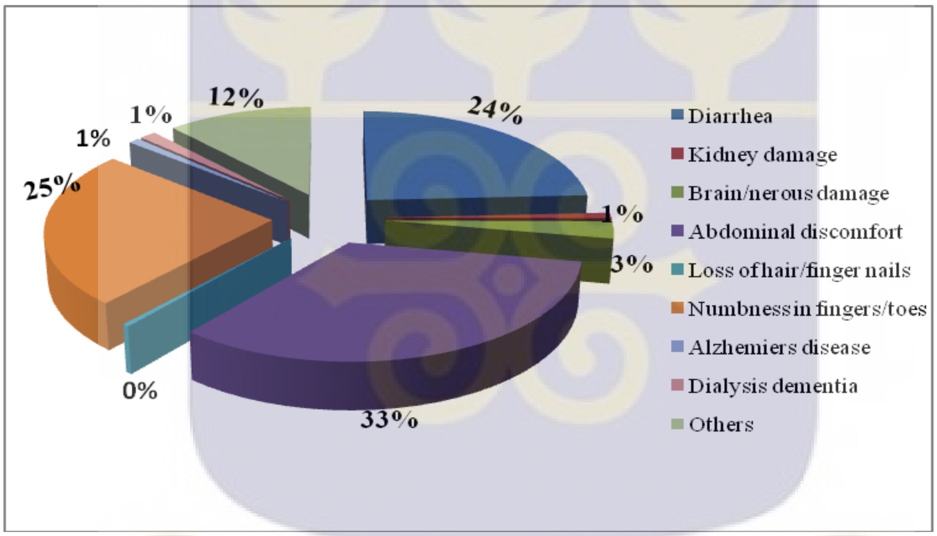


Figure 5-31: Diseases reported by respondents within the Lower Pra Basin

The survey further sought to find out whether, the respondents are aware that these diseases could be as a result of long-term consumption of water contaminated with toxic trace metals. Of the 300 respondents, 22.0 % said YES and 78.0 % said they were not aware. Of the respondents who said YES, responses were sought on whether they think these diseases can be prevented 49.0 % of the respondents said NO and 51.0 % of the respondents said YES. Of the respondents who said YES, when asked how?, 59.0 % of the respondents gave no response, 22.0 % said by drinking quality water and 19.0 % said by observing personal hygiene.

The survey further shows that, a distressing health concern of Kyeikrom community is an unknown cause of blindness. The respondents identified blindness as the main health concern in the community and need to be investigated.

The survey further sought to find out about the major environmental concerns of the respondents. Results show that, 37.0 % of respondents gave no response, 41.0 % of respondents said poor sanitation and 22.0 % of respondents said contamination of water resources.

Of the respondents who said contamination of water resources, when asked what they think was the cause of their environmental concerns, 83.0 % of the respondents said bad farming practices and in the case of mining communities the respondents included "galamsey' activities and 17.0 % gave no response. Of the respondents who said poor sanitation, responses were sought on what they think is the cause of their environmental concerns, 45.0 % of respondents gave no response, 31.0 % of respondents said lack of adequate environmental facilities and 24.0 % of the respondents said bad farming practices.

Finally, the survey sought to find out whether respondents know what to do to prevent contamination of groundwater. Of the 300 respondents, 53.0 % of respondents gave no response, 22.0 % said through environmental cleanliness, 20.0 % said through routine maintenance of the borehole, 3.0 % said by banning "galamsey" activities, 1.0 % said by changing foot pumps to hand pumps and 1.0 % said through education. The responses from respondents regarding what to do in order to prevent contamination of surface and groundwater resources shows that, the respondents lack knowledge in water resources pollution prevention and therefore, educational programmes should be organized by the managers of these water resources to educate the rural communities within the Lower Pra Basin to prevent further contamination of these water resources.

CHAPTER SIX

6.1 Conclusions

Hydrochemical results have shown that, the major processes responsible for chemical evolution of groundwater within the Lower Pra Basin include: silicate $(SiO_4)^{4-}$ weathering, ion-exchange reactions, sea aerosol spray, and the leaching of biotite, chlorite and actinolite. The groundwater is moderately acidic to neutral, with pH which, ranged 3.5 - 7.0 pH units and mean 5.9 (± 0.5). Approximately, 89 % of groundwaters had pH values outside the WHO (2004) guideline value of 6.5- 9.5 due principally to natural biogeochemical processes. Groundwater acidity studies using the pH values show that, notwithstanding the moderately low pH, the groundwater still have the potential to neutralize acids due to the presence of silicates/aluminosilicates. Electrical conductivity ranged 57.6 - 1201 µS/cm, with mean 279.3 (±198.8) µS/cm. Total dissolved solids (TDS) ranged 32 - 661 mg/L, with mean 151.7 (±106.8) mg/L, with 98.6 % of groundwater as fresh (TDS < 500 mg/L).

The chemical constituents generally have low concentrations and are within the WHO (2004) guideline values for drinking water. The relative abundance of cations and anions is in the order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-}$ respectively. Acid mine drainage processes possibly taking place in groundwater within the basin is as a result of the oxidation of pyrite and/or arsenopyrite by oxygen through proton production and principally producing $Fe(OH)_3$. Mineral equilibrium computation using phreeqc for windows shows that, groundwater within the basin originates from environments where calcite and dolomite are depleted. Saturation indices for anhydrite, melantherite, and gypsum also shows that, groundwater within the basin is generally subsaturated with respect to these minerals, whilst, groundwater is generally supersaturated with respect to goethite. The stability diagrams of anorthite and albite shows that, consistent with natural waters with low silica, majority of the groundwaters plot in the kaolinite-stability field indicating that, kaolinite is the most stable secondary aluminosilicate mineral phase for the groundwater system within the basin.

Stable isotopes results show variation in $\delta^{18}O$ from -3.24 ‰ to -0.95 ‰ with mean and median values of -2.49 ‰ and -2.53 ‰ respectively. $\delta^{2}H$ values ranged from -15.25 ‰ to -1.67 ‰ with mean and median values of -10.45 ‰ and -10.35 ‰ respectively. A plot of $\delta^{18}O$ ‰ against $\delta^{2}H$ ‰ shows that, the groundwaters clustered on or closely along the *Global Meteoric Water Line*, suggesting that, the groundwater emanated primarily from meteoric origin with evaporation playing an insignificant role on the infiltrating water. However, all the surface and groundwaters clustered above the *Local meteoric water line* for the Accra Plains by Akiti (1986), suggesting evidence of isotopic enrichment by evaporation on the surface or in the unsaturated zone before recharge into the groundwater system. Hydrochemical evaluation of groundwater within the basin using Q-mode cluster analysis (HCA) have characterized groundwater within the basin into four (4) water groups and five (5) subgroups. Hydrochemical facies using Piper trilinear plot delineated two main water types –the Na-HCO_3 and Ca-Mg-HCO_3 with Na-Cl and Ca-Mg-Cl as minor water types.

Water quality data for subgroups show that, Group 1 waters (Subgroups 1A and 1B) and Group 2 waters (Subgroups 2A, 2B and 2C) both represents a transition zone between Ca-Mg-HCO_3/Na-HCO_3 and Na-Cl/ Ca-Mg-Cl /Na-SO_4 water types and therefore, can be regarded as transition zones between naturally circulating groundwaters which have not undergone pronounced water-rock interaction and the infiltration of local rain and/or permanent hard water suggesting that, groundwater within the basin perhaps, evolves from a fresh- Ca-Mg-HCO_3 type water to Na-HCO_3 type water to permanent hard- Ca-Mg-Cl type water to the influence of local rain - Na-Cl type water along the flow-path. The results also suggests that, groundwater within the basin is primarily undergoing recharge processes (mixing of fresh waters-Ca-Mg-HCO_3/Na-HCO_3) than processes involving saline-water intrusion (mixing of fresh and old waters).

A spatial plot of the water groups and subgroups consisting of waters from the basin show that, majority of waters in the same group are located in close proximity to one another suggesting that, the same hydrogeochemical processes and /or flow-path are taking place within the aquifer with which the waters are in contact. The high degree of spatial and statistical coherence suggests that, the changes between the principal hydrochemical facies define the hydrochemical evolution of groundwater within the basin.

Spearman's correlation matrix of the hydrochemical data have shown that, EC, TDS, Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-} and SO_4^{2-} are positively related and therefore, originate from the mineralization of the geological components of soils. PCA using Varimax with Kaiser Normalization for component matrix has delineated three main processes; i.e. natural geochemical and biochemical processes (water-soil-rock interactions), incongruent dissolution of silicates/aluminosilicates, and pollution of the water resources principally from agricultural inputs.

The trace metal results from this study show that, groundwater in some communities within the basin is contaminated, with Al (19.2 % of boreholes), Se (18.4 % of boreholes), Cd (18.0 % of boreholes), As (11.6 % of boreholes), Pb (39.6 % of boreholes), Mn (5.6 % of boreholes), Hg (42.0 % of boreholes) and Fe (21.6 % of boreholes) concentrations exceeding the WHO (2004) guideline limits for drinking water and therefore, constituting health hazards to consumers in these communities within the Lower Pra Basin. From the results, Al, Se, As, Pb, Cd, Mn, Hg and Fe concentrations in some boreholes exceeded the WHO (2004) guideline limits for drinking water. This suggests that, groundwater within the basin is under threat by both natural geochemical processes and anthropogenic activities.

Based on the social impact survey conducted, most of the communities within the basin have a minimum of two water sources (surface and groundwater). However, due to contamination of the surface waters, groundwater has become the principal drinking water source for most communities within the basin as 93.0 % of the inhabitants depend principally on groundwater. Majority (77.0 %) of the inhabitants seem to be aware of the health implications of drinking raw water from streams/rivers.

The survey also shows that, majority (58.0 %) of the inhabitants use groundwater for their drinking water needs due to quality reasons. With respect to the cost of abstracting groundwater, majority (68.0 %) of the inhabitants are of the view that, the cost is appreciably low. The survey also shows that, based on the CWSA Guidelines and Standards, 13.3 % of groundwater within the basin may become contaminated through solid waste disposal, while, 2.0 % of groundwater may become contaminated through human waste excreta.

Regarding contamination of groundwater through farming and mining activities, surface waters which are most often used in these activities are endangered since 81.0 % of farmers spray their farms with agrochemicals and all mining activities especially "galamsey"are cited close to or along the surface water course. The impact of these anthropogenic activities within the basin on groundwater is therefore critical, since these surface waters serve as recharge water reservoirs to groundwater within the basin.

The survey further shows that, majority (68.6 %) of the inhabitants who use foot pumps for groundwater abstraction want these foot pumps replaced with hand pumps to avoid doping the foot pumps with water for several minutes prior to abstraction if they are left without being used for long hours. The inhabitants also believed that, their communities require additional boreholes to meet their water needs.

Results from the social survey are consistent with the trace metal analytical results which identified the possible diseases associated with the long-term use of groundwater as potable water within the basin. However, the results further revealed that, majority (78.0 %) of the inhabitants are not aware that these diseases are as a result of the long-term consumption of contaminated water. The social survey further revealed that majority of the inhabitants does not seem to know of the hygienic practices to prevent contamination of groundwater.

6.2 Recommendations

Based on the findings from this study, the following recommendations are made towards effective management and development of groundwater resources and the well-being of consumers of these water resources within the basin:

1. The Government of Ghana through the District Assemblies and other stakeholders within the Water Sector in collaboration with the mandated institutions such as the CSIR-Water Research Institute should institute immediate monitoring (hydrochemical parameters) measures to manage and develop groundwater within the basin for sustainability since groundwater has become the primary source of drinking water for the communities within the basin.
2. The District Assemblies should institute measures to prevent the pollution of naturally circulating groundwaters which have not undergone pronounced water-rock interaction (Ca-Mg-HCO_3 and Na-HCO_3) by creating buffer zones within which the use of fertilizers and agrochemicals in agriculture should be banned. Additionally, the transition zones between Ca-Mg-HCO_3/Na-HCO_3 and Na-Cl/ Ca-Mg-Cl /Na-SO_4 should be monitored.
3. In terms of management and development of groundwater within the entire Pra Basin, future groundwater studies should be focused on similar hydrogeochemical studies in the Upper Pra Basin to generate similar data.
4. Data obtained from the hydrogeochemical studies in the Lower and Upper Pra Basins could be put together and the results obtained used to model the hydrogeochemical processes influencing the quality of groundwater within the Pra Basin. The model could then be used to predict groundwater quality for decades to come. This will provide the basis for the monitoring

of water quality parameters to guarantee sustainability thereby, ensuring efficient management and development of groundwater within the Pra Basin.

5. Aquifer vulnerability assessment approach as proposed in DRASTIC (Depth, Recharge, Aquifer, Soil, Topographic slope, Impact of vadose zone, Conductivity of the aquifer) should be conducted periodically to assess the impact of these factors on groundwater quality.
6. The Government of Ghana through the Environmental Protection Agency (EPA) should enforce the existing laws on mining, especially small-scale (‘*galamsey*’) operations to deter the small-scale miners from the indiscriminate amalgamation of gold with mercury (Hg) or arsenic (As) in order to prevent further pollution of the water resources. This would prevent further contamination of the water resources and ensure the safety of consumers of these water resources within the basin.
7. There should be educational programmes to create awareness to farmers on the safe use of fertilizers and micronutrient fertilizers, agrochemicals and animal wastes in agriculture in order to prevent or minimise contamination of the water resources, thereby, eliminating the health risks associated with the use of nitrogen and phosphorus based fertilizers as well as organic chemicals.
8. Iron removal compartment should be constructed and attached to boreholes with Fe and Mn concentrations above the WHO (2004) guideline limit as a possible solution to the removal of Fe and Mn, since Ferric hydroxide which may be produced in the iron removal plant during aeration has the tendency to absorb manganous ions, and therefore, the dual removal ability of both iron and manganese.
9. The Government of Ghana through the District Assemblies and other stakeholders within the Water Sector in collaboration with the mandated health institutions should institute health monitoring programs with respect to the health disorders associated with toxic trace metals

such as; Al, Se, Pb, Cd and Hg in order to prevent the long-term effects of intake of these trace metals through water.

10. The Government of Ghana through the District Assemblies in collaboration with other stakeholders within the Water Sector should take measures to replace all constructed boreholes with foot pumps with hand pumps as the foot pumps in most communities would have to be doped (see Plate 6-1) with water (sometimes several buckets) in order to create the required pressure in the system to abstract water. This problem is widespread throughout the basin and in some cases gives cause for the communities to abandon the boreholes especially if there are other alternatives such as nearness of a stream or a river source.
11. The main health concern (blindness) of kyeikrom Community needs to be investigated as a matter of urgency to prevent other inhabitants from becoming blind.

Plate 6-1: A caretaker at Worakesse Habitat doping the borehole with a foot pump with water to create the required pressure in the system for water abstraction.

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APPENDICES

APPENDIX A: BOREHOLE DATA FOR GROUNDWATER WITHIH THE LOWER PRA BASIN

Table A-1: Borehole data for the Lower Pra Basin

Source	Longitude	Latitude	BH ID	BH Depth (m)	Aquifer zone (screen position)	Geology	SWL (m)	Yield (m^3/h)
Bremang	5.70878	-1.60277	260BU2	36.0	24 - 33	Granite-schist contact	0.4	1.6
Bremang	5.70720	-1.60261		45.0	33 - 42	Granite-schist contact	6.5	1.6
Ninkyiso	5.82117	-1.39912		24.0	13 – 21	Schist	9.5	0.8
Kwame Ankra	5.81542	-1.38199	411GU3	39.0	16 – 24	Schist	2.9	0.6
Sabina	5.86974	-1.27172	380BU1	42.0	30 – 39	Schist	3.7	6.6
Amoakokrom	5.85972	-1.25611	337BU1	39.0	24 – 36	Schist	4.6	5.1
Ayitey	5.88351	-1.25584		30.0	19 – 27	Schist	4.6	2.9
Obirikwaku	5.91571	-1.23661	099BU1	42.0	33 - 39	Schist	6.6	15
Odumase Camp	5.82454	-1.19147	405BU3	51.0	21 – 48	Granite	1.4	0.8
Odumase Camp	5.82181	-1.19419		51.0	15 – 48	Schist	2.7	1.3
Obobakrokrowa	5.82490	-1.17763		60.0	44.5 – 53.5	Granite	15.0	0.9
Dwedaama	5.80170	-1.20496		66.0	21 – 63	Granite-schist contact	7.2	0.4
Dwedaama	5.80139	-1.20575		65.0	18 - 64	Granite-schist	7.1	0.5
Bediadua	5.77278	-1.49722		60.0	51 -58	Schist	1.6	32.6
Adukrom	5.82278	-1.52444		39.0	25 – 36	Schist	3.0	1.4
Kyeikurom	5.82504	-1.52242	090BU3	30.0	18 – 27	Granite-schist	2.7	0.8
Antoabasa	5.77196	-1.46878		51.0	36 – 48	Granite-schist	8.0	5
Antoabasa	5.77020	-1.46948		45.0	14 – 30	Granite	7.1	0.4
Anum	5.78219	-1.50224	083BU3	54.0	45 - 51	Schist	3.4	4.1
Brofoyedru Habitat	5.73346	-1.28457	101BU3	51.0	33 – 48	Granite- schist	15.6	0.4
Nkranfo	5.87809	-1.23364	096BU3	42.0	30 – 39	Schist	11.5	0.9
Nkranfo	5.88087	-1.23862	098BU3	57.0	47 – 54	Schist	2.5	12.9
WoraKesse Habitat	5.76443	-1.13154	097BU3	66.0	39 – 45	Granite-gneiss	7.3	0.5
Danyiase Domeabra	5.74806	-1.53806		33.0	21 – 30	Schist	3.0	5.5

Assin Breku (SDA)	5.86625	-1.33603	100BU3	48.0	30 – 45	Schist	5.9	19.5
Assin Breku (Gyidi)	5.87059	-1.33603	102BU3	51.0	40 – 49	Schist	5.3	0.4
Assin Breku	5.86801	-1.34094		30.0	15 – 27	Schist	0.6	2.8
Akonfude	5.82570	-1.30988		90.0	36 – 48	Granite-gneiss	14.9	3.5
Akonfude	5.82950	-1.31011		63.0	32 – 47	Granite-gneiss	6.3	0.5
Akonfude	5.84528	-1.33028		48.0	34 - 45	Granite-gneiss	7.0	1.8
Assin Nyankomase	5.75724	-1.29063		45.0	30 – 42	Granite-schist	4.7	3.9
Assin Nyankomase	5.75719	-1.29084		96.0	81 – 93	Granite-gneiss	6.7	1.5
Assin Nyankomase	5.75897	-1.28625		63.0	29 – 36	Granite-gneiss	5.4	0.8
Somnyamekordur	5.66046	-1.58376		30.0	12 – 27	Schist	1.3	1.1
Somnyamekordur	5.66449	-1.58478	048D033BU3	45.0	18 – 32	Schist	21.8	1.6
Subreso	5.65596	-1.67676	048D035BU3	69.0	57 – 66	Schist		51.7
Atukrom	5.63657	-1.67850		51.0	27 – 49	Phyllite/Schist	8.2	0.9
Akwa Yaw	5.44157	-1.46580		51.0	10 – 16	Granite-schist	6.7	0.7
Nsuekyir	5.68667	-1.49722		33.0	11 – 30	Schist	1.5	3.7
Twifo Mampong	5.52016	-1.55449		63.0	20 – 39	Schist	2.7	1.2
Twifo Mampong	5.52359	-1.55681		51.0	21 – 30	Granite-schist	2.6	6
Gromsa	5.58991	-1.60607	032BU3	33.0	21 – 30	Schist	3.2	8.6
Anyinase Ankaase	5.59646	-1.60279	030BU3	42.0	28 – 39	Granite-schist contact	7.2	8.7
Jerusalem	5.81666	-1.72139	0502B1/01/097-01	60.0	48 – 57	Phyllite/Schist	13.1	3.3
Nyamebekyere	5.80139	-1.72139	339BU3	45.0	26 – 42	Phyllite/Schist	11.7	0.6
Techiman No. 1	5.80432	-1.36792	396BU3	37.5	22 – 35.5	Granite	6.2	2.8
Twifo Agona	5.74595	-1.50398	263BU2	60.0	33 – 42	Phyllite/Schist	7.9	0.9
Zion Camp	5.87217	-1.64602	014BU2	60.0	48 – 58	Phylite/Schist	5.9	4.3
Mampong	5.11142	-1.73174	22/D/73-1	22.0	6 – 22	Schists	2.3	1.7
Mamponso	5.42906	-1.63002	24/B/85-1	40.0	17 – 40	Gneiss	12.1	1.8
Asamang/Essamang	5.05042	-1.67979	24/D/89-1	24.0	4 – 24	Gneiss	1.1	0.6
Sienchem	5.47246	-1.65156	24/B/32-1	30.0	15 – 30	Gneiss	5.7	1.8
Sienchem	5.47123	-1.65053	24/B/32-2	37.0	10 – 37	Gneiss	2.8	0.7

Longitude (N), Latitude (W)

APPENDIX B: HYDROCHEMICAL DATA FOR GROUNDWATER WITHIN THE LOWER PRA BASIN

B-1: Hydrochemical data of groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 14th-18th March 2011)

Sample Source	BHID	GPS co-ordinates	pH	EC	TDS	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2	E.Bal.	CBE(%)
Assin Nyakomase		N05.75829', W001.28643'	5.3	569	256.0	7.0	16.6	6.9	62	51	69.6	112.3	1.700	53.1	12.6	0.46	4.46
Assin Nyakomase		N05.75762', W001.29058'	5.2	203	117.0	34.0	4.6	6.9	29	9.4	17.9	68.2	0.939	17.6	26.4	0.20	4.63
Assin Nyakomase		N05.75729' ,W001.29082'	5.4	69.1	44.2	38	2.1	7.5	20	6.2	12.9	36.1	1.850	18.5	6.3	0.17	5.24
Brofoyedru Habitat	101BU3	N05.78437', W001.28443'	5.8	126	72.8	31.2	8.4	1.6	15	8.3	7.3	61.6	0.586	19.2	9.3	-0.12	-3.68
Akonfude		N05.82614', W001.30953'	5.6	317	172.0	97	23.6	7.7	23	14	59.3	98.2	0.253	36.2	34	-0.34	-5.11
Akonfude		N05.82945' ,W001.31011'	5.1	531	281.0	116	22.1	17.5	34	5.5	53.7	97.8	0.655	24.8	24.8	0.40	5.11
Nkrafo	098BU3	N05.87813', W001.23365'	6.4	361	221.0	124	37.3	14.1	38	12.3	17.9	189.5	0.068	5.7	1.6	0.33	3.49
Nkrafo	096BU3	N05.88086', W001.23863'	3.8	492	255.0	57	15.6	4.1	14	5.8	11.9	0.0	1.510	9.9	24.0	0.03	0.88
Obirikwaku	099BU3	N05.91570' ,W001.23361'	6.5	273	144.0	98	31.5	5.2	17	6.9	12.9	141.8	0.202	18.2	33.1	-0.16	-2.65
Odumase Camp	405BU2	N05.82454', W001.19149'	5.3	152	81.3	22	8.3	9.2	17	3.2	11.9	32.4	0.234	11.3	5.2	0.11	2.93
Odumase Camp	407BU2	N05.19421' ,W001.19421'	5.6	303	181.7	71	14.2	10.1	41	4.7	46.8	83.3	0.545	33.2	16.7	0.06	0.86
Obobakrokrowa		N05.83490' ,W001.17768'	6.2	334	201.2	147	48.5	7.7	18	3.7	18.9	171.4	0.165	6.7	4.1	0.18	2.30
Obobakrokrowa		N05.83277', W001.17656'	5.2	296	167.0	87	16.4	12.7	36	2.8	35.7	91.2	0.692	13.1	34.3	0.29	4.25
Ayitey	094BU3	N05.88353' ,W001.25584'	6.0	217	121.2	63	13.1	4.2	18	7.2	21.9	67.3	0.573	8.2	1.6	0.08	2.01
DanyiaseDomeabra	093BU3	N05.74806',W001.53606'	6.2	225	117.0	63	20.4	5.7	20	6.4	11.9	112.5	0.070	9.0	18.0	0.15	3.03
Anyinase Ankase	030BU3	N05.59646',W001.60273'	5.6	112	57.9	38	8.9	4.3	13	1.6	6.5	42.9	0.417	10.3	8.9	0.11	4.29
Gromsa		N05.59000', W001.60611'	5.5	192	134.0	218	32.4	3.7	15	2.6	31.9	71.3	0.462	24.3	24.0	0.05	0.95
Somnyamekodur	138BU1	N05.66454', W001.58470'	6.2	801	441.0	61	17.4	5.6	67	3.9	73.5	148.8	0.329	13.1	17.4	-0.45	-4.89
Twifo Agona	236BU2	N05.74540', W001.50387'	6.4	212	108.0	52	19.8	10.1	13	8.2	10.1	94.7	0.174	23.1	17.7	0.22	4.45
Nyamebekyere	339BU3	N05.76558', W001.34666'	6.0	154	83.9	27	9.2	3.7	17	5.3	19.1	65.4	0.562	3.6	15.7	-0.05	-1.56
Jerusalem		N05.75216', W001.44366'	5.4	73.2	44.7	8.6	2.7	2.3	9.9	5.5	7.2	27.3	0.337	7.4	13.0	0.09	4.99
Assin Breku		N05.86808', W001.34099'	5.7	300	178.0	83	21.8	8.2	25	6.2	41.8	100.8	0.638	6.3	31.9	0.04	0.68
AssinBreku(Gyidi)	102BU3	N05.86625', W001.33689'	6.3	361	200.1	154	37.5	14.1	28	5.5	9.1	182.8	0.069	44.7	29.8	0.18	2.15
Assin Breku (SDA)	100BU3	N05.87056' ,W001.33793'	6.4	142	74.8	43	17.4	2.1	15	3.7	18.3	65.4	0.365	4.2	6.0	0.09	2.60
Techiman No. 1	396BU2	N05.80440', W001.36794'	5.3	57.6	34.2	13.7	3.9	2.3	9.7	3.3	6.9	27.4	0.467	13.5	1.7	-0.04	-2.31
Kwame Ankra	411BU2	N05.81540', W001.38197'	5.4	141	82.2	34	15.2	1.7	19	5.5	15.9	57.4	0.350	9.1	33.7	0.15	4.29
Ninkyiso		N05.812119',W001.39917'	5.6	228	124.0	33	6.8	4.2	26	5.9	22.8	65.1	0.667	13.1	18.3	-0.05	-1.23

Sample Source	BHID	GPS co-ordinates	pH	EC	TDS	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2	E.Bal.	CBE(%)
Dwedaama		N05.80162', W001.20490'	7.0	355	189.0	152	43.9	15.6	22	7.6	7.1	197.8	0.051	5.0	9.7	0.21	2.34
Dwedaama		N05.80159,' W001.20572'	5.2	99.1	53.3	44	17.6	2.7	9.2	3.2	11.9	35.2	0.295	13.5	18.0	0.06	1.81
WoraKesse Habitat	097BU3	N05.76445', W001.23152'	5.3	101.1	57.7	22.1	3.6	3.1	15	6.7	15.9	31.9	1.910	7.5	15.8	0.10	4.29
Antoabasa		N05.77203', W001.46879'	5.8	181	99.3	52.9	9.8	5.3	26	4.2	19.1	52.6	0.576	32.3	15.4	0.08	1.90
Antoabasa		N05.77018', W001.46949'	5.6	243	142.0	47.3	12.2	4.6	36	4.1	32.8	64.1	0.558	22.4	22.5	0.21	4.05
Anum	086BU3	N05.78218', W001.50222'	6.6	300	153.0	94	23.9	7.3	30	6.4	22.3	138.5	0.177	9.8	16.3	0.15	2.32
Mampong		N05.11146' ,W001.73174'	5.9	797	445.3	202	39.9	31.2	62	9.1	162.1	81.3	3.010	75.9	10.2	0.03	0.33
Essamang		N05.35041', W001.67974'	5.9	67.1	37.2	19	5.8	1.6	7.2	0.6	5.8	29.0	0.524	1.52	18.0	0.07	4.94
Mamponso	24-B-851	N05.42904', W001.62996'	5.3	112	58.4	25.2	15.8	4.1	14	2.4	11.2	33.2	4.010	31.2	9.1	-0.02	-0.47
Sienchem	24/B/32/1	N05.47246', W001.65157'	5.6	693	382.1	138.2	30.1	12.6	61	16.6	77.3	118.2	3.511	42.9	22.1	0.55	5.14
Sienchem	24/B/32/1	N05.47117', W001.65056'	5.4	223	125.2	41	14.2	1.7	19	15.6	23.2	37.2	1.790	33.4	11.5	0.09	2.31
Nsuekyir	219BU1	N05.77244' ,W001.50221'	5.7	189	99.8	89	16.1	10.9	17	5.3	22.9	70.3	0.732	22.7	15.5	0.16	3.11

pH(pH units), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method.

B-2: Hydrochemical data of groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 2nd-7th June 2011)

Sample Source	BHID	GPS co-ordinates	pH	EC	TDS	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2	E.Bal.	CBE(%)
Assin Nyakomase		N05.75829' ,W001.28643'	5.0	539	296.0	70.0	17.6	6.30	53	48	59.6	99.3	1.400	58.1	10.6	0.39	4.10
Assin Nyakomase		N05.75762' ,W001.29058'	5.1	192	106.0	30.0	4.0	4.90	26	9.5	14.9	62.2	0.839	19.6	24.4	0.09	2.45
Assin Nyakomase		N05.75729' ,W001.29082'	5.2	73.1	40.2	32	1.6	6.8	11	3.2	6.9	37.1	1.450	17.5	4.3	0.00	-0.16
Brofoyedru Habitat	101BU3	N05.78437' ,W001.28443'	5.7	136	74.8	28	8.8	1.4	17	7.9	7.9	58.6	0.546	17.2	9.5	-0.07	-2.22
Akonfude		N05.82614' ,W001.30953'	5.8	308	169.0	90	21.6	8.7	25	44	55.8	93.2	0.353	26.2	36.0	0.35	4.62
Akonfude		N05.82945' ,W001.31011'	5.1	529	291.0	118	20.0	16.5	34	5.2	55.7	95.8	0.645	25.8	23.8	0.28	3.64
Assin Breku		N05.86808' ,W001.34099'	5.8	306	168.0	88	20.8	8.7	26	6.6	43.8	98.8	0.738	6.1	33.9	0.04	0.64
Assin Breku (Gyidi)	102BU3	N05.86625' ,W001.33689'	6.6	358	197.0	150	38.5	13.1	25	4.5	8.9	192.8	0.069	42.7	32.8	-0.12	-1.43
Assin Breku (SDA)	100BU3	N05.87056' ,W001.33793'	6.1	140	77.0	44	14.4	1.9	14	3.3	19.3	63.4	0.345	3.9	4.0	-0.12	-3.70
Techiman No. 1	396BU2	N05.80440' ,W001.36794'	5.4	58.2	32.0	12	3.2	2.5	9.3	3.4	6.0	24.4	0.425	12.5	1.1	0.02	1.22
Kwame Ankra	411BU2	N05.81540' ,W001.38197'	5.6	144	79.2	36	12.0	1.4	18	5.0	13.9	56.4	3.300	9.4	36.7	0.05	1.72
Ninkyiso		N05.812119',W001.39917'	5.2	208	114.0	36	7.2	4.4	28	5.4	20.8	67.1	0.657	12.1	19.3	0.11	2.66
Sabina		N05.86974' , W001.27172'	6.2	262	144.0	84	22.4	6.8	24	5.5	15.9	107.4	0.270	19.0	31.3	0.25	4.65
Ayitey	094BU3	N05.88353' , W001.25584'	5.9	210	116.0	60	16.0	4.8	17	6.5	21.9	68.3	0.573	9.5	1.7	0.17	4.12
Nkrafo	098BU3	N05.87813' , W001.23365'	6.7	383	211.0	144	39.3	11.1	31	6.3	19.9	202.5	0.078	3.7	1.3	0.40	4.86
Nkrafo	096BU3	N05.88086' , W001.23863'	3.5	481	265.0	60	17.6	3.9	12	3.8	13.9	0.0	1.470	11.9	22.0	0.05	1.46
Obirikwaku	099BU3	N05.91570' , W001.23361'	6.1	280	154.0	100	30.5	5.8	18	4.9	10.9	131.8	0.206	18.5	34.3	0.07	1.19
Odumase Camp	405BU2	N05.82454' , W001.19149'	5.6	155	85.3	24	8.0	1	16	3.3	10.9	34.4	0.134	12.3	4.7	0.12	5.02
Obobakokrowa	246JBU1	N05.83277' , W001.17656'	6.4	354	195.0	144	46.5	6.7	19	3.0	21.9	168.4	0.155	6.4	4.0	0.27	3.75
Obobakokrowa		N05.83490' , W001.17768'	5.4	290	160.0	80	14.4	10.7	33	2.5	36.7	94.2	0.592	15.1	34.3	0.20	3.25
Odumase Camp	407BU2	N05.19421' , W001.19421'	5.8	313	172.0	78	15.2	9.7	42	4.4	48.8	88.3	0.525	30.2	19.7	0.04	0.50
Dwedaama		N05.80162' , W001.20490'	6.5	360	198.0	158	40.9	13.6	23	7.2	6.9	192.8	0.061	5.1	9.5	-0.27	-2.99
Dwedaama		N05.80159' , W001.20572'	5.5	95.1	52.3	46	13.6	2.9	9.5	2.9	12.9	36.2	0.274	14.5	17.9	0.14	5.29
WoraKesse Habitat	097BU3	N05.76445' , W001.23152'	5.6	99.5	54.7	20	3.2	2.9	14	6.4	14.9	31.7	1.840	7.2	16.1	0.07	2.96
Antoabasa		N05.77203' , W001.46879'	5.9	179	98.5	50	10.4	5.8	24	4.7	18.9	58.6	0.666	31.3	15.5	0.00	0.10
Antoabasa		N05.77018' , W001.46949'	5.8	240	132.0	48	11.2	4.8	34	5.1	31.8	66.1	0.528	21.4	21.5	0.13	2.58
Anum	086BU3	N05.78218' , W001.50222'	6.3	296	163.0	92	24.0	7.7	30	6.0	21.9	141.5	0.127	10.8	17.3	0.10	1.62
Kyeikurom		N05.82504' , W001.52242'	5.8	160	88.0	32	8.8	2.4	20	2.9	9.9	65.9	0.189	16.2	19.9	-0.13	-3.90

Sample Source	BHID	GPS co-ordinates	pH	EC	TDS	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2	E.Bal.	CBE(%)
Nsuekyir	219BU1	N05.77244' , W001.50221'	5.9	184	101.0	86	15.2	11.6	14	5.2	23.9	68.3	0.712	21.7	16.6	0.20	4.29
Danyiase Domeabra	093BU3	N05.74806' , W001.53606'	6.0	218	120.0	68	18.4	5.3	18	4.4	10.9	102.5	0.060	8.8	17.9	0.07	1.65
Anyinase Ankase	030BU3	N05.59646' , W001.60273'	5.7	107	58.9	36	8.0	3.9	11	1.7	6.0	46.4	0.317	9.5	9.5	0.10	4.05
Gromsa		N05.59000' , W001.60611'	5.9	189	104.0	222	33.4	3.3	14	2.4	29.9	68.3	0.408	23.3	22.0	0.15	2.88
Somnyamekordur	138BU1	N05.66454' , W001.58470'	6.7	798	439.0	58	14.4	5.3	68	3.7	72.5	140.8	0.309	14.0	17.4	-0.44	-4.99
Twifo Agona	236BU2	N05.74540' , W001.50387'	6.2	203	112.0	54	16.8	9.9	15	7.7	9.9	92.7	0.114	22.1	18.7	0.25	5.16
Nyamebekyere	339BU3	N05.76558' , W001.34666'	5.9	158	86.9	24	9.6	3.2	18	5.1	18.9	63.4	0.552	3.7	16.7	0.00	0.08
Jerusalem		N05.75216' , W001.44366'	5.6	75.9	41.7	8	2.4	2.5	9.2	5.3	6.9	29.3	0.377	7.6	13.3	0.02	1.32
Mampong		N05.11146' ,W001.73174'	5.8	797	438.0	218	42.5	27.2	64	8.8	152.9	80.5	2.970	72.9	9.0	0.15	1.01
Essamang		N05.35041' , W001.67974'	5.5	64.3	35.4	18	5.6	1	7.6	0.5	5.6	28.0	0.584	1.58	18.0	0.05	3.36
Mamponso	24-B-85-1	N05.42904' , W001.62996'	5.0	104	57.2	22	15.6	3.9	13	2.5	10.9	31.7	4.380	33.2	9.0	0.15	4.47
Sienchem	24/B/32/1	N05.47246' , W001.65157'	5.3	687	378.0	136	32.1	13.6	64	14.6	73.9	112.2	3.437	40.9	21.1	0.59	5.33
Sienchem	24/B/32/1	N05.47117' , W001.65056'	5.6	208	114.0	38	12.8	1.4	17	15.2	22.8	36.6	1.590	30.4	10.8	-0.01	-0.28

pH(pH units), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method.

B-3: Hydrochemical data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 19th- 23rd September 2011)

Sample Source	BHID	GPS co-ordinates	pH	EC	TDS	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2	E.Bal.	CBE(%)
Assin Nyankomase		N05.75829' , W001.28643'	5.7	598.0	329.0	82	20.8	7.3	37	6.5	65.5	41.5	0.155	45.3	7.1	0.70	-0.60
Assin Nyankomase		N05.75762' , W001.29058'	5.2	229.0	126.0	54	8.0	8.3	19	6.3	23.8	24.4	0.097	57.1	17.3	5.62	-4.96
Assin Nyankomase		N05.75729' , W001.29082'	5.5	76.7	42.2	22	15.6	9.9	20	3.8	10.9	34.2	0.101	72.3	17.0	0.97	3.33
Akonfude		N05.82570' , W001.30988'	6.2	288.0	158.0	94	23.2	8.7	11	3.2	21.8	129.3	0.152	27.2	23.4	0.86	-0.92
Akonfude		N05.82614' , W001.30953'	6.0	326.0	179.0	104	28.1	18.2	17	7.9	31.8	122.0	0.198	47.5	21.5	0.14	-0.77
Akonfude		N05.82945' , W001.31011'	6.2	581.0	319.0	124	28.1	13.1	35	14	55.6	115.5	0.227	25.2	16.9	0.91	4.55
Nkrafo	098BU3	N05.87813' , W001.23365'	6.2	191.6	105.0	64	16.0	5.8	35	5.2	15.9	358.7	0.244	37.5	21.4	0.29	-4.59
Nkrafo	096BU3	N05.88086' , W001.23863'	3.5	401.0	221.0	250	68.1	19.4	46	6.6	34.7	0.0	0.173	49.8	23.3	1.50	-5.01
Obirikwaku	099BU3	N05.91570' , W001.23361'	6.5	288.0	158.0	118	31.3	9.7	34	4.5	15.9	209.8	0.108	21.6	22.8	0.28	-4.41
Odumase Camp	405BU2	N05.82454' , W001.19149'	6.1	142.2	78.1	44	12.0	3.4	34	3.3	14.9	78.1	0.169	34.4	19.3	2.34	0.13
Obobakokrowa		N05.83490' , W001.17768'	5.6	295.0	162.0	82	15.2	10.7	18	3.4	41.7	41.5	0.092	42.1	18.5	0.27	-4.03
Odumase Camp	407BU2	N05.19421' , W001.19421'	6.0	352.0	194.0	80	24.0	15.1	38	5.0	37.7	144.0	0.329	52.7	29.5	3.21	-3.55
Dwedaama		N05.80162' , W001.20490'	6.4	238.0	131.0	86	20.0	18.7	45	5.4	11.9	212.3	0.219	62.9	21.8	0.41	-4.93
Dwedaama		N05.80159' , W001.20572'	6.0	118.6	65.5	44	10.4	8.4	20	5.5	12.9	87.8	0.115	28.1	17.2	4.12	-4.18
WoraKesse Habitat	097BU3	N05.76445' , W001.23152'	5.8	86.6	47.6	28	10.2	4.4	7.6	4.8	13.9	43.9	0.212	11.3	21.6	0.84	-0.93
Brofoyedru Habitat	101BU3	N05.78437' , W001.28443'	6.0	129.1	70.9	50	18.0	10.3	5.3	2.1	12.9	92.7	0.116	18.1	21.4	-0.01	-5.43
Assin Breku (SDA)	102BU3	N05.87056' , W001.33793'	6.4	205.0	113.0	72	16.0	12.8	24	3.4	9.9	156.2	0.028	12.5	30.4	-0.13	-2.08
Assin Breku (Gyidi)	100BU3	N05.86625' , W001.33689'	6.1	316.0	174.0	98	19.2	12.1	23	4.4	26.8	97.6	0.169	45.5	24.5	-0.24	-3.82
Assin Breku		N05.86808' , W001.34099'	5.9	139.0	76.5	28	15.8	6.4	23	2.9	17.9	65.9	0.106	38.0	31.4	0.00	-0.04
Kwame Ankra	411BU2	N05.81540' , W001.38197'	5.7	64.9	35.7	20	6.4	3.4	16	2.4	7.9	39.0	0.161	29.3	22.9	-0.11	-3.86
Techiman No. 1	396BU2	N05.80440' , W001.36794'	5.5	190.7	105.0	40	5.6	6.3	18	3.7	21.8	31.7	0.081	29.4	25.5	-0.09	-2.78
Ninkyiso		N05.812119' W001.39917'	6.3	269.0	148.0	80	20.4	14.2	35	7.7	19.9	178.1	0.271	40.0	33.0	-0.41	-4.95
Sabina		N05.86974' ,W001.27172'	6.2	208.0	114.0	66	18.8	11.8	25	5.1	12.9	119.6	0.386	55.2	31.7	-0.34	-5.12
Ayitey	094BU3	N05.88353' , W001.25584'	6.1	187.7	103.0	62	15.2	12.2	19	5.3	14.9	104.9	0.456	35.0	17.8	-0.14	-2.56

Sample Source	BHID	GPS co-ordinates	pH	EC	TDS	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	SO_4^{2-}	SiO_2	E.Bal.	CBE(%)
Nyamebekyere	339BU3	N05.76558' , W001.34666'	5.6	77.7	42.7	20	14.8	7.9	19	3.0	10.9	53.7	0.038	40.8	18.3	0.23	5.40
Jerusalem		N05.75216' , W001.44366'	6.2	183.0	101.0	38	18.8	13.9	28	2.5	25.3	90.3	0.071	48.6	17.5	0.14	2.13
Antoabasa		N05.82614' , W001.30953'	6.0	260.0	143.0	50	18.8	6.8	37	4.4	40.2	102.5	0.049	25.7	34.5	-0.11	-1.72
Antoabasa		N05.82945' , W001.31011'	6.5	298.0	164.0	94	25.7	7.3	29	7.2	14.9	146.4	0.024	32.5	34.3	-0.16	-2.27
Anum	086BU3	N05.78218' , W001.50222'	6.2	164.3	90.2	32	11.2	7.4	30	2.9	15.9	109.8	0.003	8.8	33.1	0.09	1.88
Kyeikurom		N05.82504' , W001.52242'	6.0	144.0	79.2	40	18.8	8.4	20	6.4	15.9	83.0	0.099	50.2	24.9	-0.18	-3.17
Adukurom	088BU3	N05.84924' , W001.52394'	6.3	314.0	173.0	104	26.5	19.2	34	4.7	29.8	192.8	0.105	33.1	35.3	-0.19	-2.07
Subriso		N05.82474' , W001.54799'	6.3	181.6	100.0	56	13.6	12.3	20	5.1	12.4	122.0	0.057	23.6	29.9	-0.16	-2.94
Nsuekyir	219BU1	N05.77244' , W001.50221'	6.3	221.0	122.0	68	14.4	10.8	35	6.0	13.9	173.2	0.059	13.2	33.0	-0.24	-3.49
Danyease Domeabra	093BU3	N05.74806' , W001.53606'	5.9	188.8	103.0	36	12.9	7.9	21	2.9	23.8	80.5	0.029	15.5	22.6	-0.04	-0.90
Bediadua		N05.77497' , W001.49742'	6.3	150.5	82.5	42	15.2	5.8	26	1.3	7.9	117.1	0.056	17.8	27.2	-0.10	-2.13
Gromsa		N05.59000' , W001.60611'	6.0	407.0	224.0	98	17.4	15.0	34	12.4	48.6	80.5	0.328	70.6	17.6	-0.29	-3.58
Atu Krom		N05.60612' , W001.67843'	6.5	281.0	154.0	108	32.1	16.8	38	15.7	9.9	248.9	0.346	57.7	27.5	-0.54	-5.14
Subreso		N05.65596' , W001.67676'	6.0	104.9	57.7	38	16.4	10.3	28	2.6	8.9	80.5	0.279	61.7	24.1	0.07	1.26
Anyinase Ankase	030BU3	N05.59646' , W001.60273'	5.9	121.0	66.5	50	13.6	3.9	19	4.2	12.9	78.1	1.641	23.8	15.9	-0.21	-5.21
Somnyamekordur	138BU1	N05.66454' , W001.58470'	6.6	824.0	453.0	226	84.2	3.8	42	12.3	81.4	278.2	0.255	10.4	27.8	-0.41	-2.96
Somnyamekordur	033BU3	N05.66044' , W001.58376'	6.7	352.0	194.0	116	37.7	5.3	15	3.3	16.9	118.2	0.115	38.5	30.5	-0.15	-2.38
Breman	260BU2	N05.70882' , W001.60273'	6.5	394.0	217.0	90	27.8	20.8	40	12.5	36.7	187.9	1.416	76.7	21.4	-0.58	-5.37
Breman		N05.70720' , W001.60270'	6.3	199.8	110.0	62	25.2	15.8	21	3.1	12.9	148.8	0.276	44.4	30.5	-0.18	-2.54
Twifo Agona	236BU2	N05.74540' , W001.50387'	6.4	292.0	161.0	88	35.7	15.8	29	15.6	19.9	205.0	0.145	57.1	26.7	-0.36	-3.62
Zion Camp	014BU3	N05.87221' , W001.64609'	6.3	1201.0	661.0	336	160.9	104.6	226	69.5	689.9	248.9	0.387	371.2	20.1	-3.03	-5.09
Twifo Mampong		N05.52361' , W001.55671'	6.0	281.0	154.0	74	11.2	11.2	27	1.4	8.9	61.0	0.216	77.9	21.2	-0.17	-3.02
Twifo Mampong		N05.52316' , W001.55452'	5.8	107.8	59.4	28	16.4	12.9	29	2.2	11.9	53.7	0.553	78.8	25.1	0.31	5.19
Akwa Yaw		N05. 44168' ,W001.48580'	6.3	181.6	99.5	62	19.2	13.4	26	2.2	7.9	148.8	0.473	22.3	23.2	0.12	1.93
Mampong		N05.11146' , W001.73174'	6.4	979.0	538.0	280	56.1	34.0	79	16.7	108.3	222.0	0.447	90.5	21.5	0.86	4.76
Essamang		N05.35041' , W001.67974'	5.9	121.1	66.5	20	7.0	6.4	15	5.1	13.9	34.2	0.330	28.4	20.2	0.13	3.95
Mamponso	24-B-85-1	N05.42904' , W001.62996'	5.8	232.0	128.0	46	11.2	8.4	16	3.7	28.8	41.5	0.167	28.4	16.8	-0.06	-1.53
Sienchem	24/B/32/1	N05.47246' , W001.65157'	5.6	721.0	127.0	136	32.1	13.6	86	18.6	109.2	145.5	0.326	40.4	20.0	0.62	4.72
Sienchem	24/B/32/1	N05.47117' , W001.65056'	6.3	462.0	254.0	124	30.5	21.6	32	6.7	60.5	107.4	0.228	74.1	22.2	-0.13	-1.35

B-4: Hydrochemical data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 12TH-17TH December 2011)

Sample Source	BHID	Long	Lat	T°C	pH	EC	TDS	Turb	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_2N	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	NH_4N	E.Bal	CBE(%)
Assin Nyakomase		5.75724	-1.2906	26.9	5.0	539	296.0	10.9	6.0	70.0	17.6	6.30	53	48.0	59.6	99.3	0.062	1.400	0.114	58.1	10.6	<0.005	<0.001	0.39	4.10
Assin Nyakomase		5.75719	-1.2908	27.6	5.1	192	106.0	1.2	10.0	30.0	12.0	4.90	25.5	9.5	14.9	62.2	0.039	0.839	0.248	19.6	24.4	<0.005	<0.001	0.18	3.72
Assin Nyakomase		5.75897	-1.2865	27.1	5.2	73.1	40.2	1.7	14.0	32	5.6	6.8	10.7	3.2	6.9	37.1	0.007	1.450	0.840	17.5	4.3	<0.005	<0.001	-0.05	-1.98
Brofoyedru Habitat	101 BU3	5.73346	-1.2846	26.3	5.7	136	74.8	1.0	48.0	28	8.8	4.5	16.7	7.9	7.9	58.6	0.006	0.546	0.490	17.2	9.5	<0.005	<0.001	-0.18	-4.68
Akonfude		5.82570	-1.3099	25.7	5.8	308	169.0	1.6	60.0	90	21.6	8.7	36	4.4	55.8	93.2	0.033	0.353	0.230	26.2	36	<0.005	<0.001	-0.18	-2.53
Akonfude		5.82950	-1.3101	26.2	5.1	529	291.0	7.3	8.0	118	20.0	16.5	34	5.2	55.7	95.8	0.011	0.645	0.273	25.8	23.8	<0.005	<0.001	0.28	3.64
Assin Breku		5.86801	-1.3409	26.9	5.8	306	168.0	1.9	40.0	88	20.8	8.7	25.5	6.6	43.8	98.8	0.034	0.738	0.355	6.1	33.9	<0.005	<0.001	0.04	0.64
Assin Breku (Gyidi)	102 BU3	5.87059	-1.3360	25.6	6.6	358	197.0	3.7	158.0	150	38.5	13.1	24.5	4.5	8.9	192.8	0.100	0.069	0.211	42.7	32.8	<0.005	<0.001	-0.12	-1.43
Assin Breku (SDA)	100 BU3	5.86625	-1.3360	25.8	6.1	140	77.0	1.3	52.0	44	14.4	1.9	13.6	3.3	19.3	63.4	0.025	0.345	0.367	3.9	4.0	<0.005	<0.001	-0.12	-3.70
Techiman No. 1	396 BU3	5.80432	-1.3679	26.7	5.4	58.2	32.0	1.2	20.0	12	3.2	2.5	9.3	3.4	6.0	24.4	0.030	0.425	0.393	12.5	1.1	<0.005	<0.001	0.02	1.22
Kwame Ankra	411 BU3	5.81542	-1.3820	26.5	5.6	144	79.2	1.7	38.0	36	12.0	1.4	17.9	5.0	13.9	56.4	0.014	3.300	0.296	9.4	36.7	<0.005	<0.001	0.05	1.72
Amoakokrom	337 BU3	5.85972	-1.2561	28.8	5.6	220.0	121.0	2.24	44.0	32	10.2	3.4	28.6	4.9	32.8	53.7	0.056	0.050	1.161	23.8	22.7	<0.005	<0.001	-0.14	-3.21
Ninkyiso		5.82117	-1.3991	28.2	5.2	208	114.0	0.9	14.0	36	7.2	4.4	27.5	5.4	20.8	67.1	0.028	0.657	0.236	12.1	19.3	<0.005	<0.001	0.11	2.66
Sabina	380 BU1	5.86974	-1.2717	29.2	6.2	262	144.0	2.8	88.0	84	22.4	6.8	24	5.5	15.9	107.4	0.022	0.270	0.181	19.0	31.3	<0.005	<0.001	0.26	4.65
Ayitey	094 BU3	5.88353	-1.2558	28.5	5.9	210	116.0	1.5	56.0	60	16.0	4.8	17.3	6.5	21.9	68.3	0.013	0.573	0.229	9.5	1.7	<0.005	<0.001	0.17	4.12
Nkrafo	098 BU3	5.87809	-1.2336	28.1	6.7	383	211.0	3.8	166.0	144	39.3	11.1	30.5	6.3	19.9	342.5	0.007	0.078	0.049	3.7	1.3	<0.005	<0.001	0.40	4.86
Nkrafo	096 BU3	5.88087	-1.2386	29.3	3.5	481	265.0	88.8	0.0	60	17.6	3.9	11.9	3.8	13.9	0.00	0.039	1.470	0.367	11.9	22.0	<0.005	<0.001	0.05	1.46
Obirikwaku	099 BU3	5.91571	-1.2366	29.1	6.1	280	154.0	1.5	108.0	100	30.5	5.8	18.4	4.9	10.9	131.8	0.095	0.206	0.174	18.5	34.3	<0.005	<0.001	0.07	1.19
Odumase Camp	405 BU2	5.82454	-1.1915	29.1	5.6	155	85.3	46.8	20.0	24	8.0	1.0	15.7	3.3	10.9	34.4	0.030	0.134	0.089	12.3	4.7	<0.005	<0.001	0.12	5.02
Obobakokrowa		5.82490	-1.1777	28.7	6.4	354	195.0	12.6	138.0	144	46.5	6.7	19.3	3.0	21.9	168.4	0.008	0.155	0.114	6.4	4.0	<0.005	<0.001	0.27	3.75
Obobakokrowa	246 J BU1	5.83276	-1.1765	28.4	5.4	290	160.0	1.7	28.0	80	14.4	10.7	33	2.5	36.7	94.2	0.024	0.592	0.151	15.1	34.3	<0.005	<0.001	0.20	3.25
Odumase Camp	407 BU2	5.82181	-1.1942	28.1	5.8	313	172.0	14.2	56.0	78	15.2	9.7	42	4.4	48.8	88.3	0.037	0.525	0.178	30.2	19.7	<0.005	<0.001	0.04	0.52
Dwedaama		5.90170	-1.2050	28.2	6.5	360	198.0	12.5	158.0	158	40.9	13.6	22.5	7.2	6.9	192.8	0.011	0.061	0.593	35.1	9.5	<0.005	<0.001	0.24	2.83
Dwedaama		5.80159	-1.2058	28.0	5.5	95.1	52.3	1.8	28.0	46	13.6	2.9	9.5	2.9	12.9	36.2	0.085	0.274	0.211	14.8	17.9	<0.005	<0.001	0.13	5.04
WoraKesse Habitat	097 BU3	5.76443	-1.1315	27.2	5.6	99.5	54.7	1.6	26.0	20	3.2	2.9	14.4	6.4	14.9	31.7	0.042	1.840	0.507	7.2	16.1	<0.005	<0.001	0.07	2.96
Antoabasa		5.77196	-1.4688	30.4	5.9	179	98.5	1.4	48.0	50	10.4	5.8	24	4.7	18.9	58.6	0.030	0.666	0.535	31.3	15.5	<0.005	<0.001	0.00	0.1
Bediadua		5.77278	-1.4972	29.2	6.3	150.5	82.5	2.1	96	42	15.2	5.8	26.2	1.3	7.9	117.1	0.054	0.056	0.455	17.8	27.2	<0.005	<0.001	-0.10	-2.31
Antoabasa		5.77020	-1.4695	30.1	5.8	240	132.0	11.5	46.0	48	11.2	4.8	34	5.1	31.8	66.1	0.014	0.528	0.284	21.4	21.5	<0.005	<0.001	0.13	2.58

Sample Source	BHID	Long	Lat	T°C	pH	EC	TDS	Turb	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_2N	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	NH_4N	E.Bal	CBE(%)
Kyeikurom	090 BU3	5.82504	-1.5224	28.3	5.8	160	88.0	1.0	54.0	32	8.8	2.4	19.8	2.9	9.9	65.9	0.015	0.189	0.346	16.2	19.9	<0.005	<0.001	-0.13	-3.9
Adukurom	088 BU3	5.82278	-1.5244	31.6	5.7	141	77.6	1.0	42.0	60	8.8	9.2	15.3	3.5	16.9	71.2	0.038	0.455	0.376	13.2	12.4	<0.005	<0.001	0.03	0.65
Subriso		5.82474	-1.5480	27.0	6.3	181.6	100.0	1.9	100	56	13.6	12.3	19.7	5.1	12.4	122.0	0.024	0.057	0.107	23.6	29.9	<0.005	<0.001	-0.16	-2.94
Nsuekyir	219 BU1	5.68667	-1.4972	27.1	5.9	184	101.0	13.1	56.0	86	15.2	11.6	14.1	5.2	23.9	68.3	0.091	0.712	0.417	21.7	16.6	<0.005	<0.001	0.20	4.28
Danyiase Domeabra	092 BU3	5.74806	-1.5381	26.5	6.0	218	120.0	1.7	84.0	68	18.4	5.3	17.9	4.4	10.9	102.5	0.010	0.060	0.608	8.8	17.9	<0.005	<0.001	0.07	1.65
Akwa Yaw		5.44157	-1.46580	26.8	6.3	181.6	99.5	4.56	122	62	19.2	13.4	26.2	2.2	7.9	148.8	0.049	0.473	0.156	22.3	23.2	0.187	<0.001	0.12	1.93
Twifo Mampong		5.52016	-1.5545	26.8	6.0	281.0	154.0	2.8	50	74	11.2	11.2	27.4	1.4	8.9	61.0	0.085	0.216	0.149	77.9	21.2	<0.005	<0.001	-0.17	-3.02
Twifo Mampong		5.52359	-1.5568	27.4	5.8	107.8	59.4	2.4	44	28	16.4	12.9	28.6	2.2	11.9	53.7	0.073	0.553	0.165	78.8	25.1	<0.005	<0.001	0.31	5.19
Anyinase Ankase	030 BU3	5.59446	-1.6028	28.0	5.7	107	58.9	1.2	38.0	36	8.0	3.9	10.7	1.7	6.0	46.4	0.018	0.317	0.705	9.5	9.5	<0.005	<0.001	0.09	4.05
Subreso	048D035 BU3	5.65596	-1.6768	28.1	6.0	104.9	57.7	2.4	66	38	16.4	10.3	27.6	2.6	8.9	80.5	0.058	0.279	0.154	61.7	24.1	<0.005	<0.001	0.07	1.26
Breman	260 BU2	5.70878	-1.6028	28.9	6.5	394.0	217.0	79.2	154	90	27.8	20.8	40.8	12.5	36.7	187.9	1.285	1.416	0.269	76.7	21.4	0.181	<0.001	-0.54	-4.94
Breman		5.70720	-1.6026	28.5	6.3	199.8	110.0	2.7	122	62	25.2	15.8	20.9	3.1	12.9	148.8	0.091	0.276	0.262	44.4	30.5	<0.005	<0.001	-0.18	-2.53
Atu Kurom		5.63657	-1.67850	29.5	6.5	281.0	154.0	17	204	108	32.1	16.8	37.6	15.7	9.9	248.9	0.047	0.346	0.419	57.7	27.5	0.193	<0.001	-0.54	-5.14
Gromsa	032 BU3	5.58991	-1.6061	28.6	5.9	189	104.0	1.6	56.0	222	33.4	3.3	13.8	2.4	29.9	68.3	0.024	0.408	1.390	23.3	22.0	<0.005	<0.001	0.15	2.88
Zion Camp	014 BU2	5.87217	-1.6460	29.9	6.4	1221.2	691.0	3.8	194	315	151.8	115.2	231	63.5	691.3	238.9	0.072	0.487	0.403	354.2	29.1	<0.005	<0.001	-2.06	-3.46
Somnyamekodur	048D033 BU3	5.66046	-1.5838	30.7	6.7	798	439.0	5.0	140.0	58	14.4	5.3	68	3.7	72.5	140.8	0.027	0.309	2.600	14.0	17.4	<0.005	<0.001	-0.44	-4.99
Somnyamekordur		5.66046	-1.5838	29.2	6.6	824	453.0	3.6	228.0	226.0	84.2	3.8	42.3	12.3	81.4	278.2	0.021	0.255	0.309	10.4	27.8	<0.005	<0.001	-0.41	-2.96
Twifo Agona	263 BU2	5.74595	-1.5040	29.8	6.2	203	112.0	4.6	76.0	54	16.8	9.9	15.1	7.7	9.9	92.9	0.038	0.114	1.970	22.1	18.7	<0.005	<0.001	0.24	5.09
Nyamebekyere	339 BU3	5.80139	-1.7214	29.2	5.9	158	86.9	1.4	52.0	24	9.6	3.2	18.1	5.1	18.9	63.4	0.019	0.552	1.950	3.7	16.7	<0.005	<0.001	0.00	0.08
Jerusalem	0502B1/6/097-01	5.81667	-1.71750	28.8	5.6	75.9	41.7	1.9	24.0	8	2.4	2.5	9.2	5.3	6.9	29.3	0.009	0.377	3.030	7.6	13.3	<0.005	<0.001	0.02	1.32
Mampong	22/D/73-1	5.11147	-1.7317	27.3	5.8	797	438.0	3.43	66.0	218	42.5	27.2	63.5	8.8	152.9	80.5	0.013	2.970	0.417	72.9	9.0	<0.005	<0.001	0.15	1.01
Essamang		5.05042	-1.6798	26.4	5.5	64.3	35.4	4.43	18.0	18	5.6	1.0	7.6	0.5	5.6	28.0	0.036	0.584	0.506	1.58	18.0	<0.005	<0.001	0.05	\3.36
Mamponso	24/B/85-1	5.42906	-1.6300	26.4	5.0	104	57.2	1.35	26.0	22	15.6	3.9	13.2	2.5	10.9	31.7	0.021	4.380	0.200	33.2	9.0	<0.005	<0.001	0.15	4.46
Sienchem	24/B/32-1	5.47123	-1.6505	25.3	5.3	687	378.0	1.0	36.0	136	32.1	13.6	64	14.6	73.9	112.2	0.109	3.437	0.291	63.9	21.1	<0.005	<0.001	0.57	5.08
Sienchem	24/B/32-2	5.47246	-1.6516	25.9	5.6	208	114.0	1.0	30.0	38	12.8	1.4	17.2	15.2	22.8	36.6	0.041	1.590	0.322	30.4	10.8	<0.005	<0.001	-0.01	-0.28

pH(pH units), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method, Long=Longitude (N), Lat=Latitude (W)

B-5: Hydrochemical data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 24th -28th January 2012)

Sample Source	BHID	Long	Lat	T°C	pH	EC	TDS	Turb	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	NH_4N	E.Bal	CBE(%)
Assin Nyakomase		5.75724	-1.290630	26.9	4.9	470	276.0	11.9	7.0	38.5	17.1	6.6	57.5	50	64.6	105.8	1.550	0.160	55.6	11.6	<0.005	<0.001	0.37	4.10
Assin Nyakomase		5.75719	-1.290840	27.6	5.3	180	118.1	2.3	13.4	34.7	4.4	6.9	28.3	9.2	18.1	68.6	0.941	0.351	18.1	26.7	<0.005	<0.001	0.18	3.72
Assin Nyakomase		5.75897	-1.286520	27.1	5.2	70	44.4	2.1	16.7	38.4	2.4	7.3	19.9	6.4	13.1	36.3	1.853	0.643	18.7	6.8	<0.005	<0.001	-0.05	-1.98
Brofoyedru Habitat	101 BU3	5.73346	-1.284570	26.3	5.9	120	59.5	1.5	32.2	33.0	5.5	4.5	18.2	7.1	10.4	47.4	1.200	0.570	17.9	7.9	<0.005	<0.001	-0.18	-4.68
Akonfude		5.82570	-1.309880	25.7	6.2	290	170.5	1.5	61.5	93.5	22.6	8.2	24.0	15.0	57.6	95.7	0.300	0.260	31.2	35.0	<0.005	<0.001	-0.18	-2.58
Akonfude		5.82950	-1.310110	26.2	5.8	500	286.0	7.6	8.6	117.0	21.1	17.0	34.0	5.4	54.7	96.8	0.650	0.320	25.3	24.3	<0.005	<0.001	0.28	3.64
Assin Breku		5.86801	-1.340940	26.9	6.2	280	173.0	2.0	41.0	85.5	21.3	8.5	25.3	6.4	42.8	99.8	0.690	0.410	6.2	32.9	<0.005	<0.001	0.04	0.64
Assin Breku (Gyidi)	102 BU3	5.87059	-1.336030	25.6	6.9	320	198.6	3.8	153.0	152.0	38.0	13.6	26.0	5.0	9.0	187.8	0.070	0.210	43.7	31.3	<0.005	<0.001	-0.12	-1.43
Assin Breku (SDA)	100 BU3	5.86625	-1.336030	25.7	6.4	140	75.9	1.4	53.1	43.5	15.9	2.0	14.1	3.5	18.8	64.4	0.360	0.380	4.0	5.0	<0.005	<0.001	-0.12	-3.70
Techiman No. 1	396 BU3	5.80432	-1.367920	26.7	5.3	60	33.1	1.3	20.8	12.9	3.6	2.4	9.5	3.4	6.5	25.9	0.450	0.400	13.0	1.4	<0.005	<0.001	0.02	1.22
Kwame Ankra	411 BU3	5.81542	-1.381990	26.5	5.8	143	80.7	1.6	35.9	35.0	13.6	1.6	18.6	5.3	14.9	56.9	3.300	0.260	9.3	35.2	<0.005	<0.001	0.05	1.72
Ninkyiso		5.82117	-1.399120	28.2	5.2	210	119.0	1.4	13.6	34.5	7.0	4.3	26.5	5.7	21.8	66.1	0.660	0.250	12.6	18.8	<0.005	<0.001	-0.14	-3.21
Sabina	380 BU1	5.86974	-1.271720	29.2	6.9	270	141.6	2.9	87.0	82.5	21.2	6.6	25.5	5.7	16.0	109.9	0.280	0.200	18.8	32.8	<0.005	<0.001	0.11	2.66
Ayitey	094 BU3	5.88353	-1.255840	28.5	7.3	200	118.6	1.5	54.2	61.5	14.6	4.5	17.8	6.9	21.9	67.8	0.570	0.180	8.9	1.6	<0.005	<0.001	0.25	4.65
Nkrafo	098 BU3	5.87809	-1.233640	28.1	7.9	360	216.0	4.0	161.0	134.0	38.3	12.6	34.0	9.3	18.9	196	0.070	0.060	4.7	1.4	<0.005	<0.001	0.17	4.12
Nkrafo	096 BU3	5.88087	-1.238620	29.3	6.5	180	260.0	90.8	8.7	58.5	16.6	4.0	12.9	4.8	12.9	64.5	1.490	0.030	10.9	23.0	<0.005	<0.001	0.40	4.86
Obirikwaku	099 BU3	5.91571	-1.236610	29.1	6.3	260	149.0	1.4	113.0	99.0	31.0	5.5	17.7	5.9	11.9	136.8	0.200	0.180	18.4	33.7	<0.005	<0.001	0.05	1.46
Odumase Camp	405 BU2	5.82454	-1.191470	30.5	6.0	150	83.3	44.3	19.1	23.0	8.2	5.1	16.2	3.3	11.4	33.4	0.180	0.090	11.8	5.0	<0.005	<0.001	0.07	1.19
Obobakokrowa		5.82490	-1.177680	28.7	6.3	310	198.1	14.1	139.6	145.5	47.5	7.2	18.8	3.4	20.4	169.9	0.160	0.160	6.6	4.1	<0.005	<0.001	0.12	5.02
Obobakokrowa	246 J BU1	5.83276	-1.176530	28.3	5.7	290	163.5	2.0	29.5	83.5	15.4	11.7	34.5	2.7	36.2	92.7	0.640	0.200	14.1	34.3	<0.005	<0.001	0.27	3.75
Odumase Camp	407 BU2	5.82181	-1.194190	29.1	6.1	310	176.9	15.2	61.0	74.5	14.7	9.9	41.5	4.6	47.8	85.8	0.540	0.170	31.7	18.2	<0.005	<0.001	0.20	3.25
Dwedaama		5.90170	-1.204960	28.0	6.5	240	193.5	13.0	153.0	155.0	42.4	14.6	22.0	7.4	7.0	195.3	0.060	0.560	35.0	9.6	<0.005	<0.001	0.04	0.52
Dwedaama		5.80159	-1.205750	28.2	5.8	90	52.8	1.9	27.8	45.0	15.6	2.8	9.4	3.1	12.4	35.7	0.280	0.250	14.0	18.0	<0.005	<0.001	0.24	2.83
Amoakokrom	337 BU3	5.85972	-1.256110	28.8	5.8	320	131.0	2.9	47	34.0	12.2	3.8	30.6	5.2	34.8	54.7	0.070	1.200	24.1	24.7	<0.005	<0.001	0.13	5.04
WoraKesse Habitat	097 BU3	5.76443	-1.131540	27.2	5.6	80	56.2	1.4	27.1	21.1	3.4	3	14.8	6.6	15.4	31.8	1.880	0.540	7.4	15.9	<0.005	<0.001	0.07	2.96
Antoabasa		5.77196	-1.468780	30.4	6.1	170	98.8	1.6	50.1	51.5	10.1	5.6	25.0	4.5	19	55.6	0.620	0.490	31.8	15.4	<0.005	<0.001	0.00	0.10
Antoabasa		5.7702	-1.469480	30.2	5.9	220	137.0	12.0	46.4	47.7	11.7	4.7	35.0	4.6	32.3	65.1	0.540	0.270	21.9	22.0	<0.005	<0.001	-0.10	-2.13
Bediadua		5.77278	-1.497220	29.2	5.9	220	83.5	2.4	98.0	43.2	17.2	6.1	28.2	1.5	8.1	119.2	0.061	0.480	18.3	28.2	<0.005	<0.001	0.13	2.58

Sample Source	BHID	Long	Lat	T°C	pH	EC	TDS	Turb	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	$NH_4.N$	E.Bal	CBE(%)
Anum	086 BU3	5.78219	-1.502240	28.8	6.5	270	158.0	8.8	114.0	93.0	24.0	7.5	29.7	6.2	22.1	140	0.150	0.340	10.3	16.8	<0.005	<0.001	0.10	1.62
Kyeikurom	090 BU3	5.82504	-1.522420	28.3	6.0	150	87.1	1.2	55.1	33.1	9.0	2.5	20.0	3.1	10.1	64.2	0.200	0.340	16.7	20.4	<0.005	<0.001	-0.13	-3.90
Adukurom	088 BU3	5.82278	-1.524440	31.6	5.6	140	79.6	1.4	43.6	61.2	9.0	9.6	15.8	3.6	17.4	72.2	0.410	0.430	3.6	12.9	<0.005	<0.001	0.03	0.65
Nsuekyir	219 BU1	5.68667	-1.497220	27.1	5.9	170	100.4	13.7	54.8	87.5	15.7	11.3	15.6	5.3	23.4	69.3	0.720	0.430	22.2	16.1	<0.005	<0.001	-0.16	-2.94
Subriso		5.82474	-1.547990	27.0	6.0	240	107.5	2.0	104.0	57.5	13.1	12.9	20.7	5.5	13.4	132	0.055	0.100	24.2	30.5	<0.005	<0.001	0.20	4.28
Danyiase Domeabra	092 BU3	5.74806	-1.538060	26.5	5.9	220	118.5	1.8	81.9	65.5	19.4	5.5	18.9	5.4	11.4	107.5	0.070	0.670	22.2	18.1	<0.005	<0.001	0.07	1.65
Anyinase Ankase	030 BU3	5.59446	-1.602790	28.0	5.6	100	58.4	1.5	37.0	37.0	8.5	4.1	11.7	1.7	6.3	44.7	0.370	0.740	9.9	9.2	0.187	<0.001	0.12	1.93
Gromsa	032 BU3	5.58991	-1.606070	28.6	6.0	190	119.0	1.8	57.1	220.0	32.9	3.5	14.3	2.5	30.9	69.8	0.440	1.410	23.8	23.0	<0.005	<0.001	-0.17	-3.02
Somnyamekodur	048D033 BU3	5.66046	-1.583760	30.7	6.4	710	440.0	6.0	139.0	59.5	14.9	5.5	67.5	3.9	73	144.8	0.320	2.610	13.6	17.4	<0.005	<0.001	0.31	5.19
Somnyamekordur		5.66046	-1.583760	29.3	6.6	824	453.0	3.6	228.0	226.0	84.2	3.8	42.3	12.3	81.4	278.2	0.255	0.309	10.4	27.8	<0.005	<0.001	0.10	4.05
Twifo Agona	263 BU2	5.74595	-1.503980	29.8	6.3	190	110.0	4.8	77.7	53.0	18.3	10	14.1	8	10.1	93.7	0.140	1.990	22.6	18.2	<0.005	<0.001	0.07	1.26
Nyamebekyere	339 BU3	5.80139	-1.721390	29.2	6.0	170	85.4	1.5	53.0	25.5	9.4	3.5	17.6	5.2	19	64.4	0.560	1.900	3.6	16.2	0.181	<0.001	-0.54	-4.95
Jerusalem	0502B1/6/097-01	5.81667	-1.717500	28.8	5.9	80	43.2	1.8	25.6	8.3	2.6	2.4	10.0	5.4	7.1	28.3	0.360	3.080	7.5	13.1	<0.005	<0.001	-0.18	-2.54
Akwa Yaw		5.44157	-1.465800	26.8	6.1	130	105.0	4.7	124.0	64.0	21.0	14.1	27.2	2.5	7.7	150.3	0.488	0.161	23.8	23.7	0.193	<0.001	-0.54	-5.14
Twifo Mampong		5.52016	-1.554490	26.8	5.3	279	156.0	195	30	68.0	10.4	10.20	28.0	23	35.7	36.6	0.691	0.669	77.8	31.7	<0.005	<0.001	-0.07	-1.15
Twifo Mampong		5.52359	-1.556810	27.4	6.3	1140	627.0	153	106	324.0	57.7	43.70	23.6	20	174	129.3	0.36	0.558	76.8	17.8	<0.005	<0.001	-2.06	-3.47
Atu Kurom		5.63657	-1.678500	29.5	5.6	350	159.0	18.0	209.5	110.0	32.5	17	37.9	16	10.1	250.4	0.393	0.429	58.7	28.5	<0.005	<0.001	-0.44	-4.99
Subreso	048D035 BU3	5.65596	-1.676760	28.1	6.1	250	63.1	2.6	67.5	40.2	17.1	10.8	28.6	2.9	9.1	82.1	0.285	0.156	62.1	24.3	<0.005	<0.001	-0.41	-2.96
Breman	260 BU2	5.70878	-1.602770	28.9	6.9	310	222.0	80.3	155.6	92.5	29.1	21.8	41.3	13	37.7	190.4	1.419	0.271	75.7	22.9	<0.005	<0.001	0.24	5.09
Breman		5.70720	-1.602610	28.5	6.4	240	114.0	2.8	125.0	64.0	26.0	16.3	21.9	3.4	13.9	150.8	0.280	0.268	44.9	32.2	<0.005	<0.001	0.00	0.08
Zion Camp	014 BU3	5.87217	-1.646020	29.9	6.6	1601	674.0	4.4	204.0	320.0	155.0	109	226.0	65	693	241.6	0.457	0.362	353	25.5	<0.005	<0.001	0.02	1.32
Mampong	22/D/73-1	5.111470	-1.731740	27.2	6.1	800	453.0	3.9	64.6	215.0	42.7	30.2	63.5	9.5	163	82.4	3.045	0.437	75.9	10.6	<0.005	<0.001	0.15	1.01
Essamang		5.05042	-1.679790	26.4	5.3	60	36.3	4.6	18.5	18.5	5.7	1.3	7.4	0.6	5.7	28.5	0.554	0.502	1.6	18.0	<0.005	<0.001	0.06	4.18
Mamponso	24/B/85-1	5.42906	-1.630020	26.7	5.8	110	57.8	1.4	26.6	23.4	15.7	4.0	13.5	2.5	11.1	32.5	4.190	0.210	32.2	9.1	<0.005	<0.001	0.18	5.38
Sienchem	24/B/32-1	5.47123	-1.650530	25.3	5.7	560	380.0	1.2	37.1	137.0	31.1	13.1	62.5	16	75.6	115.2	3.474	0.306	91	21.6	<0.005	<0.001	-0.21	-1.82
Sienchem	24/B/32-2	5.47246	-1.651560	25.9	5.8	230	120.0	1.3	31.2	39.5	13.5	1.7	18.2	15	23.2	36.9	1.690	0.342	31.9	11.1	<0.005	<0.001	0.04	0.97

pH (pH units), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method, Long=Longitude (N), Lat=Latitude (W)

B-6: Hydrochemical data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 5th – 9th March 2012)

Sample Source	GPS Co-ordinates	BHID	T°C	pH	EC	TDS	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^-	NO_2N	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^-	NH_4N	E.Bal	CBE(%)
Sabina	N05.86974' , W001.27172'		28.5	6.28	269.0	151.0	84.0	90.0	18.8	10.4	32.0	4.2	18.9	102.5	0.041	0.392	0.496	53.0	21.6	<0.005	<0.001	-0.03	-0.45
Ayitey	N05.88353' , W001.25584'	094BU3	27.6	5.96	209.0	117.0	58.0	64.0	14.8	6.5	38.5	4.3	12.9	120.8	0.055	0.337	0.570	83.4	21.4	0.015	<0.001	0.26	4.49
Nkrafo	N05.87813' , W001.23365'	098BU3	27.1	6.71	374.0	209.0	152.0	144.0	38.5	11.6	48.5	4.5	11.9	185.4	0.042	0.198	0.592	80.4	23.4	<0.005	<0.001	0.05	0.48
Nkrafo	N05.88086' , W001.23863'	096BU3	27.5	7.00	469.0	262.0	10.0	64.0	14.4	6.8	47.9	11.5	57.6	12.2	0.055	1.966	0.484	92.1	21.5	<0.005	<0.001	-0.12	-1.59
Obirikwaku	N05.91570' , W001.23361'	099BU3	27.9	6.07	495.0	277.0	94.0	100.0	27.3	7.7	40.0	3.6	12.9	114.7	0.079	0.434	0.523	76.4	16.9	<0.005	<0.001	-0.01	-0.18
Odumasi Camp	N05.82454' , W001.19149'	405BU2	28.1	66.2	269.0	150.0	40.0	38.0	10.4	2.9	36.2	10.6	11.9	48.8	0.073	2.787	0.533	66.2	21.4	<0.005	<0.001	0.04	0.86
Obobakokrowa	N05.80277' , W001.17656'	246JBU1	27.8	5.64	135.9	75.6	58.0	84.0	20.0	8.2	32.2	8.6	30.8	70.8	0.072	0.481	1.280	61.4	23.3	<0.005	<0.001	-0.02	-0.33
Odumasi Camp	N05.19421' , W001.19421'	407BU2	29.4	6.14	295.0	165.0	66.0	60.0	11.2	7.8	56.1	6.3	31.8	80.5	0.081	0.666	1.190	74.8	22.8	<0.005	<0.001	0.02	0.23
Dwendaama	N05.80162' , W001.20490'		27.5	6.12	246.0	138.0	104.0	86.0	18.4	9.7	32.4	8.6	7.9	126.9	0.069	0.243	0.700	50.3	19.3	<0.005	<0.001	-0.01	-0.12
Dwendaama	N05.80159' , W001.20572'		26.5	6.47	90.4	50.4	28.0	31.0	5.6	4.1	45.0	25.6	10.2	34.2	0.066	0.482	0.725	110.0	18.5	<0.005	<0.001	0.08	1.29
WoraKesse Habitat	N05.76445' , W001.23152'	097BU3	27.5	5.33	76.2	42.7	18.0	9.0	3.2	0.2	37.0	4.3	19.9	22.0	0.085	2.029	0.976	48.1	29.5	0.198	<0.001	-0.06	-1.57
Brofoyedru Habitat	N05.78437' , W001.28443'	101BU3	26.4	5.59	119.2	66.8	42.0	24.0	7.2	1.4	32.3	3.5	8.9	51.2	0.046	0.759	0.761	43.8	21.8	<0.005	<0.001	-0.05	-1.14
Assin Nyankumase	N05.75829' , W001.28643'		28.6	5.24	846.0	474.0	12.0	14.0	2.2	1.9	28.6	4.5	7.9	14.6	0.047	3.220	0.501	50.7	17.2	0.184	<0.001	0.06	1.74
Assin Nyankumase	N05.75762' , W001.29058'		27.6	5.64	178.4	100.0	52.0	56.0	12.0	6.3	25.0	5.5	14.9	63.4	0.057	0.584	0.323	38.0	7.1	<0.005	<0.001	0.09	1.85
Assin Nyankumase	N05.75729' , W001.29082'		29.6	4.80	180.1	101.0	12.0	38.0	4.8	6.3	17.3	4.3	17.9	14.6	0.059	5.014	0.293	38.9	17.3	0.198	<0.001	-0.01	-0.04
Akonfude	N05.82614' , W001.30953'		26.7	6.87	295.0	165.0	54.0	24.0	22.8	3.1	36.7	9.6	30.8	65.9	0.047	0.301	0.273	62.3	17.0	<0.005	<0.001	-0.02	-0.25
Akonfude	N05.82945' , W001.31011'		27.9	5.31	533.0	298.0	18.0	90.0	22.0	8.5	31.2	5.1	58.6	22.0	0.081	0.677	0.290	58.4	22.7	<0.005	<0.001	0.04	0.68
Assin Breku (SDA)	N05.86625' , W001.33689'	100BU3	27.9	5.76	132.5	73.9	52.0	134.0	8.3	11.5	20.0	6.3	6.9	63.4	0.046	0.753	0.435	50.2	25.8	<0.005	<0.001	0.10	2.14
Assin Breku (Gyidi)	N05.87056' , W001.33793'	102BU3	26.2	6.55	336.0	188.0	146.0	134.0	36.1	10.6	24.6	12.6	10.9	178.1	0.065	0.988	0.373	44.2	18.3	0.193	<0.001	-0.10	-1.17
Assin Breku	N05.86808' , W001.34099'		27.6	5.54	291.0	163.0	38.0	94.0	18.4	11.6	9.3	6.3	27.8	46.4	<0.001	0.272	0.420	44.9	17.5	0.187	<0.001	-0.05	-0.93
Techiman No.1	N05.80440' , W001.36794'	396BU2	26.7	5.36	57.8	32.4	18.0	12.0	4.0	0.5	46.0	5.4	6.9	22.0	0.087	0.188	0.791	84.2	34.5	0.189	<0.001	0.07	1.46
Kwame Ankra	N05.81540' , W001.38197'	411BU2	26.5	5.31	125.7	70.4	32.0	32.0	5.6	4.4	45.6	5.6	6.9	39.0	0.049	0.312	0.764	92.9	34.3	<0.005	<0.001	-0.01	-0.09
Ninkyiso	N05.812119' ,W001.39917'		27.6	4.82	216.0	121.0	14.0	44.0	6.8	6.8	45.6	18.6	28.8	17.1	0.082	0.755	2.250	113.0	33.1	<0.005	<0.001	-0.10	-1.46
Amoakokrom	N05.78654' , W001.34582'	337BU3	28.4	4.94	329.0	184.0	20.0	46.0	9.6	5.3	34.0	22.0	51.6	24.4	0.100	0.622	11.200	63.8	24.9	<0.005	<0.001	-0.24	-3.85
Nyamebekyere	N05.76558' , W001.34666'	339BU3	26.9	5.56	151.6	84.9	53.0	32.0	17.0	19.0	100.0	65.0	12.9	64.7	0.060	0.732	0.412	359.0	35.3	<0.005	<0.001	-0.89	-2.81
Jerusalem	N05.75216' , W001.44366'	0502B1/01/097-01	26.5	5.16	70.5	39.5	21.0	17.0	4.8	1.2	50.0	35.0	9.9	25.6	0.082	0.918	0.609	116.0	29.9	<0.005	<0.001	0.28	4.28
Antoabasa	N05.77203' , W001.46879'		27.5	5.61	168.0	94.1	40.0	41.0	10.6	15.6	90.0	49.0	23.8	48.8	0.051	0.702	10.900	255.0	33.0	<0.005	<0.001	0.19	1.37
Antoabasa	N05.77018' , W001.46949'		27.8	5.59	220.0	123.0	44.0	48.0	8.8	6.3	46.0	60.0	36.7	53.7	0.060	0.482	0.646	136.0	22.6	<0.005	<0.001	-0.26	-2.83

Sample Source	GPS Co-ordinates	BHID	T°C	pH	EC	TDS	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_2N	NO_3N	$PO_4.P$	SO_4^{2-}	SiO_2	F^{-}	$NH_4.N$	E.Bal	CBE(%)
Anum	N05.78218' , W001.50222'	086BU3	26.9	6.10	273.0	153.0	110.0	94.0	42.2	32.0	50.0	40.0	13.9	134.2	0.089	0.198	8.020	253.0	30.4	0.183	<0.001	0.07	0.47
Kyeikurom	N05.82504' , W001.52242'		27.3	5.70	145.6	87.0	50.0	32.0	6.4	3.9	21.2	19.0	13.9	61.0	0.046	0.370	11.20	38.5	24.5	<0.005	<0.001	-0.15	-3.56
Adukrom	N05.84924' , W001.52394'	088BU3	27.2	5.52	135.8	74.3	40.0	38.0	8.8	3.9	33.6	27.5	15.2	48.8	0.088	0.717	0.887	87.0	31.4	<0.005	<0.001	-0.13	-2.13
Subrisu	N05.82474' , W001.54799'		26.8	5.70	245.0	140.0	72.0	72.0	19.2	6.5	52.1	30.6	27.8	87.8	0.070	0.280	0.524	119.0	22.9	<0.005	<0.001	-0.16	-1.77
Nsuekyir	N05.77244' , W001.50221'	219BU1	26.8	5.66	169.8	101.0	56.0	54.0	12.0	9.8	26.3	19.3	10.9	68.3	0.081	0.499	0.691	71.5	25.5	0.190	<0.001	0.12	1.20
Denyease Domeabra	N05.74806' , W001.53606'	093BU3	28.0	5.78	222.0	124.0	92.0	76.0	20.0	9.2	30.6	24.8	12.9	112.2	0.091	0.328	0.635	69.1	33.0	0.191	<0.001	0.07	0.10
Twifo Mampong	N05.52361' , W001.55671'		27.1	5.32	279.0	156.0	30.0	68.0	10.4	10.2	28.0	23.0	35.7	36.6	0.067	0.691	0.669	77.8	31.7	<0.005	<0.001	-0.07	-1.15
Twifo Mampong	N05.52316' , W001.55452'		27.4	5.73	1140.0	627.0	106.0	324.0	57.7	43.7	23.6	19.5	173.7	129.3	0.097	0.360	0.558	76.8	17.8	<0.005	<0.001	-0.62	-3.75
Akwa Yaw	N05. 44168' , W001.48580'		27.9	5.28	107.7	60.3	26.0	28.0	6.4	2.9	26.5	19.8	10.9	31.7	0.072	0.960	0.692	71.5	17.6	<0.005	<0.001	-0.11	-2.51
Bremang	N05.70882' , W001.60273'	260BU2	26.5	6.15	308.0	172.0	122.0	106.0	33.7	10.2	22.9	19.8	16.9	148.8	0.107	0.339	0.674	82.7	27.5	0.193	<0.001	-0.04	-0.52
Bremang	N05.70720' , W001.60270'		27.4	6.27	216.0	121.0	92.0	92.0	24.0	7.7	24.3	17.3	12.9	112.2	0.088	0.411	0.306	62.7	24.1	<0.005	<0.001	0.24	3.79
Twifo Agona	N05.74540' , W001.50387'	236BU2	27.9	6.06	1797.0	988.0	74.0	96.0	19.2	11.6	24.6	18.8	31.8	90.3	0.101	0.204	0.331	64.2	15.9	<0.005	<0.001	0.31	4.67
Zion Camp	N05.87221' , W001.64609'	014BU3	26.8	5.88	265.0	148.0	82.0	96.0	25.7	7.7	20.6	15.4	28.8	100.0	0.089	0.288	0.414	65.9	27.8	<0.005	<0.001	-0.03	-0.54
Somnyamekordru	N05.66454' , W001.58470'	138BU1	26.4	6.41	799.0	447.0	124.0	246.0	28.2	17.6	22.6	14.5	34.4	151.3	0.117	0.242	0.326	23.6	30.5	<0.005	<0.001	0.26	3.24
Somnyamekordru	N05.66044' , W001.58376'	033BU3	27.7	5.47	57.1	31.4	20.0	48.0	5.6	8.3	25.6	10.6	10.9	24.4	0.066	0.369	0.252	81.6	21.4	0.181	<0.001	-0.07	-1.37
Atu Kurom	N05.60612' , W001.67843'		27.3	5.29	330.0	181.5	34.0	100.0	10.4	18.0	28.8	19.4	49.6	41.5	0.064	0.255	0.252	85.7	30.5	<0.005	<0.001	-0.12	-1.56
Subreso	N05.65596' , W001.67676'		28.3	6.06	236.0	132.2	112.0	108.0	31.3	14.3	29.1	23.4	8.9	136.6	0.125	0.294	0.361	43.0	26.7	<0.005	<0.001	0.25	2.80
Gromsa	N05.59000' , W001.60611'	032BU3	26.4	5.75	171.3	95.9	54.0	88.0	17.6	10.7	24.1	22.5	18.9	65.9	0.079	0.346	0.443	86.3	20.1	<0.005	<0.001	-0.03	-0.49
Anyinase Ankase	N05.59646' , W001.60273'	030BU3	27.5	5.60	92.4	51.7	42.0	44.0	14.4	1.9	25.7	22.8	7.9	51.2	0.092	0.389	0.284	76.9	21.2	<0.005	<0.001	-0.09	-1.78
Sienchem	N05.47246' , W001.65157'	24/B/32/1	27.3	5.25	213.0	119.0	36.0	56.0	12.8	9.2	26.3	24.8	32.8	43.9	0.114	0.349	0.268	81.9	25.1	<0.005	<0.001	-0.18	-2.78
Sienchem	N05.47117' , W001.65056'	24/B/32/1	26.6	5.07	527.0	295.0	24.0	124.0	27.3	13.6	28.9	25.1	97.3	29.3	0.081	0.304	0.394	61.9	23.2	0.187	<0.001	-0.14	-1.55
Mamponso	N05.42904' , W001.62996'	24-B-85-1	26.4	5.39	98.1	54.9	26.0	28.0	8.8	1.4	27.9	24.6	13.9	31.7	0.084	0.718	0.386	71.1	20.0	0.182	<0.001	-0.01	-0.13
Essamang	N05.35041' , W001.67974'		27.2	5.05	54.2	30.4	12.0	28.0	6.4	2.9	26.4	20.6	12.9	14.6	0.115	2.240	0.345	74.6	26.6	<0.005	<0.001	0.04	0.93

pH(pH units), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method.

B-7: Hydrochemical data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 19th – 23rd June 2012)

Sample source	GPS Co-ordinates	BHID	T°C	pH	EC	TDS	Turb	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	$NH_4.N$	E.Bal	CBE(%)
Sabina	N05.86974' , W001.27172'		28.5	6.1	250	138	4.7	45.2	80.8	20.6	11.6	33.5	5.1	18.9	110.9	0.527	0.357	43.8	21.6	<0.005	<0.001	0.32	4.60
Ayitey	N05.88353' , W001.25584'	094BU3	27.6	6.1	207	114	2.8	59.4	66.2	16.2	10.2	24.9	5.5	11.9	69.3	0.849	0.532	34.5	21.4	<0.005	<0.001	0.12	2.08
Nkrafo	N05.87813' , W001.23365'	098BU3	27.1	6.1	180	99.0	2.6	98.8	59.6	12.3	7.0	31.6	8.4	11.9	109	0.735	0.206	33.6	21.5	<0.005	<0.001	-0.06	-0.99
Nkrafo	N05.88086' , W001.23863'	096BU3	27.5	7.0	385	212	4.1	287	257	69.9	18.7	45.6	5.6	37.9	347	0.195	0.314	44.3	23.4	<0.005	<0.001	-0.53	-3.55
Obirikwaku	N05.91570' , W001.23361'	099BU3	27.9	6.2	249	137	3.6	152.0	89.8	32.5	5.7	27.6	12.4	13.8	179	0.128	0.158	18.0	21.9	<0.005	<0.001	-0.09	-1.19
Odumase Camp	N05.82454' , W001.19149'	405BU2	28.1	6.0	137	75.4	7.2	62.4	34.4	11.7	4.1	30.6	8.5	15.2	75.4	0.184	0.112	33.7	21.4	<0.005	<0.001	0.24	5.14
Odumase Camp	N05.19421' , W001.19421'	407BU2	27.8	5.9	305	168	2.7	112	66.2	21.8	18.9	33.6	5.6	36.5	143	0.257	0.294	52.0	23.3	<0.005	<0.001	-0.22	-2.51
Obobakokrowa	N05.80277' , W001.17656'	246JBU1	29.4	5.5	301	166	2.8	14.0	75.0	16.0	8.5	21.2	4.2	42.6	43.1	0.099	0.292	42	22.8	<0.005	<0.001	-0.25	-4.79
Dwedaama	N05.80162' , W001.20490'		27.5	6.4	222	122	4.3	154.6	80.6	18.9	18.1	40.9	7.6	10.8	202	0.213	0.396	58.4	19.3	<0.005	<0.001	-0.43	-4.69
Dwedaama	N05.80159' , W001.20572'		26.5	5.6	120	70.7	3.8	73.2	49.0	10.9	7.2	18.4	5.2	13.2	86.1	0.119	0.278	24.2	18.5	<0.005	<0.001	-0.22	-5.04
WoraKesse Habitat	N05.76445' , W001.23152'	097BU3	27.5	5.5	84.2	46.3	1.9	27.0	30.0	9.4	3.7	6.9	3.9	11.9	40.4	0.22	0.362	10.8	19.5	<0.005	<0.001	-0.05	-2.20
Brofoyedru Habitat	N05.78437' , W001.28443'	101BU3	26.4	5.9	121	66.6	1.8	82.4	48.1	17.7	8.8	5.8	2.4	11.9	87.3	0.184	0.361	17.0	21.8	<0.005	<0.001	-0.20	-5.01
Assin Nyankomase	N05.75829' , W001.28643'		28.6	6.1	640	352	13.1	8.4	7.2	17.2	5.5	48.5	43	62.9	103	1.693	0.258	52.8	11.2	<0.005	<0.001	-0.07	-0.74
Assin Nyankomase	N05.75762' , W001.29058'		27.6	5.1	184	101	2.2	13.9	32.3	5.20	5.3	28.2	9.6	17.5	67.3	0.942	0.376	18.3	25.8	<0.005	<0.001	0.17	4.20
Assin Nyankomase	N05.75729' , W001.29082'		29.6	5.1	75.6	41.6	2.3	16.8	35.0	2.3	7.3	18.2	6.8	15.0	37.8	1.419	0.680	22.3	6.2	<0.005	<0.001	0.15	4.71
Akonfude	N05.82614' , W001.30953'		26.7	5.8	307	169	2.0	32.2	97.4	22.5	7.6	23.6	17.0	49.8	95.3	0.377	0.283	26.5	27.0	<0.005	<0.001	-0.32	-4.68
Akonfude	N05.82945' , W001.31011'		27.9	5.4	556	306	10.0	42.4	145	20.4	16.2	34.8	5.7	57.6	95.7	0.654	0.216	27.3	25.7	<0.005	<0.001	0.24	3.06
Assin Breku (SDA)	N05.86625' , W001.33689'	100BU3	27.9	6.1	139	76.5	1.8	50.8	42.8	14.5	1.8	12.9	4.3	19.7	64.1	0.324	0.368	3.3	44.1	<0.005	<0.001	-0.14	-4.26
Assin Breku (Gyidi)	N05.87056' , W001.33793'	102BU3	26.2	6.9	346	190	5.3	149.8	151	42.4	12.9	23.3	4.8	8.9	194	0.689	0.289	42.4	31.3	<0.005	<0.001	-0.01	-0.12
Assin Breku	N05.86808' , W001.34099'		27.6	6.2	301	166	2.4	23.0	103	20.2	9.0	24.4	6.8	42.8	98.1	0.789	0.396	5.5	33.9	<0.005	<0.001	0.04	0.70
Techiman No.1	N05.80440' , W001.36794'	396BU2	26.7	5.5	59.1	32.5	1.6	22.8	12.8	4.3	2.8	9.9	4.9	7.9	32.3	0.499	0.458	15.2	4.5	<0.005	<0.001	-0.08	-3.65
Kwame Ankra	N05.81540' , W001.38197'	411BU2	26.5	5.5	133	73.2	3.1	31.2	30.6	14.9	1.6	19.3	5.6	16.4	59.4	0.332	0.237	11.5	34.3	<0.005	<0.001	0.18	5.00
Ninkyiso	N05.812119' , W001.39917'		27.6	5.1	223	121	1.7	12.4	37.6	6.0	5.5	23.1	6.3	23.1	64.9	0.702	0.252	13.8	33.1	<0.005	<0.001	-0.07	-1.88
Amoakokrom	N05.78654' , W001.34582'	337BU3	28.4	5.3	277	152	3.0	43.2	41.4	11.1	3.7	27.6	4.2	32.8	54.1	0.093	1.285	22.9	22.9	<0.005	<0.001	-0.12	-2.78
Nyamebekyere	N05.76558' , W001.34666'	339BU3	26.9	5.8	151	83.1	1.5	53.6	27.2	9.7	3.8	16.9	4.9	19.4	65	0.558	1.863	3.9	15.3	<0.005	<0.001	-0.04	-1.20
Jerusalem	N05.76558' , W001.34666'	339BU3	26.5	5.4	76.0	41.8	2.3	26.8	8.2	2.8	2.1	9.7	5.1	7.5	29	0.341	3.344	8.1	12.6	<0.005	<0.001	0.00	-0.06
Antoabasa	N05.75216' , W001.44366'	0502B1/01/097-01	27.5	5.8	176	96.8	1.9	53.6	55.6	10.1	5.7	25.2	4.7	18.8	53	0.562	0.441	33.3	14.9	<0.005	<0.001	0.08	1.97
Antoabasa	N05.77203' , W001.46879'		27.8	5.6	233	148	12.1	50.4	46.4	11.9	4.4	37	3.9	32.4	65	0.555	0.276	22.9	22.2	<0.005	<0.001	0.20	3.90

Sample source	GPS Co-ordinates	BHID	T°C	pH	EC	TDS	Turb	Alk	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	$NH_4.N$	E.Bal	CBE(%)
Anum	N05.77497' , W001.49742'		26.9	5.9	260	83.1	1.8	88.4	33.2	11.5	7.2	29.2	3.1	16.2	111.0	0.005	0.263	9.1	33.8	<0.005	<0.001	0.05	0.94
Kyeikurom	N05.78218' , W001.50222'	086BU3	27.3	5.8	142	77.7	2.0	65.0	47.0	18.2	7.9	21.2	6.9	16.1	82.1	0.102	0.241	49.7	25.1	<0.005	<0.001	-0.18	-3.26
Subrisu	N05.82474' , W001.54799'		27.2	6.3	250	138	4.2	50.4	92.6	14.4	13.7	28.3	20.1	19.9	135	0.202	0.689	26.2	22.9	<0.005	<0.001	-0.14	-2.34
Adukrom	N05.84924' , W001.52394'	088BU3	26.8	6.4	140	78.3	2.5	29.2	47.0	11.4	4.5	36.3	4.1	27.9	74.2	0.317	0.512	33.8	25.5	<0.005	<0.001	-0.09	-1.67
Subriso	N05.82474', W001.54799'		26.8	6.8	240	103.5	2.3	116.2	63.1	14.7	13.2	21.3	6.2	14.3	130	0.62	0.112	24.3	30.3	<0.005	<0.001	-0.14	-2.34
Nsuekyir	N05.77244' , W001.50221'	219BU1	28.0	6.0	226	124	2.2	143.8	84.0	15.1	11.2	35.2	6.4	14.3	176	0.063	0.274	13.8	33.5	<0.005	<0.001	-0.20	-2.90
Denyease Domeabra	N05.74806' , W001.53606'	093BU3	27.1	6.7	287	158	1.8	67.2	41.4	13.4	8.2	21.8	3.4	24.4	88.3	0.035	0.378	17.2	21.7	<0.005	<0.001	-0.12	-2.37
Twifo Mampong	N05.52361' , W001.55671'		27.4	6.0	270	63.5	2.6	61.0	42.8	16.7	13.1	29.2	2.7	12.3	57.2	0.571	0.153	79.2	24.8	<0.005	<0.001	0.31	4.97
Twifo Mampong	N05.52316' , W001.55452'		27.9	6.2	490	268.6	6.3	69.4	113.1	15.7	14.3	29.1	2.6	13.2	100.3	0.314	0.152	75.3	25.9	<0.005	<0.001	-0.30	-4.31
Akwa Yaw	N05. 44168' , W001.48580'		26.5	6.2	106	58.3	2.4	16.0	35.0	18.7	12.9	24.7	2.6	7.8	151	0.468	0.158	22.4	23.7	<0.005	<0.001	-0.04	-0.58
Bremamg	N05.70882' , W001.60273'	260BU2	27.4	6.7	325	179	3.7	70.2	129	28.1	21.2	40.1	13.1	37.2	188	1.423	0.271	77.8	22.5	<0.005	<0.001	-0.55	-5.02
Bremamg	N05.70720' , W001.60270'		27.9	6.6	268	147	10.7	56.6	108	26.1	16.2	21.3	3.4	13.1	150	0.281	0.257	45.1	31.2	<0.005	<0.001	-0.12	-1.67
Twifo Agona	N05.74540' , W001.50387'	236BU2	26.8	5.9	230	127	2.0	128.8	78.8	36.2	16.3	30.1	15.1	20.2	210	0.148	0.433	55.8	27.8	0.246	<0.001	-0.33	-3.33
Zion Camp	N05.87221' , W001.64609'	014BU3	26.4	6.8	1191	657.0	4.3	214	326	158.1	114.2	236	67.5	692.1	242	0.377	0.309	353	20.7	<0.005	<0.001	-1.57	-2.61
Somnyamekordur	N05.66454' , W001.58470'	138BU1	27.7	6.7	740	407	3.0	76.6	268	83.7	4.2	42.4	12.9	81.7	278	0.292	0.321	11.6	28.5	<0.005	<0.001	-0.41	-2.96
Somnyamekordur	N05.66044' , W001.58376'	033BU3	27.3	5.8	75.3	41.4	4.9	11.4	22.0	38.1	5.4	16.1	3.7	17.1	119.4	0.124	0.383	39.2	29.4	<0.005	<0.001	-0.12	-1.83
Atu Kurom	N05.60612' , W001.67843'		28.3	5.6	365	201	2.5	20.2	111	32.8	17.2	38.2	16.1	10.3	252	0.352	0.421	58.1	29.1.	<0.005	<0.001	-0.50	-4.67
Subreso	N05.65596' , W001.67676'		26.4	6.5	272	150	21.1	67.0	126	17.3	11.1	28.3	2.9	9.2	81.2	0.281	0.157	62.5	24.7	<0.005	<0.001	0.19	3.10
Gromsa	N05.59000' , W001.60611'	032BU3	27.5	6.4	202	111	2.4	30.8	84.8	18.1	15.6	34.2	12.1	49.5	82.7	0.314	0.172	71.3	18.1	<0.005	<0.001	-0.26	-3.13
Anyinase Ankase	N05.59646' , W001.60273'	030BU3	27.3	5.9	97.7	53.5	5.8	59.8	45.8	13.9	4.4	19.7	4.1	13.2	78.6	1.652	0.183	24.1	16.7	<0.005	<0.001	-0.17	-4.08
Sienkyem	N05.47246' , W001.65157'	24/B/32/1	26.6	5.4	226	124	2.7	18.8	59.4	13.6	1.9	18.3	12.4	23.4	42.3	1.621	0.321	30.3	11.2	<0.005	<0.001	-0.08	-1.96
Sienkyem	N05.47117' , W001.65056'	24/B/32/1	26.4	5.5	686	377	2.3	19.0	161	32.2	13.1	62.4	13.2	35.2	120	3.512	0.295	51.3	23.2	<0.005	<0.001	0.52	4.75
Mamponso	N05.42904' , W001.62996'	24-B-85-1	27.2	5.8	106	58.3	2.5	15.0	29.4	16.1	4.2	13.7	2.9	11.3	33.2	4.37	0.198	34.2	11.1	<0.005	<0.001	0.17	5.01
Essamang	N05.35041' , W001.67974'		26.8	5.3	62.2	34.2	4.4	7.60	19.0	6.2	1.3	8.2	0.9	6.3	31.2	0.591	0.512	1.7	18.3	<0.005	<0.001	0.06	4.04
Mampong	N05.11142', W001.73174'	22/D/73-1	27.8	5.5	856	471	3.2	26.2	250	44.1	26.6	66.2	10.4	154	82.2	2.987	0.432	73.0	10.2	<0.005	<0.001	0.27	1.84

pH (pH units), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method.

B-8: Hydrochemical data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 23rd – 27th October 2012)

Sample Source	BH ID	Long	Lat	T°C	pH	Eh	EC	TDS	ALK	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	$NH_4.N$	E.Bal	CBE(%)
Sabina	380 BU1	5.86974	-1.27172	28.2	6.45	58.3	180	110	95.8	63.2	19.1	8.2	21.7	6.5	9.9	117	0.111	0.368	19.1	32.1	<0.005	<0.001	0.14	2.66
Ayitey	094 BU3	5.88353	-1.25584	31.8	5.94	72.4	180	100	65.0	59.8	15.3	4.7	17.6	6.7	21.9	68.1	0.408	0.373	9.2	1.6	0.065	<0.001	0.15	3.71
Nkrafo	098 BU3	5.87809	-1.23364	30.1	6.87	23.7	260	195	188	140.0	38.8	11.9	32.3	7.8	19.4	199.3	0.074	0.278	31.3	1.3	<0.005	<0.001	0.05	0.53
Nkrafo	096 BU3	5.88087	-1.23862	27.6	6.33	51.7	150	93.0	61.2	51.2	17.1	4.0	12.4	4.3	13.4	65.8	1.480	0.473	11.4	22.5	<0.005	<0.001	0.11	3.13
Obirikwaku	099 BU3	5.91571	-1.23661	29.5	6.05	66.8	210	142	112	94.4	30.8	5.7	18.1	5.4	11.4	134	0.203	0.416	18.5	34.0	<0.005	<0.001	0.01	0.22
Odumase Camp	405 BU2	5.82454	-1.19147	27.5	5.56	93.4	110	68.8	38.8	32.0	8.1	3.1	16.0	3.3	11.2	53.9	0.157	0.290	12.1	4.9	<0.005	<0.001	-0.02	-0.66
Odumase Camp	407 BU2	5.82181	-1.19419	27.7	5.67	86.8	200	154	73.0	49.8	15.0	9.8	41.8	4.5	48.3	87.1	0.533	0.303	30.9	19.0	<0.005	<0.001	0.04	0.61
Obobakokrowa	246 J BU1	5.82490	-1.17768	28.7	5.24	109.0	210	156	20.6	62.8	47.0	7.0	19.1	3.2	21.2	169.2	0.158	0.221	6.5	4.1	<0.005	<0.001	0.32	4.37
Dwedaama		5.90170	-1.20496	27.3	6.26	56.0	180	123	117	76.0	41.7	14.1	22.3	7.3	7.0	194	0.061	0.234	35.0	9.5	<0.005	<0.001	0.29	3.38
Dwedaama		5.80159	-1.20575	26.3	5.37	105.2	70	44.7	26.6	40.8	14.6	2.9	9.45	3.0	12.7	46.0	0.277	0.316	14.4	18.0	<0.005	<0.001	0.04	1.28
WoraKesse Habitat	097 BU3	5.76443	-1.13154	25.7	4.73	132.6	80	44.1	24.6	22.2	3.3	3.0	14.6	6.5	15.2	31.8	1.860	0.293	7.3	16.0	<0.005	<0.001	0.08	3.38
Brofoyedru Habitat	101 BU3	5.73346	-1.28457	25.6	4.47	153.2	100	63.8	53.0	26.2	7.2	4.5	17.5	7.5	9.2	53.0	0.873	0.501	17.6	8.7	0.591	<0.001	0.17	5.37
Assin Nyankomase		5.75724	-1.29063	27.6	4.90	126.4	70	40.1	14.4	13.8	17.4	6.5	55.3	48.8	62.1	102.6	1.475	0.496	56.9	11.1	0.475	<0.001	0.41	4.20
Assin Nyankomase		5.75719	-1.29084	28.5	5.09	116.8	380	299	24.4	72.4	8.2	5.9	26.9	9.4	16.5	75.4	0.890	0.288	18.9	25.6	0.704	<0.001	0.20	4.44
Assin Nyankomase		5.75897	-1.28652	27.8	4.69	138.2	160	101	11.6	26.0	4.0	7.1	15.3	4.8	10.0	46.7	1.652	0.342	18.1	5.5	0.403	<0.001	0.12	3.88
Akonfude		5.82570	-1.30988	26.8	5.07	114.7	230	160	68.2	85.2	22.1	8.5	30.9	9.7	56.7	94.5	0.327	0.208	28.7	35.5	0.169	<0.001	-0.36	-5.04
Akonfude		5.82950	-1.31011	27.2	5.14	99.5	360	286	21.4	120	20.6	16.8	34.0	5.3	55.2	96.3	0.648	0.298	25.6	24.0	0.74	<0.001	0.34	4.42
Assin Breku (Gyidi)	102 BU3	5.87059	-1.33603	26.4	6.41	35.1	260	185	190	139	38.3	13.4	25.3	4.8	9.0	190	0.070	0.257	43.2	32.1	0.503	<0.001	-0.04	-0.52
Assin Breku		5.86801	-1.34094	27.3	5.53	87.9	230	157.0	47.0	80.6	21.1	8.6	25.4	6.5	43.3	99.3	0.714	0.373	6.14	33.4	0.525	<0.001	0.04	0.65
Techiman No.1	396 BU3	5.80432	-1.36792	26.9	5.12	112.4	60	40.0	19.2	12.8	3.4	2.5	9.4	3.4	6.3	25.2	0.438	0.278	12.8	1.3	0.459	<0.001	0.01	0.35
Kwame Ankra	411 BU3	5.81542	-1.38199	26.2	5.35	98.4	110	30.0	39.8	26.4	12.8	1.5	18.3	5.2	14.4	56.7	3.300	0.429	9.36	35.9	0.738	<0.001	0.11	3.21
Ninkyiso		5.82117	-1.39912	26.9	4.92	124.2	170	70.4	14.4	32.4	7.1	4.4	27.0	5.6	21.3	66.6	0.659	0.308	12.4	19.0	1.36	<0.001	0.07	1.72
Amoakokrom	338 BU3	5.85972	-1.25611	27.3	4.96	123.0	240	109	23.6	54.0	11.2	3.6	29.6	5.1	33.8	54.2	0.060	0.334	23.9	23.7	1.08	<0.001	-0.07	-1.50
Nyamebekyere	339 BU3	5.80139	-1.72139	26.8	5.63	80.8	130	79.8	63.4	30.0	9.5	3.4	17.9	5.2	19.0	63.9	0.556	0.010	3.6	16.4	1.05	<0.001	-0.01	-0.26
Jerusalem	0502B1/6/097-01	5.81667	-1.71750	26.6	5.03	117.2	70	40.0	25.4	20.2	2.5	2.5	9.6	5.4	7.0	28.8	0.369	0.380	7.5	13.2	0.771	<0.001	0.05	2.82
Antoabasa		5.77196	-1.46878	28.3	5.34	104.9	140	91.9	59.0	39.8	10.3	5.7	24.5	4.6	19.0	57.1	0.643	0.632	31.6	15.4	0.92	<0.001	0.03	0.61
Antoabasa		5.7702	-1.46948	27.6	5.08	114.5	170	118	54.6	37.0	11.1	5.3	29.5	4.7	25.6	61.9	0.603	0.506	26.6	18.7	0.909	<0.001	0.09	1.84
Bediedua		5.77278	-1.49722	28.3	5.15	119.3	170	118	49.6	44.6	16.2	6.0	27.2	1.4	8.0	118.2	0.059	0.458	18.1	27.7	0.983	<0.001	-0.02	-0.43

Sample Source	BH ID	Long	Lat	T°C	pH	Eh	EC	TDS	ALK	TotH	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	Cl^{-}	HCO_3^{-}	NO_3N	PO_4P	SO_4^{2-}	SiO_2	F^{-}	NH_4.N	E.Bal	CBE(%)
Nsuekyir	219 BU1	5.68667	-1.49722	27.3	5.40	95.4	170	79.2	63.4	41.4	15.5	11.5	14.85	5.3	23.7	68.8	0.716	0.733	22.0	16.3	0.544	<0.001	0.23	4.83
Denyease Domeabra	092 BU3	5.74806	-1.53806	27.1	5.98	60.7	160	113	82.0	71.2	18.9	5.4	18.4	4.9	11.2	105.0	0.097	0.789	15.5	18.0	0.89	<0.001	-0.05	-1.00
Twifo Mampong		5.52016	-1.55449	29.6	4.24	166.3	220	149	34.0	69.2	10.8	10.7	27.7	12.2	22.3	48.8	0.454	0.532	77.9	26.4	1.19	<0.001	-0.12	-2.02
Twifo Mampong		5.52359	-1.55681	29.1	5.90	65.6	590	590	134	319	37.1	28.3	26.1	10.9	92.8	91.5	0.457	0.920	77.8	21.4	0.787	<0.001	-0.16	-1.37
Breman	260 BU2	5.70878	-1.60277	31.2	6.18	49.4	260	186	180	125	28.5	21.3	41.1	12.9	37.2	189.2	1.418	0.109	76.2	22.1	0.666	<0.001	-0.47	-4.26
Breman		5.70720	-1.60261	31.4	6.06	55.8	200	134	128	86.2	25.6	16.1	21.4	3.3	13.4	149.8	0.278	0.938	44.6	31.3	0.931	<0.001	-0.15	-2.09
Twifo Agona	263 BU2	5.74595	-1.50398	29.3	4.96	122.3	140	99.0	90.4	57.4	17.6	10.0	14.6	7.9	10.0	93.3	0.127	0.175	22.4	18.4	0.812	<0.001	0.25	5.23
Somnyamekordur	048D033 BU3	5.66046	-1.58376	28.1	6.24	41.6	410	378	167	216	14.7	5.4	67.75	3.8	72.8	142.8	0.315	0.866	13.8	17.4	1.01	<0.001	-0.47	-5.23
Somnyamekordur		5.66046	-1.58376	28.4	5.95	74.3	130	75.9	44.0	46.2	84.2	3.8	42.3	12.3	81.4	278.2	0.255	0.137	10.4	27.8	0.564	<0.001	-0.41	-2.96
Atu Kurom		5.63657	-1.67850	28.1	4.95	121.6	240	197	45.4	92.4	32.3	16.9	37.8	16.0	10.0	249.7	0.370	0.156	58.2	28.0	0.765	<0.001	-0.54	-5.06
Subreso	048D035 BU3	5.65596	-1.67676	28.4	5.29	99.4	200	144	156	114	16.8	10.6	28.1	2.8	9.0	81.3	0.282	0.115	61.9	24.2	0.713	<0.001	0.12	1.99
Gromsa	032 BU3	5.58991	-1.60607	27.1	4.40	156.6	150	99.6	60.4	65.6	33.2	3.4	14.05	2.5	30.4	69.1	0.424	0.509	23.6	22.5	0.566	<0.001	0.12	2.38
Anyinase Ankase	030 BU3	5.59446	-1.60279	26.3	4.66	136.2	90	52.3	44.2	30.6	8.3	4.0	11.2	1.7	6.2	47.6	0.344	0.488	9.7	9.4	0.801	<0.001	0.11	4.56
Sienkyem	24/B/32-1	5.47123	-1.65053	29.6	4.88	180.5	200	118	33.0	48.4	31.6	13.4	63.25	15.3	74.8	113.7	3.456	0.491	77.5	21.3	0.771	<0.001	0.18	1.55
Sienkyem	24/B/32-2	5.47246	-1.65156	27.6	4.56	162.5	450	380	35.6	146	13.2	1.6	17.7	15.1	23.0	36.8	1.640	0.506	31.2	10.9	0.818	<0.001	0.01	0.36
Mamponso	24/B/85-1	5.42906	-1.63002	27.6	5.02	185.1	100	55.6	32.4	28.8	15.7	4.0	13.35	2.5	11.0	32.1	4.285	0.707	32.7	9.1	0.903	<0.001	0.16	4.92

pH (pH units), Eh (mV), EC (µS/cm), all other parameters in mg/L, E. Bal = electrical balance, CBE = charge balance error. Computation of electrical balance (E.Bal) and charge balance error (CBE) were carried out using the anion-cation balance method, Long = Longitude (N), Lat = Latitude (W)

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APPENDIX C: TRACE METAL DATA FOR GROUNDWATER WITHIN THE LOWER PRA BASIN

C-1: Trace metal analyses data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 2nd – 7th June 2011)

Sample Source	BHID	Longitude	Latitude	Cu	Mn	Zn	Cd	Pb	Fe	Al	As	Hg	Se
Assin Nyakomase		5.75724	-1.29063	0.053	0.092	<0.005	<0.002	0.062	0.526	0.226	<0.001	0.005	0.300
Assin Nyakomase		5.75719	-1.29084	<0.02	0.008	<0.005	<0.002	0.059	0.160	<0.01	<0.001	0.059	0.140
Assin Nyakomase		5.75897	-1.28652	<0.02	0.027	<0.005	<0.002	0.022	0.576	0.251	<0.001	0.005	<0.01
Brofoyedru Habitat	101 BU3	5.73346	-1.28457	0.02	0.013	<0.005	<0.002	0.054	0.075	0.067	<0.001	0.008	<0.01
Akonfude		5.82570	-1.30988	0.02	0.058	<0.005	<0.002	0.026	0.465	0.061	<0.001	0.007	<0.01
Akonfude		5.82950	-1.31011	<0.02	0.035	0.007	<0.002	0.049	0.714	0.055	<0.001	0.005	<0.01
Assin Breku		5.86801	-1.34094	<0.02	0.050	<0.005	<0.002	0.055	0.492	0.237	<0.001	0.004	<0.01
Assin Breku (Gyidi)	102 BU3	5.87059	-1.33603	<0.02	0.400	<0.005	<0.002	0.059	<0.01	<0.01	<0.001	0.003	<0.01
Assin Breku (SDA)	100 BU3	5.86625	-1.33603	<0.02	<0.005	<0.005	<0.002	<0.005	0.156	<0.01	<0.001	0.096	<0.01
Techiman No. 1	396 BU3	5.80432	-1.36792	0.083	0.036	0.010	<0.002	0.039	0.087	0.010	<0.001	0.003	<0.01
Kwame Ankra	411 BU3	5.81542	-1.38199	<0.02	0.043	<0.005	<0.002	0.040	0.044	0.132	<0.001	0.001	<0.01
Ninkyiso		5.82117	-1.39912	<0.02	0.041	<0.005	<0.002	0.036	0.042	<0.01	<0.001	0.002	<0.01
Sabina	380 BU1	5.86974	-1.27172	<0.02	<0.005	<0.005	<0.002	<0.005	0.042	0.019	<0.001	0.001	<0.01
Ayitey	094 BU3	5.88353	-1.25584	<0.02	0.067	<0.005	<0.002	0.014	0.186	<0.01	<0.001	0.003	<0.01
Nkrafo	098 BU3	5.87809	-1.23364	<0.02	0.083	<0.005	<0.002	<0.005	0.068	<0.01	<0.001	0.003	<0.01
Nkrafo	096 BU3	5.88087	-1.23862	<0.02	0.141	<0.005	<0.002	<0.005	0.040	<0.01	<0.001	0.004	<0.01
Obirikwaku	099 BU3	5.91571	-1.23661	0.079	0.258	0.066	<0.002	0.018	0.088	<0.01	<0.001	0.005	<0.01
Odumase Camp	405 BU2	5.82454	-1.19147	<0.02	0.044	<0.005	<0.002	0.048	2.130	0.112	<0.001	0.003	<0.01
Obobakokrowa		5.82490	-1.17768	<0.02	0.096	<0.005	<0.002	0.015	0.249	<0.01	<0.001	0.002	<0.01
Obobakokrowa	246 J BU1	5.83276	-1.17653	<0.02	<0.005	<0.005	<0.002	0.048	0.068	0.081	<0.001	0.002	0.990
Odumase Camp	407 BU2	5.82181	-1.19419	<0.02	<0.005	0.043	<0.002	0.005	0.047	0.195	<0.001	0.002	0.350
Dwedaama		5.90170	-1.20496	<0.02	<0.005	<0.005	<0.002	0.010	0.106	<0.01	<0.001	0.001	0.014
Dwedaama		5.80159	-1.20575	<0.02	0.009	<0.005	<0.002	<0.005	0.409	0.727	<0.001	0.004	<0.01
Amoakokrom	337 BU3	5.85972	-1.25611	<0.02	0.087	<0.005	<0.002	<0.005	0.121	0.119	<0.001	0.004	0.200
WoraKesse Habitat	097 BU3	5.76443	-1.13154	<0.02	<0.005	<0.005	<0.002	<0.005	0.108	0.296	<0.001	0.005	0.200
Antoabasa		5.77196	-1.46878	<0.02	<0.005	0.098	0.0030	<0.005	<0.01	0.182	<0.001	0.003	0.350
Antoabasa		5.77018	-1.46948	<0.02	0.053	<0.005	<0.002	<0.005	0.476	0.179	<0.001	0.001	<0.01

Sample Source	BHID	Longitude	Latitude	Cu	Mn	Zn	Cd	Pb	Fe	Al	As	Hg	Se
Bediadua		5.77278	-1.49722	<0.02	0.071	<0.005	<0.002	<0.005	0.178	0.176	<0.001	0.005	<0.01
Anum	086 BU3	5.78219	-1.50224	<0.02	0.027	<0.005	<0.002	<0.005	0.038	<0.01	<0.001	0.003	<0.01
Kyeikurom	090 BU3	5.82504	-1.52242	<0.02	0.057	<0.005	<0.002	<0.005	0.368	0.162	<0.001	0.003	0.016
Adukurom	088 BU3	5.82278	-1.52444	<0.02	<0.005	<0.005	<0.002	<0.005	0.045	0.399	<0.001	0.003	<0.01
Nsuekyir	219 BU1	5.68667	-1.49722	<0.02	<0.005	<0.005	<0.002	<0.005	0.101	0.157	<0.001	0.003	<0.01
Subriso		5.82474	-1.54799	<0.02	0.006	<0.005	<0.002	0.008	0.101	<0.01	<0.001	0.003	<0.01
Danyiase Domeabra	092 BU3	5.74806	-1.53806	<0.02	0.008	<0.005	<0.002	<0.005	0.924	<0.01	<0.001	0.004	<0.01
Anyinase Ankase	030 BU3	5.59446	-1.60279	<0.02	<0.005	<0.005	<0.002	<0.005	<0.01	<0.01	<0.001	0.002	<0.01
Gromsa	032 BU3	5.58991	-1.60607	0.020	0.093	<0.005	<0.002	<0.005	0.178	0.694	<0.001	0.004	<0.01
Somnyamekodur	048D033 BU3	5.66046	-1.58376	0.020	0.021	0.030	<0.002	<0.005	0.081	0.528	<0.001	0.010	<0.01
Somnyamekordur		5.66046	-1.58376	<0.02	0.021	<0.005	<0.002	<0.005	0.078	0.017	<0.001	0.003	<0.01
Twifo Agona	263 BU2	5.74595	-1.50398	<0.02	0.053	<0.005	<0.002	<0.005	0.181	<0.01	<0.001	0.003	<0.01
Nyamebekyere	339 BU3	5.80139	-1.72139	<0.02	0.047	<0.005	<0.002	<0.005	0.514	0.386	<0.001	0.003	<0.01
Jerusalem	0502B1/6/09701	5.81667	-1.71750	<0.02	0.037	<0.005	<0.002	<0.005	0.220	<0.01	<0.001	0.002	<0.01
Akwa Yaw		5.44157	-1.46580	<0.02	0.069	<0.005	<0.002	<0.005	0.103	0.285	<0.001	0.003	<0.01
Twifo Mampong		5.52016	-1.55449	<0.02	0.089	<0.005	<0.002	<0.005	0.441	0.359	<0.001	0.002	<0.01
Twifo Mampong		5.52359	-1.55681	<0.02	0.073	<0.005	<0.002	0.007	0.150	<0.01	<0.001	<0.01	<0.01
Atu Kurom		5.63657	-1.67850	<0.02	0.261	0.041	<0.002	<0.005	0.186	0.043	<0.001	0.004	<0.01
Subreso	048D035 BU3	5.65596	-1.67676	<0.02	0.103	<0.005	<0.002	<0.005	<0.01	0.123	<0.001	0.002	<0.01
Breman	260 BU2	5.70878	-1.60277	<0.02	0.014	<0.005	<0.002	<0.005	0.113	<0.01	<0.001	0.002	<0.01
Breman		5.70720	-1.60261	<0.02	<0.005	<0.005	<0.002	0.024	0.103	<0.01	<0.001	0.003	<0.01
Zion Camp	014 BU3	5.87217	-1.64602	0.023	0.185	<0.005	<0.002	0.021	0.108	<0.01	<0.001	0.005	<0.01
Mampong	22/D/73-1	5.11147	-1.73174	<0.02	0.682	0.008	<0.002	0.026	0.105	<0.01	<0.001	0.002	<0.01
Essamang		5.05042	-1.67979	<0.02	0.015	<0.005	<0.002	<0.005	0.068	0.162	<0.001	<0.01	<0.01
Mamponso	24/B/85-1	5.42906	-1.63002	<0.02	0.044	<0.005	<0.002	0.031	0.170	0.176	<0.001	<0.01	<0.01
Sienchem	24/B/32-1	5.47123	-1.65053	0.395	0.752	0.314	<0.002	<0.005	0.108	0.072	<0.001	<0.01	<0.01
Sienchem	24/B/32-2	5.47246	-1.65156	<0.02	2.280	<0.005	<0.002	<0.005	0.125	<0.01	<0.001	<0.01	<0.01

All parameters are in mg/L, Longitude (N), Latitude (W)

C-2: Trace metal analyses data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 19th- 23rd September 2011)

Sample source	BHID	Longitude	Latitude	Cd	Mn	Pb	Fe	Se	Zn	Cu	Al	Hg	As
Assin Nyakomase		5.75724	-1.29063	<0.002	0.057	0.009	0.057	0.190	0.036	<0.02	<0.01	0.005	0.001
Assin Nyakomase		5.75719	-1.29084	<0.002	0.051	<0.005	0.079	0.628	0.021	<0.02	0.245	0.005	0.003
Assin Nyakomase		5.75897	-1.28652	<0.002	<0.005	<0.005	0.035	0.330	<0.005	<0.02	0.025	0.005	0.001
Brofoyedru Habitat	101 BU3	5.73346	-1.28457	<0.002	<0.005	0.015	0.017	0.283	<0.005	<0.02	<0.01	0.005	<0.001
Akonfude		5.82570	-1.30988	<0.002	0.134	<0.005	0.030	0.233	0.025	<0.02	<0.01	0.005	<0.001
Akonfude		5.82950	-1.81011	<0.002	0.160	0.011	0.034	<0.010	0.051	<0.02	0.096	0.005	<0.001
Assin Breku		5.86801	-1.34094	<0.002	0.014	0.005	0.098	0.183	0.015	<0.02	0.257	0.005	<0.001
Assin Breku (Gyidi)	102 BU3	5.87059	-1.33603	<0.002	0.054	<0.005	0.032	<0.010	0.048	0.025	<0.01	0.005	<0.001
Assin Breku (SDA)	100 BU3	5.86625	-1.33603	<0.002	0.034	<0.005	0.043	0.607	0.016	<0.02	0.096	0.005	<0.001
Techiman No. 1	396 BU3	5.80432	-1.36792	<0.002	0.008	<0.005	0.040	0.452	0.215	0.311	<0.01	0.003	<0.001
Kwame Ankra	411 BU3	5.81542	-1.38199	<0.002	0.016	<0.005	0.033	0.279	0.010	<0.02	<0.01	0.002	<0.001
Ninkyiso		5.82117	-1.39912	<0.002	0.018	<0.005	0.011	0.207	0.019	<0.02	0.005	0.002	<0.001
Sabina	380 BU1	5.86974	-1.27172	<0.002	0.071	<0.005	0.056	0.471	0.011	<0.02	<0.01	0.002	<0.001
Ayitey	094 BU3	5.88353	-1.25584	<0.002	0.031	<0.005	0.069	0.481	<0.005	0.024	<0.01	0.003	<0.001
Nkrafo	098 BU3	5.87809	-1.23364	<0.002	0.015	<0.005	0.188	0.435	0.006	<0.02	<0.01	0.003	<0.001
Nkrafo	096 BU3	5.88087	-1.23862	<0.002	0.174	<0.005	0.787	0.477	0.203	0.056	0.005	0.004	<0.001
Obirikwaku	099 BU3	5.91571	-1.23661	<0.002	0.141	<0.005	0.075	0.705	0.006	<0.02	<0.01	0.003	<0.001
Odumase Camp	405 BU2	5.82454	-1.19147	<0.002	0.059	<0.005	0.241	0.668	0.080	<0.02	0.205	0.007	0.015
Odumase Camp		5.82490	-1.17768	<0.002	0.267	<0.005	1.905	<0.01	0.011	<0.02	<0.01	0.004	<0.001
Obobakokrowa	246 J BU1	5.83276	-1.17653	<0.002	0.080	<0.005	0.051	0.539	0.163	<0.02	0.089	0.002	<0.001
Obobakokrowa	407 BU2	5.82181	-1.19419	<0.002	0.303	<0.005	0.092	0.087	0.014	<0.02	0.481	0.002	<0.001
Dwedaama		5.90170	-1.20496	<0.002	0.153	0.005	2.488	<0.01	0.007	<0.02	0.066	0.002	0.014
Dwedaama		5.80159	-1.20575	<0.002	0.027	0.019	0.063	0.188	0.106	0.217	<0.01	0.004	<0.001
WoraKesse Habitat	097 BU3	5.76443	-1.13154	<0.002	<0.005	<0.005	0.041	0.241	<0.005	<0.02	<0.01	0.003	0.001
Antoabasa		5.77196	-1.46878	<0.002	<0.005	<0.005	0.157	0.159	0.019	<0.02	<0.01	0.004	<0.001
Antoabasa		5.77018	-1.46948	0.002	0.085	<0.005	0.112	<0.01	0.020	<0.02	0.170	0.002	<0.001
Anum	086 BU3	5.78219	-1.50224	<0.002	0.199	<0.005	1.375	<0.01	0.010	<0.02	<0.01	0.001	0.001

Sample source	BHID	Longitude	Latitude	Cd	Mn	Pb	Fe	Se	Zn	Cu	Al	Hg	As
Adukurom	088 BU3	5.82278	-1.52444	0.003	0.056	<0.005	<0.01	0.124	0.020	<0.02	0.400	0.002	<0.001
Nsuekyir	219 BU1	5.68667	-1.49722	<0.002	0.094	<0.005	0.86	0.006	0.013	<0.02	<0.01	0.002	<0.001
Danyiase Domeabra	092 BU3	5.74806	-1.53806	<0.002	0.093	<0.005	0.054	0.049	0.005	<0.02	0.193	0.002	<0.001
Anyinase Ankase	030 BU3	5.59446	-1.60279	0.003	0.009	<0.005	0.046	0.092	0.062	0.044	0.296	0.002	<0.001
Gromsa	032 BU3	5.58991	-1.60607	<0.002	0.099	<0.005	0.107	0.307	0.040	<0.02	<0.01	0.004	<0.001
Somnyamekodur	048D033 BU3	5.66046	-1.58376	<0.002	0.053	<0.005	0.165	0.403	<0.005	<0.02	0.204	0.003	<0.001
Twifo Agona	263 BU2	5.74595	-1.50398	<0.002	0.038	<0.005	0.408	0.801	0.003	<0.02	<0.01	0.003	<0.001
Nyamebekyere	339 BU3	5.80139	-1.72139	0.002	0.009	0.012	0.021	0.124	0.012	<0.02	<0.01	0.001	<0.001
Jerusalem	0502B1/6/09701	5.81667	-1.71750	0.003	0.008	0.005	<0.01	0.493	<0.005	0.034	<0.01	0.002	0.001
Mampong	22/D/73-1	5.11147	-1.73174	<0.002	0.043	0.008	0.067	0.047	0.047	0.030	<0.01	0.002	0.004
Essamang		5.05042	-1.67979	<0.002	0.553	0.008	0.054	0.114	0.021	<0.02	<0.01	0.002	<0.001
Mamponso	24/B/85-1	5.42906	-1.63002	0.002	0.046	0.018	0.033	0.048	0.039	0.025	0.268	0.002	<0.001
Sienchem	24/B/32-1	5.47123	-1.65053	<0.002	0.227	0.014	0.015	<0.01	0.031	0.023	<0.01	0.002	<0.001
Sienchem	24/B/32-2	5.47246	-1.65156	<0.002	0.304	0.011	0.089	0.127	0.016	0.035	<0.01	0.143	<0.001

All parameters are in mg/L, Longitude (N), Latitude (W)

C-3: Trace metal analyses data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 24th – 28th January 2012)

Sample Source	BHID	GPS Co-ordinates	Cu	Cd	Mn	Fe	Pb	Hg	Se	Zn	Al	As
WoraKesse Habitat	097BU3	N05.75829' , W001.28643'	<0.02	<0.002	0.18	1.09	0.005	0.005	0.008	0.062	0.213	<0.001
Brofoyedru Habitat	101BU3	N05.75762' , W001.29058'	<0.02	<0.002	0.017	0.151	<0.005	0.008	0.004	<0.005	<0.01	<0.001
Akonfude		N05.75729' , W001.29082'	<0.02	<0.002	0.084	0.313	<0.005	<0.01	0.022	0.029	<0.01	<0.001
Akonfude		N05.82570' , W001.30988'	<0.02	<0.002	0.138	0.029	<0.005	0.005	0.003	<0.005	<0.01	0.015
Akonfude		N05.82614' , W001.30953'	<0.02	<0.002	0.211	<0.01	<0.005	0.005	0.002	0.051	<0.01	<0.001
Nkrafo		N05.82945' , W001.31011'	<0.02	<0.002	<0.005	<0.01	<0.005	0.005	0.006	<0.005	<0.01	<0.001
Nkrafo	098BU3	N05.87813' , W001.23365'	<0.02	<0.002	0.033	0.677	<0.005	0.001	0.000	<0.005	0.297	<0.001
Obirikwaku	096BU3	N05.88086' , W001.23863'	<0.02	<0.002	0.072	0.189	0.008	0.002	0.007	<0.005	0.089	<0.001
Odumase Camp	099BU3	N05.91570' , W001.23361'	<0.02	<0.002	<0.005	<0.01	<0.005	<0.01	0.007	<0.005	<0.01	<0.001
Obobakokrowa	405BU2	N05.82454' , W001.19149'	<0.02	<0.002	0.094	<0.01	<0.005	<0.01	0.002	0.353	<0.01	0.001
Odumase Camp		N05.83490' , W001.17768'	<0.02	<0.002	0.338	<0.01	0.012	<0.01	0.003	0.006	<0.01	0.006
Dwedaama	407BU2	N05.19421' , W001.19421'	0.067	<0.002	0.041	<0.01	<0.005	0.001	0.004	<0.005	<0.01	0.001
Dwedaama		N05.80162' , W001.20490'	<0.02	<0.002	<0.005	<0.01	0.013	0.001	0.008	0.009	<0.01	<0.001
Assin Nyankomase		N05.75724' , W001.29036'	<0.02	<0.002	0.039	<0.01	<0.005	<0.01	0.005	0.028	<0.01	<0.001
Assin Nyankomase		N05.75719' , W001.29084'	<0.02	<0.002	0.102	0.210	0.013	<0.01	0.008	0.074	0.562	<0.001
Assin Nyankomase		N05.75897' , W001.28657'	<0.02	<0.002	0.007	0.079	0.009	<0.01	0.007	<0.005	0.370	0.010
Amoakokrom	102BU3	N05.87056' , W001.33793'	<0.02	0.002	0.039	<0.01	0.019	<0.01	0.002	0.052	<0.01	<0.001
Nyamebekyere	100BU3	N05.86625' , W001.33689'	0.032	<0.002	<0.005	<0.01	0.018	<0.01	0.007	0.073	0.112	<0.001
Jerusalem		N05.86808' , W001.34099'	<0.02	<0.002	<0.005	<0.01	0.013	<0.01	0.008	0.033	0.032	<0.001
Antoabasa	411BU2	N05.81540' , W001.38197'	<0.02	<0.002	0.028	0.416	0.008	<0.01	0.006	0.024	0.031	<0.001
Antoabasa	396BU2	N05.80440' , W001.36794'	<0.02	<0.002	0.083	<0.01	0.013	<0.01	0.003	0.017	0.065	<0.001
Anum		N05.812119' W001.39917'	<0.02	<0.002	0.231	0.739	<0.005	<0.01	0.003	0.005	0.060	<0.001
Kyeikurom		N05.86974' ,W001.27172'	<0.02	<0.002	0.010	<0.01	0.028	<0.01	0.007	0.020	<0.01	<0.001
Adukurom	094BU3	N05.88353' , W001.25584'	<0.02	<0.002	<0.005	<0.01	<0.005	<0.01	0.001	0.017	0.119	0.001
Subriso	337BU3	N05.78654' , W001.34582'	0.236	<0.002	0.594	0.145	0.046	<0.01	0.001	0.563	0.101	0.001
Nsuekyir	339BU3	N05.76558' , W001.34666'	<0.02	<0.002	0.007	<0.010	0.010	<0.01	0.007	<0.005	0.065	0.006
Danyease Domeabra		N05.75216' , W001.44366'	<0.02	<0.002	0.064	<0.010	<0.005	<0.01	0.003	<0.005	0.109	<0.001
Bediadua		N05.82614' , W001.30953'	0.020	<0.002	<0.005	<0.010	0.007	<0.01	0.008	<0.005	<0.01	0.001
Assin Breku (SDA)		N05.82945' , W001.31011'	<0.02	<0.002	<0.005	<0.010	0.023	<0.01	0.001	<0.005	<0.01	0.001

Sample Source	BHID	GPS Co-ordinates	Cu	Cd	Mn	Fe	Pb	Hg	Se	Zn	Al	As
Assin Breku		N05.82504' , W001.52242'	<0.02	<0.002	<0.005	<0.01	<0.005	<0.01	0.025	<0.005	0.031	<0.001
Kwame Ankra	088BU3	N05.84924' , W001.52394'	<0.02	<0.002	<0.005	<0.01	<0.005	<0.01	0.010	<0.005	<0.01	<0.001
Techiman No. 1		N05.82474' , W001.54799'	<0.02	<0.002	<0.005	<0.01	0.023	<0.01	0.001	<0.005	<0.01	0.001
Ninkyiso	219BU1	N05.77244' , W001.50221'	<0.02	<0.002	<0.005	<0.01	0.008	<0.01	0.008	0.034	<0.01	<0.001
Sabina	093BU3	N05.74806' , W001.53606'	<0.02	<0.002	0.052	<0.01	0.028	<0.01	0.009	<0.005	0.081	0.003
Ayitey		N05.77497' , W001.49742'	<0.02	0.002	0.051	0.494	0.015	<0.01	0.009	0.042	0.054	0.005
Gromsa		N05.59000' , W001.60611'	<0.02	<0.002	0.097	<0.01	<0.005	<0.01	0.005	<0.005	<0.01	0.0008
Atu Kurom		N05.60612' , W001.67843'	<0.02	<0.002	0.201	<0.01	0.008	<0.01	0.012	0.147	0.224	<0.001
Subreso		N05.65596' , W001.67676'	0.036	<0.002	0.232	2.430	0.014	<0.01	0.001	0.085	<0.01	0.001
Anyinase Ankase	030BU3	N05.59646' , W001.60273'	0.043	<0.002	0.025	0.016	0.022	<0.01	0.002	0.057	0.054	<0.001
Somnyamekordur	138BU1	N05.66454' , W001.58470'	<0.02	<0.002	<0.005	<0.01	<0.005	<0.01	0.001	<0.005	<0.01	0.005
Somnyamekordur	033BU3	N05.66044' , W001.58376'	<0.02	<0.002	0.199	0.363	<0.005	<0.01	0.004	0.029	0.197	<0.001
Breman	260BU2	N05.70882' , W001.60273'	<0.02	<0.002	0.178	0.275	<0.005	0.003	0.010	0.008	<0.01	<0.001
Breman		N05.70720' , W001.60270'	0.022	<0.002	0.132	1.340	<0.005	0.003	0.008	0.031	0.014	<0.001
Twifo Agona	236BU2	N05.74540' , W001.50387'	<0.02	<0.002	0.041	0.230	<0.005	0.001	0.001	0.027	0.060	<0.001
Zion Camp	014BU3	N05.87221' , W001.64609'	0.026	<0.002	0.041	<0.01	0.008	<0.01	0.008	0.011	<0.01	<0.001
Twifo Mampong		N05.52361' , W001.55671'	<0.02	<0.002	0.006	0.111	0.011	0.001	0.000	0.149	0.138	0.005
Twifo Mampong		N05.52316' , W001.55452'	0.026	<0.002	0.085	0.099	<0.005	0.001	0.005	0.308	0.018	<0.001
Akwa Yaw		N05. 44168' ,W001.48580'	<0.02	<0.002	0.028	0.036	0.009	<0.01	0.001	0.134	<0.01	<0.001
Mampong		N05.11146' , W001.73174'	<0.02	<0.002	0.234	1.840	<0.005	0.001	0.001	0.228	0.107	0.001
Essamang		N05.35041' , W001.67974'	0.076	<0.002	0.051	0.547	<0.005	0.003	0.011	0.178	0.090	<0.001
Mamponso	24-B-851	N05.42904' , W001.62996'	0.043	<0.002	0.481	0.281	<0.005	0.010	0.001	0.130	0.010	<0.001
Sienchem	24/B/32/1	N05.47246' , W001.65157'	0.112	<0.002	0.281	0.664	0.021	0.012	0.010	0.083	0.074	<0.001
Sienchem	24/B/32/1	N05.47117' , W001.65056'	0.036	<0.002	0.323	<0.01	<0.005	0.011	0.001	0.006	<0.01	<0.001

All parameters are in mg/L

C-4: Trace metal analyses data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 19th – 23rd June 2012)

Sample Source	BHID	Longitude	Latitude	Cu	Mn	Zn	Cd	Pb	Fe	Al	Hg	Se	As
Assin Nyakomase		5.75724	-1.290630	0.053	0.092	<0.005	<0.002	0.062	0.526	0.226	0.005	0.010	<0.001
Assin Nyakomase		5.75719	-1.290840	<0.02	0.008	<0.005	<0.002	0.059	0.160	<0.01	0.006	0.005	<0.001
Assin Nyakomase		5.75897	-1.286520	<0.02	0.027	<0.005	<0.002	0.022	0.576	0.251	0.005	<0.01	<0.001
Brofoyedru Habitat	101 BU3	5.73346	-1.284570	0.020	0.013	<0.005	<0.002	0.054	0.075	0.067	0.008	<0.01	<0.001
Akonfude		5.82570	-1.309880	0.020	0.058	<0.005	<0.002	0.026	0.465	0.061	0.007	<0.01	<0.001
Akonfude		5.82950	-1.310110	<0.02	0.035	0.007	<0.002	0.049	0.714	0.055	0.004	<0.01	<0.001
Assin Breku		5.86801	-1.340940	<0.02	0.050	<0.005	<0.002	0.055	0.492	0.237	0.004	<0.01	<0.001
Assin Breku (Gyidi)	102 BU3	5.87059	-1.336030	<0.02	0.400	<0.005	<0.002	0.059	<0.01	<0.01	0.003	<0.01	<0.001
Assin Breku (SDA)	100 BU3	5.86625	-1.336030	<0.02	<0.005	<0.005	<0.002	0.038	0.156	<0.01	0.001	<0.01	<0.001
Techiman No. 1	396 BU3	5.80432	-1.367920	0.083	0.036	0.010	<0.002	0.039	0.087	0.010	0.002	<0.01	<0.001
Kwame Ankra	411 BU3	5.81542	-1.381990	<0.02	0.043	<0.005	<0.002	0.040	0.044	0.132	0.001	<0.01	<0.001
Ninkyiso		5.82117	-1.399120	<0.02	0.041	<0.005	<0.002	0.036	0.042	<0.01	0.001	<0.01	<0.001
Sabina	380 BU1	5.86974	-1.271720	<0.02	<0.005	<0.005	<0.002	<0.005	0.042	0.019	0.001	<0.01	<0.001
Ayitey	094 BU3	5.88353	-1.255840	<0.02	0.067	<0.005	<0.002	0.014	0.186	<0.01	0.008	<0.01	<0.001
Nkrafo	098 BU3	5.87809	-1.233640	<0.02	0.083	<0.005	<0.002	<0.005	0.068	<0.01	0.008	<0.01	<0.001
Nkrafo	096 BU3	5.88087	-1.238620	<0.02	0.141	<0.005	<0.002	<0.005	0.040	<0.01	0.004	<0.01	<0.001
Obirikwaku	099 BU3	5.91571	-1.236610	0.079	0.258	0.066	<0.002	0.018	0.088	<0.01	0.005	<0.01	<0.001
Odumase Camp	405 BU2	5.82454	-1.191470	<0.02	0.044	<0.005	<0.002	0.048	2.130	0.112	0.002	<0.01	<0.001
Obobakokrowa		5.82490	-1.177680	<0.02	0.096	<0.005	<0.002	0.015	0.249	<0.01	0.001	<0.01	<0.001
Obobakokrowa	246 J BU1	5.83276	-1.176530	<0.02	<0.005	<0.005	<0.002	0.048	0.068	0.081	0.002	0.001	<0.001
Odumase Camp	407 BU2	5.82181	-1.194190	<0.02	<0.005	0.043	<0.002	0.005	0.047	0.195	0.002	0.001	<0.001
Dwedaama		5.90170	-1.204960	<0.02	<0.005	<0.005	<0.002	0.010	0.106	<0.01	0.001	0.001	<0.001
Dwedaama		5.80159	-1.205750	<0.02	0.009	<0.005	<0.002	<0.005	0.409	0.727	0.004	<0.01	<0.001
Amoakokrom	337 BU3	5.85972	-1.256110	<0.02	0.087	<0.005	<0.002	<0.005	0.121	0.118	0.004	0.001	<0.001
WoraKesse Habitat	097 BU3	5.76443	-1.131540	<0.02	<0.005	<0.005	<0.002	<0.005	0.108	0.296	0.004	0.001	<0.001
Antoabasa		5.77196	-1.468780	<0.02	<0.005	0.098	0.003	<0.005	<0.01	0.182	0.002	0.001	0.001
Antoabasa		5.77018	-1.469480	<0.02	0.053	<0.005	<0.002	<0.005	0.476	0.179	0.004	<0.01	0.001
Bediadua		5.77278	-1.497220	<0.02	0.071	<0.005	<0.002	<0.005	0.178	0.176	0.006	<0.01	0.001

Sample Source	BHID	Longitude	Latitude	Cu	Mn	Zn	Cd	Pb	Fe	Al	Hg	Se	As
Kyeikurom	090 BU3	5.82504	-1.522420	<0.02	0.057	<0.005	<0.002	<0.005	0.368	0.162	0.001	0.001	<0.001
Adukurom	088 BU3	5.82278	-1.524440	<0.02	<0.005	<0.005	<0.002	<0.005	0.045	0.399	0.001	<0.01	<0.001
Nsuekyir	219 BU1	5.68667	-1.497220	<0.02	<0.005	<0.005	<0.002	<0.005	0.101	0.157	0.002	<0.01	<0.001
Subriso		5.82474	-1.547990	<0.02	0.006	<0.005	<0.002	0.008	0.101	<0.01	0.002	<0.01	<0.001
Danyiase Domeabra	092 BU3	5.74806	-1.538060	<0.02	0.008	<0.005	<0.002	<0.005	0.924	<0.01	0.004	<0.01	<0.001
Anyinase Ankase	030 BU3	5.59446	-1.602790	<0.02	<0.005	<0.005	<0.002	<0.005	<0.01	<0.01	0.002	<0.01	<0.001
Gromsa	032 BU3	5.58991	-1.606070	0.020	0.093	<0.005	<0.002	<0.005	0.178	0.694	0.004	<0.01	<0.001
Somnyamekordur	048D033 BU3	5.66046	-1.583760	0.020	0.021	0.030	<0.002	<0.005	0.081	0.528	0.010	<0.01	<0.001
Somnyamekordur		5.66046	-1.583760	<0.02	0.021	<0.005	<0.002	<0.005	0.078	0.017	0.006	<0.01	<0.001
Twifo Agona	263 BU2	5.74595	-1.503980	<0.02	0.053	<0.005	<0.002	<0.005	0.181	<0.01	0.003	<0.01	<0.001
Nyamebekyere	339 BU3	5.80139	-1.721390	<0.02	0.047	<0.005	<0.002	<0.005	0.514	0.386	0.007	<0.01	<0.001
Jerusalem	0502B1/6/09701	5.81667	-1.717500	<0.02	0.037	<0.005	<0.002	<0.005	0.220	<0.01	0.004	<0.01	<0.001
Akwa Yaw		5.44157	-1.465800	<0.02	0.069	<0.005	<0.002	<0.005	0.103	0.285	0.003	<0.01	<0.001
Twifo Mampong		5.52016	-1.554490	<0.02	0.089	<0.005	<0.002	<0.005	0.441	0.359	0.003	<0.01	<0.001
Twifo Mampong		5.52359	-1.556810	<0.02	0.073	<0.005	<0.002	0.007	0.150	<0.01	<0.01	<0.01	<0.001
Atu Kurom		5.63657	-1.678500	<0.02	0.261	0.041	<0.002	<0.005	0.186	0.043	0.002	<0.01	0.01
Subreso	048D035 BU3	5.65596	-1.676760	<0.02	0.103	<0.005	<0.002	<0.005	2.530	0.123	0.002	<0.01	0.003
Breman	260 BU2	5.70878	-1.602770	<0.02	0.014	<0.005	<0.002	<0.005	0.113	<0.01	0.001	<0.01	0.002
Breman		5.70720	-1.602610	<0.02	<0.005	<0.005	<0.002	0.024	0.103	<0.01	0.005	<0.01	0.002
Zion Camp	014 BU3	5.87217	-1.646020	0.023	0.185	<0.005	<0.002	0.021	0.108	<0.01	0.005	<0.01	0.002
Mampong	22/D/73-1	5.111470	-1.731740	<0.02	0.682	0.008	<0.002	0.026	0.105	<0.01	0.005	<0.01	0.002
Essamang		5.05042	-1.679790	<0.02	0.015	<0.005	<0.002	<0.005	0.068	0.162	<0.01	<0.01	<0.001
Mamponso	24/B/85-1	5.42906	-1.630020	<0.02	0.044	<0.005	<0.002	0.031	0.170	0.176	<0.01	<0.01	<0.001
Sienchem	24/B/32-1	5.47123	-1.650530	0.395	0.752	0.314	<0.002	<0.005	0.108	0.072	<0.01	<0.01	<0.001
Sienchem	24/B/32-2	5.47246	-1.651560	<0.02	2.280	<0.005	<0.002	<0.005	0.125	<0.01	<0.01	<0.01	<0.001

All parameters are in mg/L, Longitude (N), Latitude (W)

C-5: Trace metal analyses data for groundwater within the Lower Pra Basin and their GPS Co-ordinates (Sampling Dates: 23rd – 27th October 2012)

Sample source	BH ID	Longitude	Latitude	Fe	Cu	Mn	Cd	Zn	Al	Pb	Hg	Se	As
Sabina	380 BU1	5.86974	-1.27172	0.077	<0.02	0.182	0.006	0.013	<0.01	0.055	<0.01	<0.01	0.005
Ayitey	094 BU3	5.88353	-1.25584	0.102	<0.02	0.043	<0.002	0.007	<0.01	0.059	<0.01	<0.01	0.001
Nkrafo	098 BU3	5.87809	-1.23364	0.505	<0.02	0.058	<0.002	<0.005	<0.01	0.050	<0.01	<0.01	0.002
Nkrafo	096 BU3	5.88087	-1.23862	0.013	<0.02	0.023	<0.002	<0.005	<0.01	0.056	<0.01	<0.01	0.002
Obirikwaku	099 BU3	5.91571	-1.23661	0.151	0.051	0.116	<0.002	0.068	<0.01	0.034	<0.01	<0.01	0.004
Odumase Camp	405 BU2	5.82454	-1.19147	0.668	<0.02	0.164	<0.002	0.073	<0.01	0.065	<0.01	<0.01	<0.001
Odumase Camp	407 BU2	5.82181	-1.19419	0.038	<0.02	0.322	<0.002	0.246	<0.01	<0.005	<0.01	<0.01	<0.001
Obobakokrowa	246 J BU1	5.82490	-1.17768	0.049	0.074	0.165	<0.002	0.162	<0.01	0.078	<0.01	<0.01	<0.001
Dwedaama		5.90170	-1.20496	1.890	<0.02	0.458	<0.002	0.013	0.035	<0.005	<0.01	<0.01	<0.001
Dwedaama		5.80159	-1.20575	0.144	0.191	0.031	<0.002	0.094	0.228	<0.005	<0.01	<0.01	<0.001
WoraKesse Habitat	097 BU3	5.76443	-1.13154	<0.01	<0.02	0.008	<0.002	0.005	0.063	<0.005	<0.01	<0.01	<0.001
Brofoyedru Habitat	101 BU3	5.73346	-1.28457	<0.01	0.057	0.009	0.005	0.011	0.013	0.075	0.015	<0.01	<0.001
Assin Nyankomase		5.75724	-1.29063	0.024	0.087	0.010	0.005	0.012	0.023	<0.005	0.002	<0.01	<0.001
Assin Nyankomase		5.75719	-1.29084	0.061	0.031	0.062	<0.002	0.035	0.499	0.024	0.051	<0.01	<0.001
Assin Nyankomase		5.75897	-1.28652	0.032	<0.02	0.111	0.01	0.042	0.468	<0.005	<0.01	<0.01	<0.001
Akonfude		5.82570	-1.30988	0.067	0.072	0.162	0.007	0.033	0.079	0.032	<0.01	<0.01	<0.001
Akonfude		5.82950	-1.31011	0.027	0.024	0.256	0.008	0.062	0.175	<0.005	<0.01	<0.01	<0.001
Assin Breku (Gyidi)	102 BU3	5.87059	-1.33603	0.483	<0.02	0.132	0.008	0.019	0.027	0.037	0.010	<0.01	<0.001
Assin Breku		5.86801	-1.34094	<0.01	0.093	0.024	0.004	0.005	0.039	<0.005	<0.01	<0.01	<0.001
Techiman No.1	396 BU3	5.80432	-1.36792	0.028	0.166	0.009	0.007	0.191	0.134	0.010	<0.01	<0.01	<0.001
Kwame Ankra	411 BU3	5.81542	-1.38199	0.019	0.031	0.031	0.006	0.019	0.096	0.056	<0.01	<0.01	<0.001
Ninkyiso		5.82117	-1.39912	0.015	<0.02	0.017	0.004	0.019	0.497	0.026	<0.01	<0.01	0.001
Amoakokrom	338 BU3	5.85972	-1.25611	0.028	0.060	0.110	0.012	0.264	0.099	<0.005	0.001	0.007	<0.001
Nyamebekyere	339 BU3	5.80139	-1.72139	0.056	<0.02	0.049	0.009	0.027	0.129	0.023	0.001	<0.01	0.001
Jerusalem	0502B1/6/097-01	5.81667	-1.71750	0.035	0.119	0.031	0.006	0.183	0.025	0.011	0.002	0.007	<0.001
Antoabasa		5.77196	-1.46878	0.021	<0.02	0.014	0.011	0.012	0.147	<0.005	0.003	0.007	<0.001
Antoabasa		5.77018	-1.46948	0.035	<0.02	0.072	0.016	0.025	0.132	0.016	0.001	<0.01	<0.001
Bediedua		5.77278	-1.49722	0.041	0.021	0.045	0.011	0.028	0.091	<0.005	<0.01	0.006	<0.001

Sample source	BH ID	Longitude	Latitude	Fe	Cu	Mn	Cd	Zn	Al	Pb	Hg	Se	As
Nsuekyir	219 BU1	5.68667	-1.49722	0.192	<0.02	0.043	<0.002	0.027	0.057	<0.005	<0.01	0.007	0.002
Denyease Domeabra	092 BU3	5.74806	-1.53806	0.125	<0.02	0.126	0.009	0.014	0.197	0.042	<0.01	<0.01	<0.001
Twifo Mampong		5.52016	-1.55449	0.034	<0.02	0.101	0.01	0.027	0.044	<0.005	<0.01	0.007	<0.001
Twifo Mampong		5.52359	-1.55681	0.018	<0.02	<0.005	0.011	0.046	0.064	<0.005	<0.01	<0.01	<0.001
Breman	260 BU2	5.70878	-1.60277	2.91	0.053	1.544	<0.002	0.032	0.019	0.03	0.002	0.001	<0.001
Breman		5.70720	-1.60261	1.48	<0.02	0.523	0.003	0.016	<0.01	0.043	0.005	<0.01	0.001
Twifo Agona	263 BU2	5.74595	-1.50398	0.135	<0.02	0.071	0.002	0.024	<0.01	<0.005	0.002	<0.01	0.001
Somnyamekordur	048D033 BU3	5.66046	-1.58376	0.459	0.041	0.169	0.006	0.009	0.179	0.033	0.001	<0.01	<0.001
Somnyamekordur		5.66046	-1.58376	0.334	<0.02	0.095	0.005	0.029	0.168	0.118	0.010	0.002	0.001
Atu Kurom		5.63657	-1.67850	0.406	0.027	0.202	<0.002	0.082	0.567	0.05	0.008	<0.01	<0.001
Subreso	048D035 BU3	5.65596	-1.67676	2.24	<0.02	0.839	<0.002	0.096	0.19	0.005	0.001	0.009	<0.001
Gromsa	032 BU3	5.58991	-1.60607	0.115	0.078	0.169	<0.002	0.034	0.127	0.03	0.016	0.002	<0.001
Anyinase Ankase	030 BU3	5.59446	-1.60279	0.015	0.015	0.041	<0.002	0.062	<0.01	<0.005	0.001	0.001	<0.001
Sienkyem	24/B/32-1	5.47123	-1.65053	0.035	0.048	0.155	<0.002	0.018	0.031	0.009	0.008	<0.01	<0.001
Sienkyem	24/B/32-2	5.47246	-1.65156	0.043	<0.02	0.983	0.004	0.107	0.185	0.035	0.000	0.001	<0.001
Mamponso	24/B/85-1	5.42906	-1.63002	0.232	0.028	0.133	0.002	<0.005	0.182	0.112	<0.01	<0.01	<0.001

All parameters are in mg/L, Longitude (N), Latitude (W)

APPENDIX D: QUESTIONNAIRE ON WATER RESOURCES AVAILABILITY, USAGE, ASSOCIATED PROBLEMS AND HEALTH IMPACT.

This study is the social impact component of a 3-year PhD (Environmental Science) study on **"Hydrogeochemical Processes influencing groundwater quality within the Lower Pra Basin Ghana"** which commenced in January 2011 at the Institute of Environmental and Sanitation Studies, University of Ghana. Any information provided would be treated exclusively as academic and would not be made public. Please spend the next 10 to 15 minutes of your time to respond to the questions that borders on the use of groundwater for drinking and other domestic purposes within the Lower Pra Basin. We assure you of your utmost privacy.

Thank you very much for your co-operation.

SECTION A: WATER RESOURCES AVAILABILITY, USAGE AND ASSOCIATED PROBLEMS

1. Age: 5-17 [ ] 18-30 [ ] 31-40 [ ] above 40 [ ]
2. Sex: Female [ ] Male [ ]
3. Educational Background: None [ ] Primary [ ] Secondary [ ] Tertiary [ ]
4. Marital Status: Single [ ] Married [ ] Divorced [ ]
5. Occupation: Farmer [ ] Trader [ ] Miner [ ]
   Others, Please, specify……………………………………………………………………
6. How long have you been in the area? 1-10yrs [ ] 11-20yrs [ ] 21-30yrs [ ]
   31- 40 yrs [ ] above 40yrs [ ]
7. How many water sources do you have in the area? One [ ] Two [ ] Three [ ]
8. What is the main source of drinking water in the area? Stream [ ] River [ ] Well [ ]
   Borehole [ ] Harvested rainwater [ ]
9. What do you use the water for? Drinking [ ] Washing [ ] Bathing [ ]
   Cooking [ ] All Purpose [ ]
10. Do you drink water from the River/Stream raw without treatment? YES [ ] NO [ ]
11. If your answer to Ques 10 is YES, Do you know the consequences? YES [ ] NO [ ]
12. What informs your choice of the source? The only source [ ] Availability [ ]
    Distance [ ] Water Quality [ ] Poverty [ ]

13. What is your level of usage of the borehole?

    High [ ] Moderately High [ ] Very High [ ]

14. What in your opinion is the quality (taste) of the borehole? Salty [ ] Good [ ] very Good [ ] Excellent [ ]

15. Do you pay for water from the borehole? YES [ ] NO [ ]

16. If your answer to Question 15 is YES, how much do you pay per bucket?

    Ten Pesewa [ ] Twenty Pesewa [ ]

    Others, Please specify……………………………………..

17. Do you consider the price to be high? YES [ ] NO [ ]

18. If you have other alternatives such as Streams/ Rivers, would you have patronize the Borehole water? YES [ ] NO [ ]

19. If your answer to Ques 18 is YES, Why? Due to its; Taste [ ] Price [ ] Distance from home [ ] Others, Please specify……………………………………………

20. Did you used to have other sources of water in the area? YES [ ] NO [ ]

21. If your answer to Ques 20 is YES, what happened to those sources of water?

    Contamination from farming activities [ ] Contamination from mining activities [ ]

    Dried up [ ] Still available and being used [ ]

    Others, Please specify………………………

22. How are solid wastes disposed off in the area?

    Around the house/compound [ ] Disposal site [ ] Dumped in open pits [ ]

    By burning [ ] Others, Please specify………………………………………

23. How close is the disposal site from the Stream/Borehole/River?

    20m [ ] 40m [ ] 60m [ ] 80m [ ] 100m [ ] over 100m [ ]

24. What type of toilet facility do you have in the area?

    Own pit latrine [ ] Public pit latrine [ ] Water Closet [ ] Open defecation [ ]

25. How far away is the toilet facility from the River/Stream/Borehole?

    20m [ ] 40m [ ] 60m [ ] 80m [ ] 100m [ ] over 100m [ ]

26. Are farming activities taking place along the River/Stream? YES [ ] NO [ ]

27. Do the farmers use pesticides/ agro-chemicals? YES [ ] NO [ ]

28. What in your view are the ways of borehole water contamination in the area?

    Farming [ ] Mining [ ]

    Others, Please specify……………………………….......................................

29. Is your borehole fitted with hand pump or foot pump?

    Hand pump [ ] Foot pump [ ]

30. Do you have any problem with the hand/foot pump? YES [ ] NO [ ]

31. If your answer to Ques 30 is YES, what is the nature of the problem?

    Hand pump out of order [ ] Foot pump out of order [ ]

    Doping with water for several minutes [ ]

    Others, Please specify ………………………………………………………………

32. Do you prefer hand pump to the foot pump? YES [ ] NO [ ]

33. If your answer to Ques 32 is YES, WHY?

    Due to doping [ ] pumping for several minutes prior to abstraction [ ]

    Others, Please specify………………………………………………………………

34. Do you wish that Government/ NGO changes the foot pump to hand pump?

    YES [ ] NO [ ]

35. In your view do you think that the area needs additional borehole?

    YES [ ] NO [ ]

SECTION B: HEALTH IMPACT OF AVAILABLE DRINKING WATER WITHIN THE BASIN.

1. Do you have a medical facility in the area? YES [ ] NO [ ]
2. How far away is this medical facility from the area?

   Less than 5 km [ ] 5-10 km [ ] Greater than 10 km [ ]
3. Have you /any member of your family visited the medical facility? YES [ ] NO [ ]
4. If your answer to Ques 3 is YES, what disease were you / family member diagnosed of?

   Diarrhoea [ ] kidney damage [ ] Brain/nervous breakdown [ ]

   Abdominal discomfort [ ] Loss of hair/finger nails [ ] Numbness in fingers/toes [ ]

   Alzheimer's disease [ ] Dialysis dementia [ ]

   Others, please specify………………………………………………………………
5. What disease is prevalent in this area? Malaria [ ] Diarrhoea [ ] Typhoid [ ]

   Others, Please specify………………………………………………………………
6. What in your opinion do you think are the causes of this disease?

   Drinking water contamination [ ] unknown [ ]

7. Do you think this disease can be prevented? YES [ ] NO [ ]

8. If your answer to Ques 7 is YES, HOW?
   Citing farm lands far away from water source [ ]
   Citing mining (“large-scale’) activities far away from water source [ ]
   Citing dumping sites far away from water source [ ] Avoiding Galamsey activities [ ]
   Others, please specify..
9. What in your opinion do you think is the major environmental issue in this community?
   Poor sanitation [ ] Water contamination [ ]
   Others, Please specify…………………………..
10. What do you think is the cause of this problem?
    Bad farming practices [ ] mining activities e.g. ‘Galamsey’ [ ]
    Others, Please specify ………………………………...
11. What in your opinion do you think can be done to prevent contamination of Borehole water?
    ....
    ……………………………………………………………………………………………
    ……………………………………………………………………………………………

APPENDIX E: METHODS OF MEASUREMENT OF HYDROCHEMICAL CONSTITUENTS.

1. Measurement of Total hardness

50 ml of the sample was pipetted or an aliquot made up to 50 ml into a conical flask. 1ml of buffer solution was added to produce a pH of 10.0 (± 0.1). A few crystals (0.1- 0.2 g) of Eriochrome Black T Indicator were then added and the contents constantly mixed. The resulting solution was then titrated against standard 0.01M Ethylenediaminetetraacetic acid (EDTA) until the last trace of purple disappeared or the colour turned bright blue. For quality control (QC) and quality assurance (QA), after every batch of 5 samples a duplicate was prepared and analysed together with the samples. The end point of duplicate determinations was within ± 0.1 ml.

Additionally, a control standard (20 mg/L Ca) was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 25, 2010).

Calculation of results:

$$\text{Total hardness} = \frac{\text{ml EDTA x B x 1000}}{\text{ml of sample}}$$

where, B = mg of $CaCO_3$ equivalent to 1.00 ml EDTA titrant

$$\text{i.e., } \frac{\text{ml of EDTA}}{\text{ml of } CaCO_3}$$

2. Measurements of Alkalinity and bicarbonate

100 ml of sample was mixed with two to three drops of phenolphthalein indicator in a conical flask. If no colour change was produced, then alkalinity to phenolphthalein was zero. If the sample turned pink or red, then the alkalinity to phenolphthalein was determined by titration against standard acid until the pink colour just disappeared. In both cases, a few drops of methyl

orange indicator was added. If the sample turns orange without the addition of the standard acid, the total alkalinity was zero. If the sample turned yellow, the resulting solution was titrated with standard acid until the first perceptible colour change towards orange took place.

For quality control (QC) and quality assurance (QA), after every batch of 10 samples, a duplicate was prepared and analysed together with the samples. The end point of duplicate determination was within ± 0.1 ml. Additionally, a control standard (50 mg $NaCO_3$/L) was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 22, 2010).

Calculation of results:

Phenolphthalein alkalinity as $CaCO_3$ (P) = $\frac{50{,}000 \times A \times N \text{ mg/l}}{V}$

Total alkalinity as $CaCO_3$ (T) = $\frac{50{,}000 \times B \times N \text{ mg/l}}{V}$

If, Phenolphthalein alkalinity (P) = 0, then, bicarbonate is total alkalinity (T)

If, Phenolphthalein alkalinity (P) < ½ T, then, bicarbonate equals the difference between total alkalinity (T) and 2 × Phenolphthalein alkalinity (P) (i.e. bicarbonate = T-2P)

If, Phenolphthalein alkalinity (P) = ½ T, T or > ½ T, then, bicarbonate = 0

where, A = ml of standard acid solution added to obtain the phenolphthalein end-point of 8.3,

B = ml of standard acid solution added to obtain the methyl orange end-point of 4.5 pH,

N = Normality of the mineral acid,

V = volume of sample used.

3. Measurement of Total Dissolved Solids

The sample to be determined was vigorously shaken and a measured volume (to yield between 10 and 200 mg dried residue) was rapidly transferred into a funnel by means of a 100 ml graduated cylinder. The sample was then, filtered through a glass fibre filter and vacuum was continuously applied for about 3 minutes after filtration to ensure that as much water was removed as possible. The filtrate was washed with 10 ml deionised water and suction continued for 3 minutes. The total filtrate (with washings) was transferred into a weighed evaporating dish and evaporated to dryness on a water-bath. The evaporated sample was dried for at least 1hr at 180^{o}C and weighed.

For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. The duplicate determination was within 5 %. Additionally, a control standard was prepared and analysed together with the samples. The value of the control standard is plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 7, 2010).

Calculation of results:

TDS (mg/l) = (A- B)/ C*10^{6}

where, A –weight of dried residue and dish (g), B-weight of dish (g) and C –volume of sample (ml).

4. Measurement of turbidity

The sample to be determined was vigorously shaken and poured into a sample cell to at least ⅔ full. The appropriate range on the turbidimeter (Partech Model-DRT 100B) was selected using the knob. If the red light on the turbidimeter showed, the next range was selected. The stable turbidity reading on the turbidimeter was then recorded.

For quality control (QC) and quality assurance (QA), a turbidity free water of 0.02 NTU was prepared and used as a blank. The value of the turbidity free water was within ± 0.01. Additionally, a control standard of 5 NTU was prepared and analysed together with the samples and the value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 3, 2010).

5. Measurement of calcium

50 ml of the sample (or a smaller portion diluted to 50 ml) was collected into a conical flask and 2.0 ml of NaOH solution was added. The solution was stirred and 0.1- 0.2 g of murexide indicator was added. The resulting solution was titrated immediately using Ethylenediaminetetraacetic acid (EDTA) slowly, with continuous stirring until the colour changed from salmon to orchid purple. The end-point was then checked by adding 1 or 2 drops of titrant in excess to make sure that no further colour change took place.

For quality control (QC) and quality assurance (QA), blanks were analysed after every batch of 5 samples. Additionally, a control standard (10 mg/L Ca) was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 23, 2010).

Calculation of results:

$$\text{Ca (mg/l)} = \frac{A \times B \times 400.8}{\text{ml of sample}}$$

where A= ml of EDTA titrant used, $B = \frac{\text{ml of standard calcium solution}}{\text{ml of EDTA titrant}}$

6. Measurement of magnesium

Calcium and total hardness were determined by Ethylenediaminetetraacetic acid (EDTA) titrimetric method. Magnesium hardness was calculated from the difference between the total hardness and the calcium hardness when these were expressed in the same units. Magnesium content was obtained by multiplying the magnesium hardness value by 0.243. Total hardness and calcium determinations as stated above were followed.

For quality control (QC) and quality assurance (QA) procedures under Total hardness and Calcium determinations were referred to (CSIR-WRI/ ECD, Method No. 26, 2010).

Calculation of results:

(i) From the calcium titration, calculate calcium hardness as follows:

(a) Calcium hardness (as $CaCO_3$ mg/L) = $\frac{A \times B \times 1000}{\text{ml of sample}}$

where, A= ml titrant for sample, B = mg $CaCO_3$ equivalent to 1.0 ml Ethylenediaminetetraacetic acid (EDTA) titrant at the calcium indicator end-point, or

(b) From the calcium titration, calculate calcium concentration as follows:

Calcium (as Ca mg/ L) = $\frac{A \times B \times 400}{\text{ml of sample}}$

where, A= ml of titrant for sample, B = mg $CaCO_3$ equivalent to 1.0 ml Ethylenediaminetetraacetic acid (EDTA) titrant at the calcium indicator end-point.

Then, calcium hardness (as $CaCO_3$ mg /L) = $\frac{\text{Concentration of Ca}}{0.4}$

where, 0.4 = atomic weight of Ca / molecular weight of $CaCO_3$.

(ii) Record the total hardness and Calcium hardness concentrations (as mg/l $CaCO_3$)

Magnesium hardness (as $CaCO_3$ mg/ L) = Total hardness – Calcium hardness

or, Mg (mg/ L) = (Total hardness – Calcium hardness) x 0.243

where, 0.243 = Atomic weight of Mg

Molecular weight of $CaCO_3$

7. Measurements of sodium and potassium

Power from the mains into the flame photometer and the compressor was switched ON and the filter selector on the flame photometer was pushed to either sodium (Na) or potassium (K), depending on the parameter to be determined. The coarse sensitivity knob was then adjusted to select either Na or K. The liquefied petroleum gas attached to the machine was then opened. The gas knob on the photometer was turned ON to allow the gas to flow into the machine. The power switch on the flame photometer was turned ON to ignite the gas and also to display the digital readings. The decimal push button was then pressed to set the decimal point. The flame was then adjusted into fine distinct cones by using the gas knob on the machine. Alternatively, a known standard solution was used, whilst, adjusting the flame till the highest possible reading was obtained. The photometer was set to zero with the zero knob, whilst, aspirating the diluent or the deionised water. The highest concentration was set with the fine sensitivity knob whilst aspirating the highest standard solution. Approximately, 15 minutes was then allowed for the machine to warm up whilst aspirating the diluents. The zero setting and the highest standard setting were checked again. The standards were then run from the lowest to the highest in order to obtain a calibration curve, followed by the samples to be determined.

For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. Two known standards were also read after every batch of 5 samples. Additionally, a control standard (5 mg/L Na or K) was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits ($\pm 3\sigma$), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. ?, 2010).

Calculation of results:

This method reads the optical density and therefore, the actual concentration in mg/L was read from the calibration curve. Where, sodium or potassium concentration was high and had to be diluted, the results were calculated as follows:

Na or K (mg/L) = (mg/ L Na or K in aliquots) x D

where, D = dilution ratio

$$\text{i.e. } D = \frac{\text{ml sample + distilled water}}{\text{ml of sample}}$$

8. Measurement of sulphate

100 ml of the sample was measured and transferred into 250 ml Erlenmeyer flask. 5 ml conditioning reagent was then added and mixed thoroughly by stirring. A spoonful of barium chloride crystals were added while, still stirring and timing immediately started for 60 seconds at a constant speed. The absorbance was then measured at 420 nm on the spectrophotometer within 5 minutes. For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. Additionally, a control standard (10 mg/L SO_4) was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 19, 2010).

Calculation of results:

The concentration of the sample was read directly from the calibration curve.

9. Measurement of chloride

A 50 ml of clear sample was measured. If the sample pH was not in the range of 7- 10, the sample pH was adjusted (between 7 and 10) using H_2SO_4 or NaOH. A 1ml of K_2CrO_4 indicator solution was added and titrated against standard $AgNO_3$ titrant to a pinkish yellow end-point. A reagent blank value (0.2 to 0.3 ml) was established in this titration method. For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. The end point of the duplicate was within ± 0.1 ml. Additionally, a control standard of 20 mg/L prepared from NaCl stock solution was analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 24, 2010).

Calculation of results:

$$Cl^{-}\ (mg/L) = \frac{(A-B) \times M \times 35{,}450}{\text{ml of sample}}$$

where, A = ml titrant for sample, B = ml titrant for blank, M = Molarity of $AgNO_3$.

10. Measurement of nitrate- nitrogen

Nitrate calibration standards in the range of 0.2 - 1.0 mg/L and a control standard of 0.5 mg/L were prepared. A nitrate calibration curve was drawn from the calibration standards. 10.0 ml of the sample or an aliquot to 10.0 ml was pipetted into a test-tube and 1.0 ml of 1.3M NaOH was added, followed by 1.0 ml of reducing mixture and gently mixed. The resulting solution was heated at 60 °C for 10 minutes in a water bath and then, cooled to room temperature and 1.0 ml colour developing reagent was added. The mixture was shaken to mix and the absorbance read. For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. Additionally, a control standard of 0.5 mg/L NO_3-N was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard is prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 14, 2010).

Calculation of results:

The sample concentration is computed directly from a calibration curve. Sample concentration is equal to the sum of NO_3-N and NO_2-N. To obtain the concentration of NO_3-N, determine the concentration of NO_2-N separately and subtract.

11. Measurement of phosphate

Standard phosphate solutions of known concentrations ranging from 0.1 - 1.0 mg/L were prepared and absorbances read on a spectrophotometer. A graph of concentration against absorbance was plotted. A 0.05 ml (1drop) phenolphthalein indicator was added to a 100 ml sample free from colour and turbidity. If sample turned pink, a strong acid solution was added dropwise to discharge the colour. If more than 0.25 ml (5 drops) was required, a smaller volume of sample was taken and diluted to 100 ml with de-ionized water and then a drop of phenolphthalein indicator was added and discharged if sample turned pink colour with the acid. A 4.0 ml molybdate reagent and 0.5 ml (10 drop) stannous chloride reagent were added with thorough mixing after each addition. The absorbance at a wavelength of 690 nm on a spectrophotometer was measured after 10 minutes. The spectrophotometer was zeroed with blank solution (this solution was prepared in the same way as samples except that instead of 100 ml of sample a 100 ml of deionised water was used) after each reading. For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. Additionally, a control standard of 1 mg/L P was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits ($\pm 3\sigma$), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 17, 2010).

Calculation of results:

The sample concentration is computed directly from a calibration curve.

12. Measurement of silica

A 1.0 ml 1-1 HCl and 2.0 ml ammonium molybdate reagent was added to a 50 ml sample in rapid succession and mixed by inverting at least six times and allowed to stand for 5-10 minutes. A 2 ml oxalic acid solution was added and mixed thoroughly. The colour was then read after 2 minutes at 410 nm. To correct for colour and turbidity, a blank was prepared by adding HCl and oxalic acid but no molybdate reagent. The photometer was then adjusted to zero absorbance with the blank containing no molybdate before reading absorbance of molybdate-treated samples. For quality control (QC) and quality assurance (QA), blanks were analysed after every batch of 5 samples. Additionally, a control standard (10 mg/L SiO_2) was prepared and analysed together with the samples. The value of the control standard is plotted on the control chart, if it fell outside the action limits (±3σ), a fresh control standard is prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 16, 2010).

Calculation of results:

Silica concentration is determined directly from the calibration curve.

13. Measurement of fluoride

Fluoride was determined using SPANDS method. The SPANDS colorimetric method was based on the reaction between fluoride and a zirconium-dye lake. Standard concentrations of fluoride were prepared in the range of 0 - 1.4 mg/L F^- by diluting appropriate quantities of the standard fluoride solution to 50 ml with de-ionized water. 5 ml each of SPANDS solution and zirconyl-acid reagent were pipetted and added to the standards and mixed well. The absorbance of the mixed solution was obtained using the spectrophotometer. A graph of the milligram fluoride-absorbance relationship was then plotted. A 50 ml of the sample to be measured was taken and a 5 ml each of SPANDS solution and zirconyl-acid reagent were added. The solution was mixed well and the absorbance was read. For quality control (QC) and quality assurance (QA), a duplicate was analysed after every batch of 5 samples. Additionally, a control standard of 1 mg/L F was prepared and analysed together with the samples. The value of the control standard was plotted on the control chart, if it fell outside the action limits ($\pm3\sigma$), a fresh control standard was prepared and the samples analysed again using the fresh control standard (CSIR-WRI/ ECD, Method No. 20, 2010).

Calculation of results:

Fluoride concentration is determined directly from the calibration curve.

14. Measurement of total metals

For the determination of metals aliquots of 100 ml of water sample was transferred into a 125 ml conical flask. 5 ml of concentrated nitric acid (HNO_3) was added and evaporated to the lowest volume on a hot plate before precipitation occurs. The appearance of a light-coloured clear solution indicates complete digestion. This was followed by filtration of the resulting solution through 0.45 μm filter paper and then, transferred into a 100 ml volumetric flask, cooled and top to the mark for analysis. To ensure quality control (QC) and quality assurance (QA), blanks were also prepared using the same procedure (APHA, 1998).

The concentrations of Cu, Fe, Mn, Cd, Zn, Pb were determined using Agilent 240FS Atomic Absorption Spectrometer by direct aspiration of water samples into an air acetylene flame, and Al into nitrous oxide acetylene flame. Se and As were determined using a hydride generator attached to the Atomic Absorption Spectrometer, while, Hg was determined using AAS- cold Vapour (VGA77) attached to the Atomic Absorption Spectrometer.

15. Measurement of stable isotopes of Deuterium (^{2}H) and Oxygen-18 (^{18}O)

The Liquid Water Isotope Analyser (LWIA) also called the Los Gatos Research (LGR) instrument -LGR DLT-100 (model 908- 0008) was used to determine $\delta^{2}H$ and $\delta^{18}O$ compositions in the ground and surface water samples. The LWIA equipment measures absorption at a wavelength of 1390 nm and calculate molecular concentrations of ^{2}HHO, $HH^{18}O$ and HHO. The molecular concentrations are then, converted into atomic ratios, $^{2}H/^{1}H$ and $^{18}O/^{16}O$. A post-processing procedure was then used to calculate delta-scale (δ) values with respect to Vienna Standard Mean Ocean Water (VSMOW) (Coplen, 1996). The LWIA is made up of a laser analysis system and an internal computer, a CTC LCPAL liquid autosampler, a small membrane vacuum pump, and a room air intake line that passes air through a Drierite column for moisture removal. A ~1 m long polytetrafluoroethylene (PTFE) transfer line connects the autosampler and the DLT-100. A Hamilton microlitre syringe (model 7701.2N) was used to inject 0.75 litre of sample through a PTFE septum in the autosampler. In order to aid the vapourization of the sample under vacuum immediately upon injection, the injection port of the autosampler was heated to 80°C. The vapour, then move down the transfer-line into the pre-evacuated mirrored chamber for analysis. The instrument has a precision of approximately 1 ‰ for $\delta^{2}H$ and 0.2 ‰ for $\delta^{18}O$.

Calculation of results:

The $\delta^{2}H$ and $\delta^{18}O$ concentrations are computed using;

$$\delta = \left(\frac{R_s - R_{std}}{R_{std}}\right) \times 1000$$

where, Rs is the isotope ratio ($^{2}H/^{1}H$ for deuterium and $^{18}O/^{16}O$ for oxygen-18) of the sample and Rstd is the isotope ratio ($^{2}H/^{1}H$ for deuterium and $^{18}O/^{16}O$ for oxygen-18) of the standard.