BASELINE STUDY INTO GROUNDWATER RESOURCES IN THE RIVER TAIN SUB-BASIN OF THE BLACK VOLTA



By

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CERTIFICATION

I hereby declare that this submission is my own work towards the MSc. And that, to the best of my knowledge, it contains no material previously published by another person or material which has been accepted for the award of any other degree of the University, except where due acknowledgement has been made in the text.

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Dedication

This thesis is dedicated to Mr and Mrs Francis Dramani's family .

Abstract

Groundwater is one of the most widely distributed and most important water resources on earth. It is safe for human consumption because it is free from pollution related to direct human activities. As interest in groundwater development intensifies, stakeholders are now more interested in the provision of baseline information for groundwater resources in the various basins to reduce the cost of exploration.

The methodology involved the collection and analysis of existing borehole data. The results indicate that groundwater occurrence in the sub-basin depends on secondary porosity and is obtained in either weathered or fractured aquifer. The depth of boreholes in the sub-basin ranges between 30 and 75 m with a mean value of 49.2 m whilst borehole yield falls between 7 and 113 l/min with a mean value of 16.9 l/min. The overall success rate of borehole in the sub-basin is 74.7 %, however, most of the boreholes are low yielding. The mean transmissivity values are 10.63 m^2/day for Birimian Sedimentary, 10.44 m^2/day for Birimian Volcanic, 7.29 m^2/day for Tarkwaian and 20.15 m^2/day for Upper Voltaian.

Groundwater accessibility in the sub-basin is not total. 60 % of the communities have less than the required number of boreholes based on the WHO threshold of 300 persons per a borehole leading to perennial water problems in these communities. The 40 % of the communities that have the required number of boreholes based on the WHO standard still face water crises due to low aquifer yield. Groundwater quality in the sub-basin is considered safe for drinking since the information gathered on 59 boreholes all have parameters falling within WHO water quality standard.

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My special thanks go my wife Mrs. Sophia Dramani for her patience and assistance during my period of study in the university. May God bless you.

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1. INTRODUCTION

1.1 Background

Water is an essential natural resource that sustains the life of man and all living things on earth. It is central to many human activities such as industrial, domestic, animal watering, hydropower generation, transport services, tourism and recreation. There is increasingly high pressure globally on the scarce water resources, especially surface water due to rapid population growth, rapid urbanization, effects of climate change and technological advancement. In addition to these, current global climate change processes are expected to affect both the spatial and temporal unpredictability of water availability. The water resource base is, therefore, under threat, especially surface water.

In 2004, WHO estimated that 1.1billion people (17 % of global population) lacked access to improved water sources. Every day, 3,900 children under the age of 5 die from water related diseases (WHO, 2004). The lives of these people, often among the poorest on our planet, are devastated by this deprivation. Lack of access to water also impedes the enjoyment of health and other human rights, example; right to education, right to adequate standard of living, right to food, (WWC, 2006).

As a result of the concerns raised, world bodies such as United Nations, World Bank, World Food Organisation (WFO) and other bilateral donors have put water crises on top of their agenda. Portable water demand is on the increase in both rural and urban communities in the world.

According to Ghana water policy (2007), improving water services and uses are essential for increasing hygiene and sanitation services levels that affect productive lives of people, enhance enrolment and retention of girls in school, enhance women's dignity and ability to lead, reduce morbidity and mortality, reduce pre and post-natal women's risks and prevent vector and water borne diseases. In view of the concerns raised and the rate at which surface water is under threat, the only alternative source is groundwater.

A study conducted by the British Geological Survey and University College, London revealed that the total volume of water in aquifers underground in Africa continent is 100 times the amount found on the surface. According to the study, the greatest groundwater storage is found in Northern Africa in the large sedimentary basin in Libya, Algeria and Chad and the amount of storage is equivalent to 75 m thickness of water across that area. Ghana is quoted as having low- moderate storage between 0.5 – 1.0 l/s (B.G.S & U.C.L, 2012).

Many people in the urban and rural communities in Ghana are battling with the problem of inadequate availability of potable water for their daily activities. Often times, this impact is greatly felt mostly by those living in the rural communities. In Tain sub-basin of the Black Volta, the situation is worrisome as many inhabitants mainly depend on water supply from nearby streams and hand-dug wells constructed by private individuals and in most cases some of the wells are seasonal in nature. Over the years, groundwater development has been taken as the only alternative source of water to supplement the erratic surface water supply in the sub-basin.

However, the number of boreholes drilled in the area is not proportionally distributed due to the difficulties of identifying the right water potential zones. For this reason most of the boreholes drilled in the area are either dry or low yielding making it difficult for some communities to have easy access to portable water. Information gathered from Wenchi Municipal Water and Sanitation Agency indicates that 27 boreholes drilled in some communities in 2012; only 18 were successful and nine (9) were abortive. Even those which were wet, 7 were low yielding ranging between 7 – 10 l/min. This might be connected to the lack of basic information on possible groundwater potential zones and the complex nature of the subsurface geology of the area prior to the drilling exercise.

1.2 Problem statement

Water scarcity is a major challenge in most rural and urban communities in the River Tain Sub-basin of the Black Volta, due to ephemeral nature of surface water bodies and frequent drying of hand-dug wells. The development of groundwater could have been an alternative source of meeting the local water supply needs of the communities within the area; however, there is little baseline information about the groundwater potential in the sub-basin. As a result, most boreholes drilled in the area dry up few years after use and most are unsuccessful. The current data for the sub-basin indicates that 45 % of the entire population walks less than 50 m to access water from water facilities. Also 46 % walks between 51 m -1 km to access water and 7.6 % moves between 1.1 and 2 km to access water facilities and 1.4 % walks more than 2 km (Districts Report, 2012).

The above problems affect the productivity of especially women and children. Children sometimes leave school in search of water at the expense of their education. Some communities also still depend on other unsafe water sources that expose them to water related diseases such as diarrhoea, cholera, bilharzias, among others.

1.3 Justification of the study

Even though, several studies on groundwater potential in the Black Volta basin have been undertaken by individuals and some research institutions, no baseline study into groundwater resources has been conducted in the River Tain sub-basin of the Black Volta. It is against this background that this research was conducted to facilitate the selection of sites for borehole drilling in the sub-basin by groundwater developers to reduce the tendency of striking dry wells during drilling. This will reduce the cost of groundwater development in the area. Moreover, grouping of the sub-basin into groundwater zones based on yield would help the stakeholders for water supply in the communities within the sub-basin to adopt alternative ways of supplying water to communities that will fall under low yielding and dry groundwater zones. This will improve water supply and reduce the high incidence of water related diseases in the sub-basin. Moreover, the research would serve as database which could be used to monitor groundwater fluctuations in the study area.

1.4 Main objective of the study

The main objective of the study is to provide baseline information into groundwater resources in the river Tain sub-basin of the Black Volta.

Specific objectives of the research are to:

- Assess the current groundwater accessibility in the river Tain sub-basin.
- Take inventory of groundwater point sources (boreholes) in the river Tain sub-basin.
- Determine groundwater potential and quality in the river Tain sub-basin.

1.5 Organisation of the Thesis

Chapter one of the thesis presents the background, the problem statement, justification and objectives of the study. Chapter two covers literature review with chapter three covering the study area. Chapter four explains the research methodology and chapter five presents the results of the study as well as discussion. Chapter six summarises the findings and gives recommendations.

2. LITERATURE REVIEW

2.1 The hydrological cycle

Groundwater is an important part of Earth's hydrological cycle or movement of water between oceans, atmosphere and land. The distribution of water on land is dependent upon the complex interaction between atmosphere and oceans. The circular path of the hydrologic cycle links evaporation, condensation, run-off, infiltration, percolation, and transpiration. This is shown in Figure 2.1 below. These processes cause water to change state (vapour, liquid, solid) as it moves between different elements of the earth system (Santosh, 1996).

The average residence time for oceanic water is 3,000- 4,000 years. The bulk of evaporation (85 %) occurs over oceans and is greatest in areas of warm climates at low latitudes. Water vapour cools and relative humidity of the air increases as it rises in the atmosphere. Condensation (water vapor converted to liquid) forms tiny moisture droplets that may coalesce to form clouds when the air becomes saturated with water vapor (100 % humidity). Atmospheric circulation patterns may redistribute the saturated air prior to precipitation (Santosh, 1996). Precipitation is concentrated over areas of rising air (e.g. along equator or above mountains) and is least in areas of descending air (e.g. along the tropics). The volume of moisture in the atmosphere is equivalent to ~25 mm of precipitation. It is estimated that moisture in the atmosphere is recharged 40 times a year (residence time ~9 days) as the average annual precipitation for the world is approximately 1000 mm. Nearly a third of all water falling as precipitation completes the circuit to the oceans by surface run-off in streams (average residence time 14 days). Most of the rest returns to the atmosphere by evaporation or through the transpiration of plants (Santosh, 1996). A slim fraction of water falling as precipitation infiltrates below the surface through bedrock or soils to form groundwater.

Some of the soil moisture is lost to evaporation or taken up by vegetation and the remainder recharges the groundwater system. Groundwater flow is termed percolation and occurs at rates from m/day to mm/year. (Santosh, 1996).

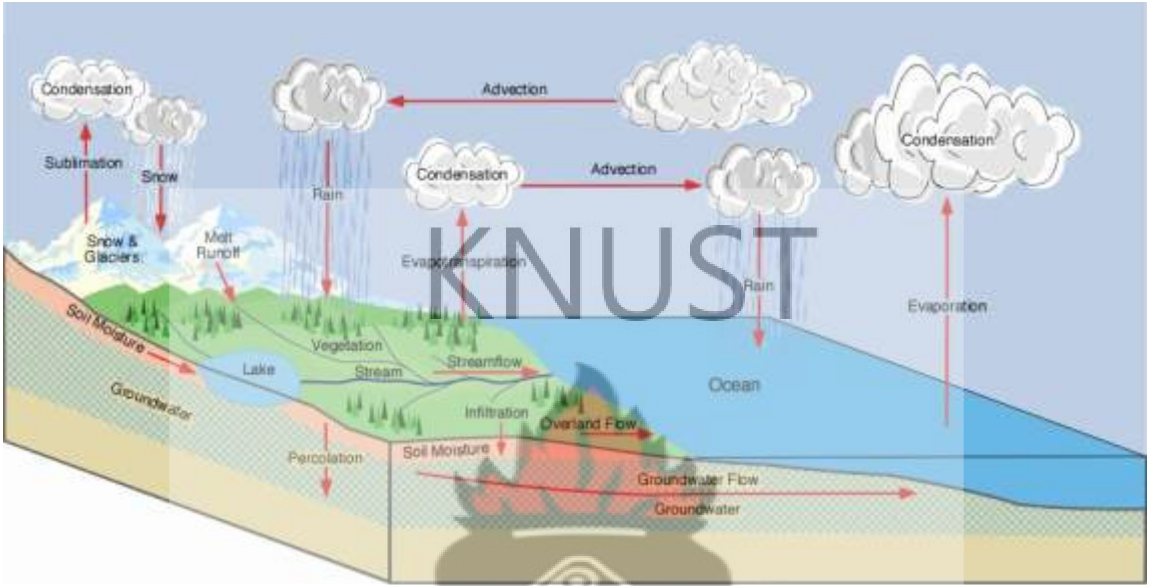

Figure 2.1. Hydrological cycle

2.2 History of Groundwater development in Ghana

Before Ghana came under colonial rule in 1844, individuals, companies (e.g., trading, mining and timber companies) and small communities were responsible for their own water supply. The sources of water supply at that time were traditional hand-dug wells, ponds, dugouts, streams and rivers, springs and rainwater harvesting from roofs. In the case of hand-dug wells, the interested parties or communities developed their own traditional techniques or methods of sitting the wells. The wells were usually dug through overburden and weathered rock material and were up to 6 m deep (Gyau-Boakye and Dapaah-Siakwan, 1999). During the dry season when yields from hand-dug wells were very low and in some cases no yield at all, the wells were abandoned for other sources of water, mainly streams and rivers until the aquifers were recharged in the rainy season.

In 1920, the Geological Survey Department was requested to assist in offering advice on where to site wells in the semi-arid northern territories where drought is frequent and the geology is complex. Further to this, a water supply division was set up in the Geological Survey Department in 1937 as a way to deal with the magnitude of water supply problems in northern and southeastern parts of the country (the driest areas of Ghana). Among other important tasks, the division was tasked to investigate new sources of water supply (both groundwater and surface water sources) and to advise medical officers and political administration personnel in well digging, lining and maintenance and the sanitary precautions to adopt against pollution.

The progress and failure rate of groundwater supplies in the dry season became a source of concern to the government to the extent that it decided in 1951 to have the situation reviewed. To this end, a consultant was invited from the United Kingdom to advise on the work being done by the Department of Rural Water Supply, the groundwater potentialities of the country and the need to invite tenders for drilling by contract. Between 1952 and 1959 the efforts of the Department of Rural Water Development were supplemented with contract drilling placed with private drilling companies as had been recommended. In addition to the efforts of the Department of Rural Water Development, other agencies like the Department of Community Development of the Ministry of Social Welfare and Community Development and the Department of Agriculture also assisted with rural water supply. The technologies used were mainly hand-dug wells, with or without hand pumps, rainfall harvesting from roofs, infiltration galleries, dug-outs and small dams (Gyau-Boakye and Dapaah-Siakwan, 1999).

2.3 Groundwater resources in sub-Saharan Africa

The availability of groundwater resources in sub-Saharan Africa depends critically on the geology, the history of weathering, faulting and the recharge to groundwater. This clearly demonstrates the arid areas, where groundwater recharge is limited and erratic. However, there is no simple direct relationship between average annual rainfall and recharge, and significant recharge (10 - 50 mm) can occur where annual rainfall is less than 500 mm (Edmunds *et al.*, 2005).

Climate change will significantly alter patterns of rainfall and recharge across Africa. Climate models predict that the number of drought episodes in Africa will increase, particularly in Sahel areas, and the number of people affected by severe drought will grow (Hulme *et al*., 2000). Rural water supply, however, does not require large quantities of recharge, and a simple mass balance indicates that recharge of 10 mm per annum would support community boreholes (5 m^3/d) with hand pumps at a spacing of 500 m across Africa. Increasing reliable water supplies throughout Africa will depend on the development of groundwater (Giordano, 2009; MacDonald and Calow, 2010).

Groundwater storage has been estimated by combining the saturated thickness and effective porosity of aquifers across Africa (MacDonald *et al*., 2012). Large sedimentary aquifers in North Africa contain a considerable proportion of Africa's groundwater. Libya, Algeria, Sudan, Egypt and Chad have the largest groundwater reserves. Many of these Saharan aquifers are not, however, actively recharged, but were recharged more than 5000 years ago when the climate of the area was wetter (Scanlon *et al*., 2006; Edmunds, 2008).

Aquifers with the least storage generally comprise thin weathered Precambrian basement rocks where average groundwater volumes are estimated to be 0.5 x 10^6 m^3 km^{-2} (equivalent to 0.5 m water depth) and range from 0.05 to 2.5 x 10^6 m^3 km^2. The limited storage of these aquifers is nevertheless highly significant as it is considerably more than the volume abstracted annually using a community hand pump (<0.003x10^6 m^3). These aquifers also have sufficient storage space to allow groundwater recharge to be stored for several decades thereby providing a vital buffer against variable climates (MacDonald *et al*., 2009). Countries with the lowest groundwater reserves are generally those with a small land area which are underlain almost exclusively by Precambrian basement rocks.

The total volume of groundwater in Africa is estimated to be 0.66 million km^3 with a range in uncertainty of between 0.36 and 1.75 million km^3 (MacDonald *et al*., 2012). Not all the groundwater volume estimated by the saturated thickness and effective porosity of the aquifer is, however, available to be abstracted. The volume of water that is released from an aquifer through pumping is often less than the effective porosity but is problematic to measure. This parameter, specific yield, represents the drainable porosity of an unconfined aquifer. There are only two published estimates of in situ specific yield at location in Africa (Wright *et al*., 1982; Taylor *et al*., 2010). Both indicate the specific yield to be approximately half of the measured porosity, consistent with global estimates (Fetter, 2000).

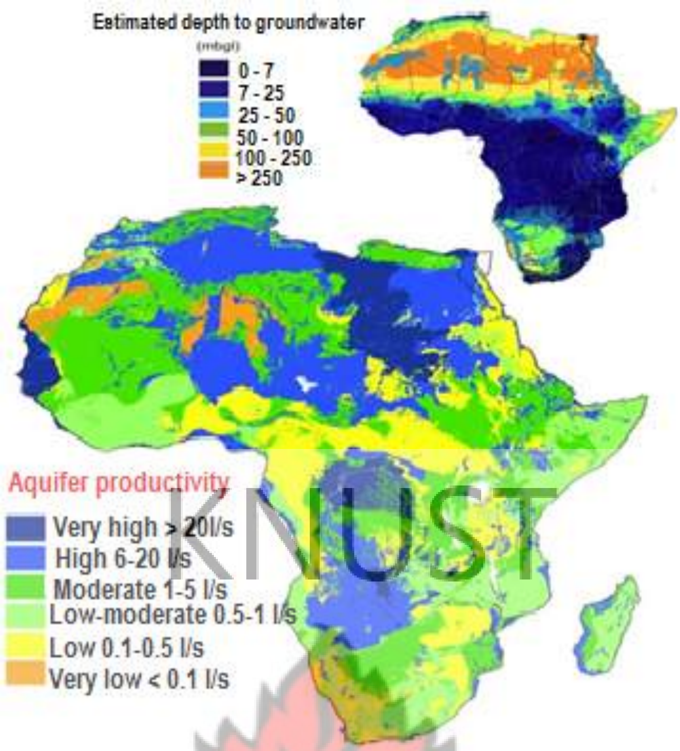

Figure 2.2 A Map of Africa showing approximate depth to groundwater (Bonsor and MacDonald, 2011).

2.4 Aquifer productivity

The accessibility of the groundwater resources is as important as overall groundwater storage in determining how far groundwater can support nations and communities to adapt to climate change and population growth (Calow *et al*., 2010). Groundwater is accessed and abstracted, generally through drilling boreholes, and the yield of the borehole will limit the rate at which groundwater can be abstracted. For a community water supply fitted with a hand pump, a borehole must be able to sustain a supply of > 0.1 l s^{-1}, and preferably 0.3 l s^{-1} (MacDonald *et al*., 2012). Urban town supplies rely on individual boreholes that can sustain a yield of at least 5 l s^{-1}. Figure 2.2 shows the calculated aquifer productivity map for Africa, indicating what boreholes yields can reasonably be expected in different hydrogeological units. The ranges indicate the approximate interquartile range of the yield of boreholes that have been sited and drilled using appropriate techniques, rather than those drilled at random. Crystalline basement rocks have the lowest yields, generally less than 0.5 l s^{-1}, though a significant minority of areas have yields that are in excess of 1 l s^{-1}. Highest borehole yields (>20 l s^{-1}) can be found in thick sedimentary aquifers, particularly in unconsolidated or poorly consolidated sediments. The aquifer productivity map (Figure 2.2) shows that for many African countries appropriately sited and constructed boreholes will be able to sustain community hand pumps (yields of 0.1–0.3 l s^{-1}) and for most of the populated areas of Africa, groundwater levels are likely to be sufficiently shallow to be accessed using a hand pump (Bonsor and MacDonald, 2011).

The majority of large groundwater stores in the sedimentary basins which can accommodate high yielding boreholes are in northern Africa. These are often far from population centres and have deep water levels and are therefore costly to develop (MacDonald *et al*., 2012). Away from the large sedimentary aquifers in northern Africa, the potential for borehole yields exceeding 5 l s^{-1} is not widespread, though higher yielding boreholes may be successful in some areas if accompanied by detailed hydrogeological investigation. The potential for intermediate boreholes yields of 0.5–5 l s^{-1}, which could be suitable for small scale household and community irrigation, or multiple use water supply systems, is much higher, but will again require effective hydrogeological investigation and borehole siting (MacDonald *et al*., 2012). Strategies for increasing the use of groundwater throughout Africa for irrigation and urban water supplies should not be predicated upon the widespread expectation of high yielding boreholes but recognize that high borehole yields may occasionally be realized where a detailed knowledge of the local groundwater conditions has been developed.

2.5 Geology and hydrogeology of Ghana

Two major hydrogeologic provinces have been delineated in Ghana. They are the

- Basement complex, which is composed of Precambrian crystalline igneous rocks and metamorphic rocks,
- Paleozoic consolidated sedimentary

The basement complex forms 54 % of the land area of Ghana and the Paleozoic sedimentary formations form 45 %. The remaining 1 % is covered by minor provinces, such as the

- Cenozoic, Mesozoic and Paleozoic sediments along the coast,
- Quaternary alluvium along major stream courses.

The basement crystalline rocks are of Precambrian age and consist of granite-gneiss-greenstone rocks, phyllite, schist, quartzite, strongly deformed metamorphic rocks and amorogenic intrusions (Key, 1992). Generally, the structural trend in these basement rocks is influenced by the principal tectonic stress orientation and therefore follow a northeast-southwest (WNW-ESE) axis (Apambire, 1996). The basement crystalline formation is commonly subdivided into the Birimian group (with associated granitoid intrusions), Granite, Tarkwain group, Dahomeyan formation, Togo formation and the Buem formation. The Birimian group dominates the basement crystalline formation and covers densely populated areas including most of western, south-central, northeast and northwest of the country and can be as thick as 15,000 m (Key, 1992).

The Paleozoic consolidated sedimentary formations are locally referred to as the Voltaian formation and consist mainly of sandstone, shale, arkose, mudstone, sandy and pebbly beds, and limestone (WARM, 1998). Based on lithology and field relationships, the Voltaian formation can be sub-grouped into the upper, middle and lower Voltaian. The upper Voltaian consists of massive and thin-bedded quartzite sandstones, which are interbeded with shale and mudstone in some areas. The middle Voltaian (Obusum and Oti Beds) mostly comprise of shales, sandstones, arkose, mudstones and siltstones. The lower Voltaian consists of massive quartzite sandstone and grit.

The major geological formations in the country are overlain by the so-called regolith, which is a weathered layer that varies in thickness and lithology (Martin, 2005; HAP, 2006). The thickness of the Regolith is influenced by lithology, structural characteristics, topography, vegetation cover, erosion, aquifer characteristics and climate. In the Precambrian formation the thickness varies widely with an average ranging from 2.7 to 40 m but can be up to 140 m in the extreme northwest of the country (Apambire *et al*., 1997; Apambire, 1996; Smedley, 1996). Generally, the regolith in the Voltaian formation is less thick compared to the Precambrian formation and ranges from 4 to 20 m in the southern part (Acheampong, 1996).

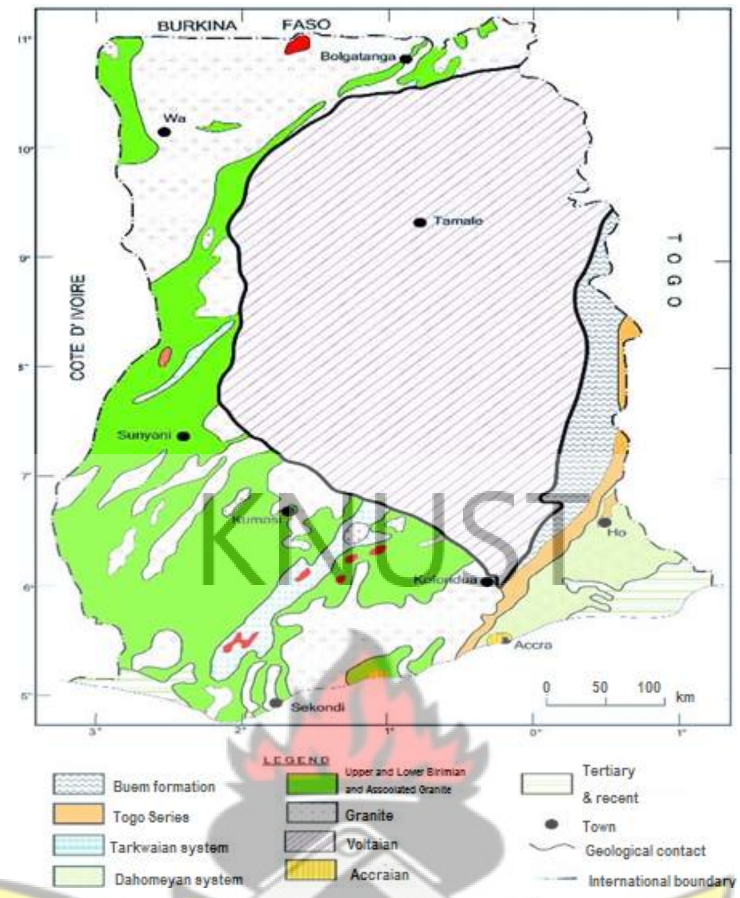

Figure 2.3 Geological map of Ghana

2.6 Borehole Yield in Ghana

Data on the total number of boreholes drilled in the Cenozoic-Mesozoic-Palaeozoic Province is not available. However, the number of listed boreholes drilled in the Costal-Plain sub-province, as of 2001, was 480 (380 in sands and clays and 100 in limestone beds) (Barry, 2010). The success rate of Boreholes varies widely amongst sub-provinces, from an average of 36 % in the Coastal Block Fault to 78 % in the Coastal-Plain. Information on borehole depths are available for the Coastal Plain sub-province only and range from 3m to 100 m in the sand and clay materials and 100m to 600 m in the limestone beds. Transmissivity values for the Cenozoic-mesozoic-Palaeozoic Province are the highest of all the hydrogeologic provinces in Ghana with average values of 22.2 and 25.1 m^2/d in the sand/clay and limestone materials, respectively, of the Coastal-Plain sub-province (Barry, 2010).

Yields of boreholes in the Precambrian formation are low due to low transmissivities and low storativities (HAP, 2006). The best yields are obtained in the Birimian and Tarkwaian formations, ranging from 0.48 to 36 m^3/h with an average of 7.6 m^3/h. Average yields in the Buem/Togo series and the Granitoids are 5.6 and 4.0 m^3/h, respectively. Transmissivity values range from 0.2 to 119 m^2/d in the Birimian (including Granitoids) and Tarkwaian formation, from 0.9 to 40 m^2/d in the Buem/Togo series, and 0.3 to 42 m^2/d in the Dahomeyan formation (Agyekum, 2004). Information on aquifer storativity is lacking. The only data available is for the Tarkwaian and Birimian formations and range from 0.003 to 0.008 (Barry, 2010).

Hydrogeologically, the Voltaian terrain is the most complex and least understood of all the formations in Ghana. The number of listed boreholes as of 2001 was 512, much fewer compared to the Precambrian basement formation. Borehole success rates are low, between 22 and 53 % (Agyekum, 2004) although slightly higher success rates (55-56 %) have been reported in literature (Dapaah-Siakwan and Gyau-Boakye, 2000). The depths of boreholes range from 45 to 75 m with an average of 55 m. Borehole yields lie in the range 0.41-9.0 m^3/h but could be up to 72 m^3/h in some areas (Darko and Krasny, 2003a). Average borehole yield is 6.3 m^3/h in the Middle Voltaian sub-province and 8.5 m^3/h in the Upper and Lower Voltaian sub-provinces. On average, transmissivity values are higher in the Voltaian province than in the Precambrian Province, ranging from 0.3 to 267 m^2/d with an average of 11.9 m^2/d (Darko and Krasny, 2003b). Specific capacity values range from 0.06 to 2.7 $m^3/h/m$ (HAP, 2006).

2.7 Groundwater Occurrence in the Black Volta Basin

The Black Volta Basin as discussed under geology is underlain by Crystalline Basement Complex rocks and well consolidated sedimentary formation whose characteristics are more or less identical to the Crystalline Basement Complex rocks. These rocks are essentially impermeable and therefore lack primary porosity (Kortatsi, 1997). They however develop secondary porosities when they are jointed, fractured, faulted or weathered. The weathered zone generally provides room for groundwater storage. Groundwater occurrence in the Black Volta Basin is therefore mainly dependent on the development of secondary porosities. There are therefore two main aquifer systems. These are weathered aquifers and the fissured aquifers (Kortatsi, 1997).

2.8 Depth to Aquifer in Black Volta Basin

The depth to aquifer generally vary widely from 4.3 to 82.0 m with a mean value of 20.11 m. However about 95 % of the aquifers occur within the depth of 50 m indicating that the probability of getting water below the depth of 50 m is very low (Kortatsi, 1997). A comparison of the mean depth to aquifer with the static water level suggests that most of the aquifers are either confined or semi confined as the static water is mostly above the aquifer horizon. Boreholes depth vary from 21.5 to 95.7 m with a mean value of 28.7 m suggesting that on average boreholes are shallow. Most of the boreholes are however only partially penetrating (Kortatsi, 1997).

2.9 Aquifer Materials in Black Volta Basin

The aquifer materials are largely composed of slightly to moderately decomposed granites granodiorite, phylites, schists, diorite, sandstones and shales. Some of the aquifer also occurs in fractures (fissured ones) within the fresh granite, schists and phyllites. Slightly to moderately decomposed quartz viens also form significant proportions of the aquifer materials (Kortatsi, 1997).

2.10 Aquifer transmissivity and storativity

This is a measure of how much water can be transmitted horizontally through a unit width of a fully saturated aquifer under a hydraulic gradient of 1.0. Readily available specific capacity data are used to assess the water bearing and yielding potential of aquifers. Specific capacity is defined as the volume of water pumped per unit of time (yield) per unit drawdown in the pumping well. Specific capacity is an important hydraulic parameter that indicates the transmitting properties of an aquifer. (Darko, 2005).

In groundwater hydrology, transmissivity (T), an important aquifer parameter, greatly facilitates the development of local and regional water resources. The aquifer parameter can be determined by performing a pumping test, in which the aquifer response is observed. The type-curve matching scheme was first adopted to determine the quantifiable T value (Theis, 1935).

A) Equation for transmissivity:

$$T = \frac{2.3Q}{4\pi\Delta(ho - h)} \qquad 2.1$$

- Note: Δ(ho - h) refers to the change in h over 1 log cycle

T= transmissivity and Q = discharge

B) Equation for storativity:

$$S = \frac{2.25Tto}{r2} \qquad 2.\ 2$$

- Note t_o refers to the time where the straight line intersects the zero drawdown line (upper x-axis on the graph)

- r = distance to an observation well. Once again, this storativity calculation requires an observation well, while estimates of T and K do not need an observation well.

2.11 Pumping Test

The principle of a pumping test involves applying a stress to an aquifer by extracting groundwater from a pumping well and measuring the aquifer response to that stress by monitoring drawdown as a function of time. These measurements are then incorporated into an appropriate well-flow equation to calculate the hydraulic parameters of the aquifer. It can be applied by single-well or multi-wells observation (Abdel-Ghafour, 2005). Figure, 2.4 indicates pumping period in a leaky aquifer.

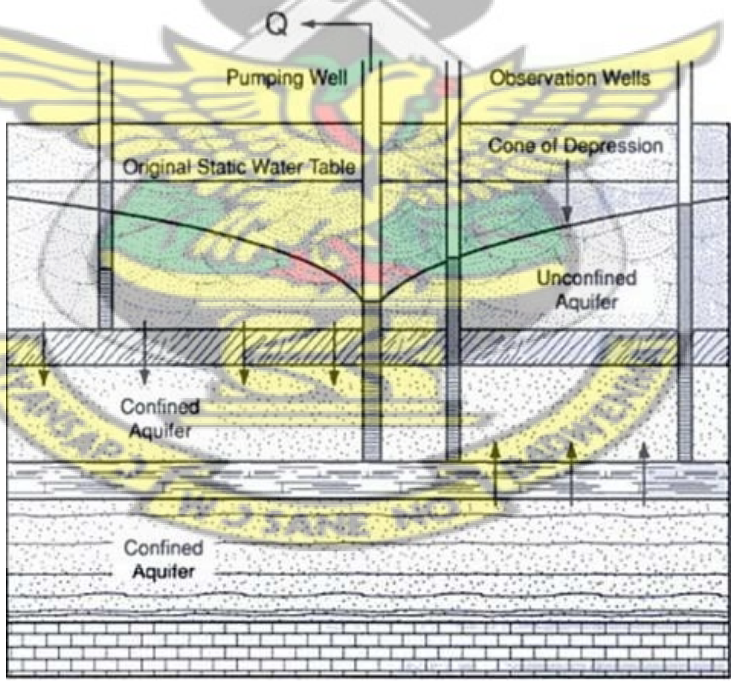

Figure. 2.4. Development of a leaky conf confined aquifer during a pumping period (USDI, 1981)

Pumping test is carried out to determine (Abdel-Ghafour, 2005);

- How much groundwater can be extracted from a well based on long-term yield, and well efficiency.
- The hydraulic parameters of an aquifer or aquifers.
- Spatial effects of pumping on the aquifer.
- Determine the suitable depth of pump.
- The information on water quality and its variability with time.

2.12 Groundwater Quality

Geology plays an important role in the determination of groundwater quality and potential water-quality problems. As the country is dominated by crystalline silicate rocks and weathered derivatives (regolith), groundwater is mainly of low salinity and commonly acidic in composition (pH < 6.5), with low values of total Hardness (Pelig-Ba, 1999). An exception occurs in areas of limestone (parts of the south-east) and along the coastal margins where hardness and pH values are higher and where seawater intrusion of the coastal aquifers may increase groundwater salinity. Minor occurrences of saline groundwater have also been noted in isolated boreholes in rocks of the Voltaian Basin. Here the salinity is typically related to high sulphate concentrations (Pelig-Ba, 1999). The principal groundwater-quality problem observed in Ghana is high iron concentrations, seen in many groundwater supplies. The most serious direct health problems related to drinking water are considered to be from fluoride excess and iodine deficiency which have been noted in parts of the Upper Regions of northern Ghana. Arsenic has also been detected in a few groundwater supplies, though not usually at concentrations significantly above guideline values. Arsenic problems are unlikely to be of large lateral extent (Pelig-Ba, 1989).

Table 2. 1 Summary of potential groundwater-quality problems in Ghana (Pelig-Ba, 1989)

Determinand	Potential Problem	Geology	Location
Iron (Fe)	Excess, often significant	All aquifers	Many locations
Manganese (Mn)	Excess	All aquifers	Several locations
Fluoride (F)	Excess (up to 4 mg/l)	Granites and some Birimian rocks	Upper Regions
Iodine (I)	Deficiency (less than 0.005 mg/l)	Birimian rocks, granites, Voltaian	Northern Ghana (especially Upper Regions)
Arsenic (As)	Excess (> 0.01 mg/l)	Birimian	Especially south-west Ghana (gold belt)

3. STUDY AREA

3.1 Geographical location

River Tain sub-basin of the Black Volta is located to the north-western part of Brong Ahafo Region of Ghana within latitude 7^{o} 15' N and 8^{o} 40' N, and longitude 1^{o}45' W and 2^{o}34' W. The sub-basin covers four (4) districts and four (4) municipalities in the Brong Ahafo Region of Ghana, namely: Jaman North, Tain, Banda and Jaman South Districts and Wenchi, Techiman, Sunyani and Brekum Municipalities. River Tain takes its source from the Republic of Cote D' Ivoire where it flows towards east into Ghana through Jaman North, Jaman South, Brekum, Sunyani Municipality, and forms a boundary between Tain District and Wenchi Municipality . The river changes direction from the boundary towards the north and passes through Banda district and finally joins the Black Volta at the downstream of Bui dam. Figure 3.1 illustrates the River Tain Basin. The ground level elevation of the sub-basin rises between 240 and 300 m above sea level with some few areas either undulating or rugged.

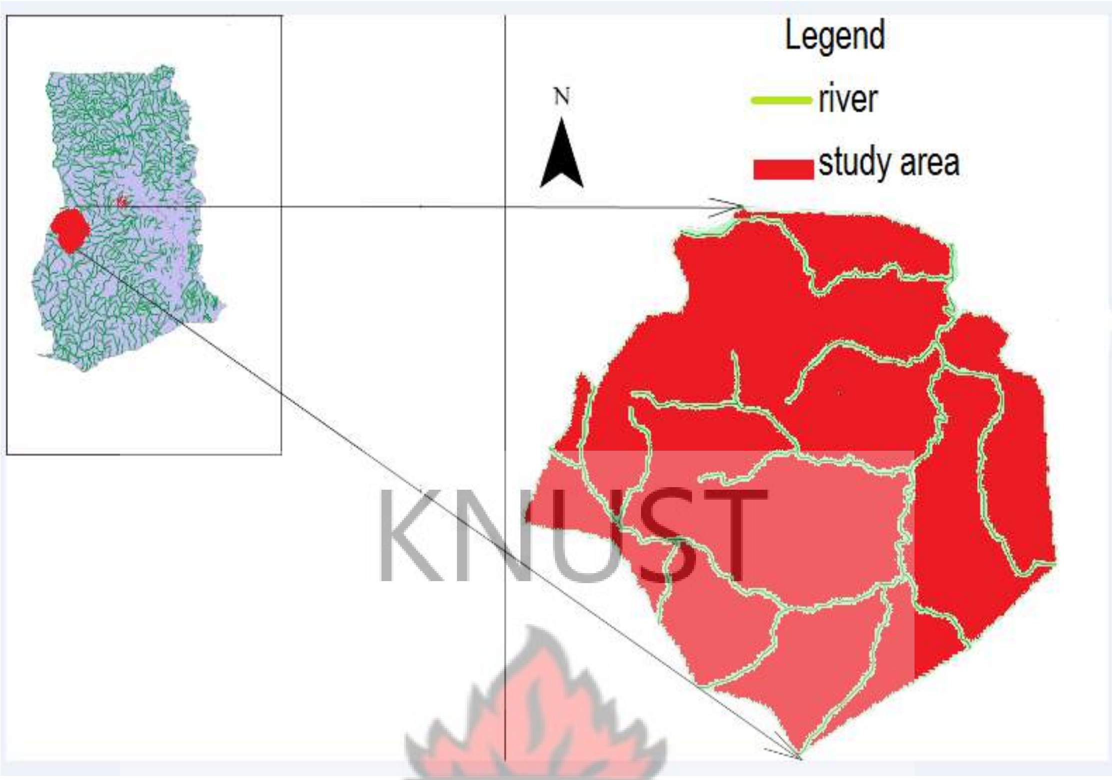

Figure 3.1. River Tain Sub-basin of the Black Volta

3.2 Climate and vegetation

Tain sub-basin of Black Volta lies in the Wet Semi-Equatorial climate region, which is characterized by double maxima rainfall regimes (Dickson and Benneh, 1980). The major rainy season occurs between April and July with peak in June while the minor rainy season occurs between September and November, with its peak occurring in October. There is a short dry spell in August with the major one occurring between November and March. The mean annual rainfall is between 1250 mm and 1400 mm (Mote, 1998). The pattern of rainfall in the sub-basin follows the Inter-Tropical Convergence Zone (ITCZ) that shows distinction between the dry air from Sahara Desert and the moist monsoon wind from the Atlantic Ocean. The North-East trade wind, locally called the Harmattan brings in hot dry weather during

December to February (Dickson and Benneh, 1980). The total mean evapotranspiration value for the sub-basin during the same period is 599.5 mm (Kortatsi, 1997). The highest mean monthly temperature is about 30.9^{o} C, and the minimum temperature of 21.2^{o} C while average monthly humidity is generally between 75 and 80 % (Dickson and Benneh, 1980).

The vegetation of the sub-basin spans the moist-semi-deciduous forest and the Guinea Savanna woodland zones. The Guinea Savanna woodland represents an eco-climatic zone which has evolved in response to climatic and edaphic limiting factors and has been modified substantially through human activities. The original forest vegetation has been subjected to degradation, caused mainly by the indiscriminate bush fires, slash and burn agriculture, logging and felling of trees for fuel over the years.

3.3 Geology and Soil

The geology of the study area is basically underlain by Birimian Sedimentary with minor occurrence of Dahomeyan, Birimian Volcanic, Tarkwain and Upper Voltain dotted around the sub-basin**.**

3.3.1 Birimian Sedimentary

The Birimian Sedimentary covers about 66.4 % of the sub-basin. It is mainly pelitic in origin and consists of great thickness of alternating Phyllites, Schist, Greywacke, shales, , and argillaceous beds with some tuffs and lavas. It shows considerable variation in lithology with dark, grey slaty, and ashy variations (Kortatsi, 1997). The phyllites contain pods and lenses of meta-siltstone and greywackes. The sediments have been subjected to high pressures and the greywackes vary from fine to medium grain. Near the contact with the granite batholith metamorphism has produced biotite, staurolite, garnet and kyanite schists. Quartz veins are common in the Birimians Sedimentary rocks particularly in the phyllites and slates. The quartz veins are usually massive and mostly fissured. The rocks of the Birimian Sedimentary particularly the phyllites, greywackes, tuff and lavas are generally foliated, jointed and deeply weathered (Kortatsi, 1997).

3.3.2 Birimian Volcanic

The Birimian Volcanic overlies the Birimian Sedimentary conformably and it is volcanic in origin. It forms 12.6 % of the rock cover of the River Tain sub-basin of the Black Volta. The formation consists of great thickness of metamorphosed lava & pyroclastic rock & hypabyssal basic intrusive, phyllite & greywacke. The basic volcanics and pyroclastic rocks have been altered largely to chloritised and epidotised rocks that are loosely grouped together as greenstones. Where the greenstones have been subjected to dynomothermal metamorphism, they are converted to hornblende, schists and amphibolites (Kortatsi, 1997).

3.3.3 The Tarkwaian formation

The area covered by the Tarkwaian formation is approximately 11.5 % of the total area of River Tain sub-basin of the Black Volta Basin. It occurs in a narrow band between two Birimian Volcanics. The geological coordinates of the formation are latitude 7^{o} 72' N to 8^{o} 24′ N and longitude 2^{o} 58′ W to 2^{o} 24′ W. The Tarkwaian formation is of the middle continental origin derived from the Birimian and its associated granitic complexes. The formation consists of quartzites, phyllites, grits, conglomerates and schists. Generally it rests unconformable on the Birimian. However in some places, the Upper Birimian and Tarkwaian rocks are interfold due to post-Tarkwaian orogenic activity and the folding is along the axes which are in the North East to South -West directions (Kortatsi, 1997). The Tarkwaian is subjected to low grade metamorphism. High grade metamorphism is uncommon but where it occurs, it is often associated with intrusive rocks. Common intrusive rocks are thick laccoliths and sills of epidiorite (Kortatsi, 1997).

3.3.4 Upper Voltaian

The Upper Voltaian system covers approximately 3.7 % of the study area and occurs to the South Eastern part of the sub-basin and it covers Wenchi, Nchiraa, Botenso, Beposo, Subinso and Amponsakrom. The geographical coordinates of the formation are latitudes 7^{o} 63' N to 7^{o} 96' N and longitudes 2^{o} 07' W to 2^{o} 03' W. The Upper Voltaian system of the study area is massive with thin bedded quartzitic and micaceous sandstone (Kortatsi, 1997).

3.3.5 The Dahomeyan formation

The Dahomeyan formation forms about 5.9 % of the River Tain sub-basin of the Black Volta Basin. The greater part of it is found at south-eastern corner of the sub-basin below the Upper Voltaian with smaller portions forming islands in the Birimian Sedimentary formation at Babakrom in Banda district. The formation is compost of granitoid undifferentiated geological units. It is generally impervious with massive crystalline structure (Kortatsi, 1997).

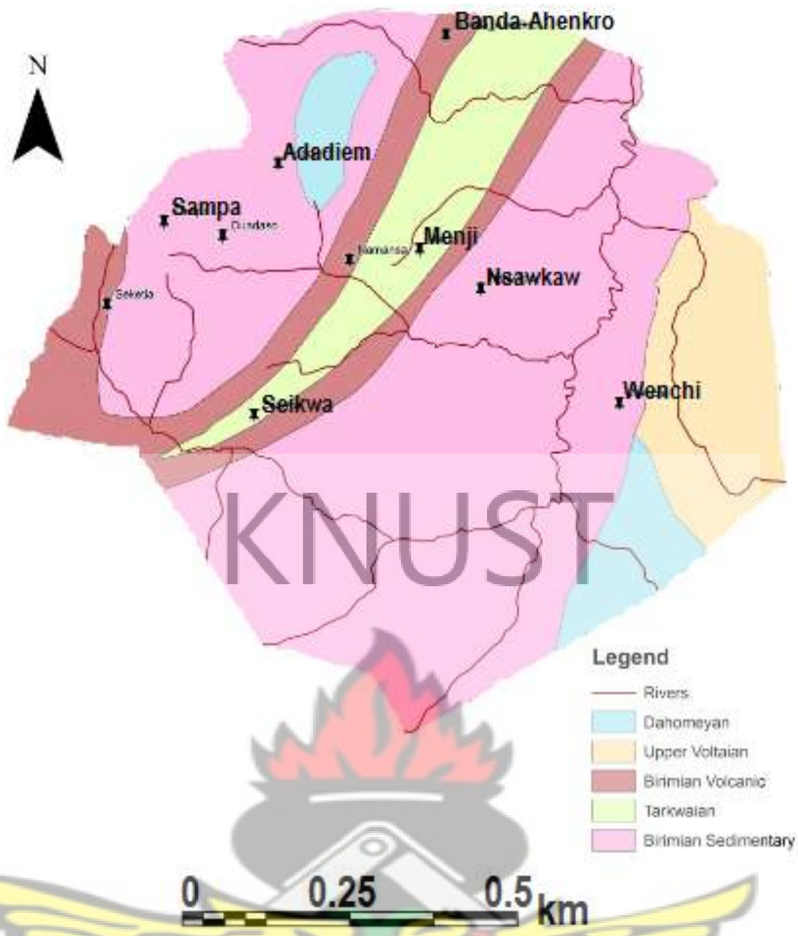

Figure 3.2 Geological map of the River Tain sub- basin

3.3.6 Soil

A greater proportion of the sub-basin falls under the savannah ochrosol with some lithosols. The land is generally low lying and most of the soils are sandy loam and in the valleys, loamy soils exist. Considering the mineral potential of these rocks, mountainous areas have potentials for gold exploitation (Districts report, 2012). The geology also provides rocks, which are quarried for road and building construction. There are clay deposits at Bonakire for pottery industry and burnt bricks and the soil supports the cultivation of savannah, transitional and forest crops.

3.4 Water and sanitation

Tain sub-basin of the Black Volta has 742 water points which are either served by a mechanised borehole or hand pump (Districts report, 2012). Towns with mechanised facilities include some district capitals and some major towns in the sub-basin such as Nchiraa, Subinso, Badu, Awisa, Droboso and Koase. In addition to these, there are 75 hand-dug wells, some of which are randomly located in the sub-basin many of which are found in Jaman North District. There are streams apart from Tain River that also serve the rest of the population. These streams are Yoyo, Subin, and Kyiridi, and are usually perennial.

The average time spent to access water in the sub-basin is 25 minutes. The waiting time in some communities such as Banda Sabiye, Adadiem, Jenini, Namasa, Yabraso and Menji are between 26.9 minutes and 58 minutes (Districts report, 2012)

4. RESEARCH METHODOLOGY

4.1 Data collection methods

The research was conducted using basically three methods that are in line with the objectives of the project topic. The methods used in the study are;

- Desk study of the project
- Field survey to collect relevant data on groundwater abstraction points and other important information relating to the objectives of the study.
- Data analysis using relevant software and interpretation of the results.

4.1.1. Desk study

In order to enhance the success of the investigations in the project area, geological and topographic maps of the study area were studied in order to identify local lineaments, their approximate locations and co-ordinates. Moreover, geophysical data of boreholes and hydrogeological reports and information were studied. The desk study enabled the inventory and diagnosis of lineament, the possible presence of aquifers, static water level, borehole logs, borehole yield, aquifer depth, the thickness of overburden and the aquifer zones pertaining to the study area. The climatic information pertaining to the study area was obtained from the Ghana meteorological services department. The population in the sub-basin was obtained from the Ghana Statistical Service Department at Sunyani. Table 4.1 indicates the type of data collected and their various sources.

Table 4.1. Types of data collected and the various sources:

Type of data	Source
Hydrogeological report	Community Water and Sanitation at Wenchi and Sunyani and private drilling companies.
Population Census	Ghana Statistical Service Department, Sunyani.
Topographical Map	Survey Department at Sunyani
Geological Report and Maps	Geological Service Department
Hydrometeorological Reports	Meteorological Service Department at Wenchi

4.1.2 Field Work

Visits were made to some communities in the sub-basin to locate their groundwater abstraction points, with the aid of Global Position System (GPS) Garmin's 76. Longitudes, Latitudes and the elevations of the water abstraction points were tracked during the field work. The elevation was important in the location of possible recharge and discharge points of the sub-basin and also to compare borehole yields in both low and highland areas.

The elevation of the sub-basin falls between 240 and 310 m above sea level. As a result, for the sake of this research, areas below 260 m above sea level were considered lowland areas. The value is the mean elevation of the sub-basin. However, this is only limited to this studies and does not apply to other areas beyond the study area. Visits were also made to on-going drilling sites in the sub-basin to have first hand information on pumping test, drilling logs, borehole depth, static water level, discharge and other parameters related to this study. Water samples were collected from twenty (25) boreholes well-spaced based on the areal extent of the various hydrogeological formations of the sub-basin for quality analysis.

4.1.3 Data Analysis

The post field activities was grouped into three, namely, hydrogeological (boreholes) approach, pumping test and water quality analysis.

4.1.3.1 Hydrogeological Data Analysis

The common borehole parameters such as well depths, discharge, static water level (SWL), dynamic water level (DWL) and Geological logs were obtained from hydrogeological reports of the sub-basin from the various groundwater developers. ArcGIS software was used to indicate the location of boreholes tracked during the field study on a map. With the aid of the drilling logs, the boreholes were partitioned according to the geological formation of the sub-basin.

The ranges of the borehole parameters were computed for the various geological formations. The specific capacity was computed using the following (Fetter, 2001):

$$Sc = Q/s \qquad 4.1$$

Where Sc = specific capacity (l/min/m)

Q = discharge in m^3/h

s = Drawdown (m) = DWL – SWL

Where DWL = dynamic water level and SWL = static water level

The relationship between borehole depth and discharge was determined using excel software.

4.1.3.2 Pumping test data analysis

A number of boreholes were selected from each geological formation for pumping test data analysis. The number of boreholes selected in each formation was based on the areal extent of that formation in the sub-basin. In all pumping test data from fifty eight (58) boreholes were analysed. Twenty five (25), sixteen (16), eleven (11) and six (6) boreholes were selected from Brimian Sedimentary, Birimian Volcanic, Upper Voltaian, and Tarkwain formations respectively. Dahomian formation was left out because pumping test had not been performed on the only wet borehole in the sub-basin during the study period. For each borehole, Displacement-time graph was drawn and Cooper and Jacob's method employed to determine aquifer transmissivity (T) using AQTESOLV software. Storage coefficient (storativity) was not determined because of the absence of observation wells in the sub-basin.

The following relation was used to determine aquifer transmissivity in the study:

$$T = \frac{2.303Q}{4\pi\Delta s} \qquad 4.2$$

Where T = Transmissivity

Q = discharge

Δs = drawdown per log cycle

4.1.4 Water Quality Analysis

The main aim of groundwater resources management and exploitation is to allocate groundwater in the right quantity and quality at the right time at the right locations. Based on this the physicochemical and bacteriological parameters of water from 25 boreholes were tested in the Civil Engineering laboratory at Kwame Nkrumah University of Science and Technology (KNUST), Kumasi. Four (9), three (7) two (6) and one (3) boreholes were selected from Brimian Sedimentary, Birimian Volcanic, Upper Voltaian, Dahomeyan and Tarkwain formations respectively. The selection was based on the areal extent of each hydrogeological formation in the study area. Factors considered in selection of boreholes for the collection of water samples were complains of hardness of water from the inhabitants, vegetation of the area and hygienic conditions of the environment. The parameters tested for are; calcium (Ca), Iron (Fe), Nitrate (NO_3^-), Magnesium (Mg), Sodium (Na), Flouride and pH. Water samples of 500 ml were taken from each borehole. In order to prevent the oxidation of the ferric ion before the laboratory analysis, 4ml of dilute Nitric acid (HNO_3) was added immediately after collection. The pH and temperature measurements were taken in situ immediately after the sample was taken on the field to prevent changes on their values that might occur on exposure to the atmosphere. Table 4.2 is the laboratory methods used for the analysis of the various parameters.

Table 4.2. Methods of physico-chemical analysis

Parameter	Method
PH, Total dissolved solids, Total suspended solids,	Electrometric
Temporary hardness, Calcium (Ca), Magnesium (Mg), Sodium (Na),	Titrimetric
Nitrite (NO_2^-), Nitrate (NO_3^-), Ammonia (NH_3), Fluoride, Total Iron, Sulphate, Manganese (Mn)	Colorimetric
Total Alkalinity	Potentiometric titration

4.2 Groundwater storage

It is the amount of water stored in the aquifers of the soil.

4.2.1 Total Groundwater storage

Total groundwater storage is the total amount of groundwater reserve underlying in a particular demarcated area. It was determined in the sub-basin by adopting the formula below after Schoeller, 1967:

$$Q_t = \bullet \theta HA \qquad 4.3$$

Where Q_{t} = total groundwater storage, $\bullet$ = percentage of study area underlain by groundwater zone, ɵ = porosity, H= mean thickness of the saturated zone, A = hydrogeological basin – extent of the study area m^2

4.2.2 Recoverable groundwater storage

The recoverable or usable storage capacity is the amount of groundwater that can be economically withdrawn from a basin as a source of long term annual supply (Schoeller, 1967). It was typically computed using equation 4.4

$$Q_r = \bullet \Psi HA \qquad 4.4$$

Where Qr = recoverable groundwater storage, Ψ= specific yield (m^3/h/m)

4.3 Population projection

Based on the WHO guidelines for 300 people per borehole threshold and the minimum yield of 13 l/min, groundwater accessibility in the study area was computed based on the population figures of 2012 population of the various communities forming the study area. This was projected from the population and housing census result of 2010. A growth rate of 2.2 % for Brong Ahafo Region was used.

The method used in projecting the population in the study is the compound rate of growth method, which can be computed with the help of the following formula adopted by Mehta, (1994):

$$Pn = Po\,(1+R/100)^n \qquad 4.5$$

Where P_n = population in the current year, Po = population in the base year, R= population growth rate and n= number of intermediary years.

5. RESULTS AND DISCUSSION

5.1 Groundwater Accessibility

WHO standards for 300 persons per a borehole as well as Community Water and Sanitation Agency (CWSA) borehole yield standard of 13 l/min was used during the study to determine the accessibility of groundwater to communities in the sub-basin. Based on this standard, it was realised in the study that majority of the population has no access to groundwater. At Amponsahkrom, in the Upper Voltaian formation, a population of 2496 depends on only one borehole with a yield of 15 l/min. Also Bonakire, Buni and Debibi all in the Birimian Sedimentary with populations of 2261, 3136, and 7006 respectively depend on 4, 6 and 9 boreholes instead of 7, 9 and 20 boreholes respectively, with yields ranging between 9 l/min and 12 l/min. This problem runs through almost all the rural communities in the sub-basin, creating tension and causing women and children to spend more man hours in queuing for water. Communities such as Adadiem, Jinago, Jenini, Nkona, Kokosua No 1&2 and Ayayor which have the required number of boreholes based on their population threshold still face water crisis due to frequent breakdown, low yield and drying of boreholes.

Figure 5.1 gives the summary of groundwater accessibility in the river Tain sub-basin. From the figure 60 % of the communities have less than the required number of boreholes based on the WHO threshold standard, 16 % of the sampled communities exceeded their threshold whiles 24 % have the exact number of boreholes based on their population. Appendix V gives the detail data on the groundwater accessibility in the sub-basin.

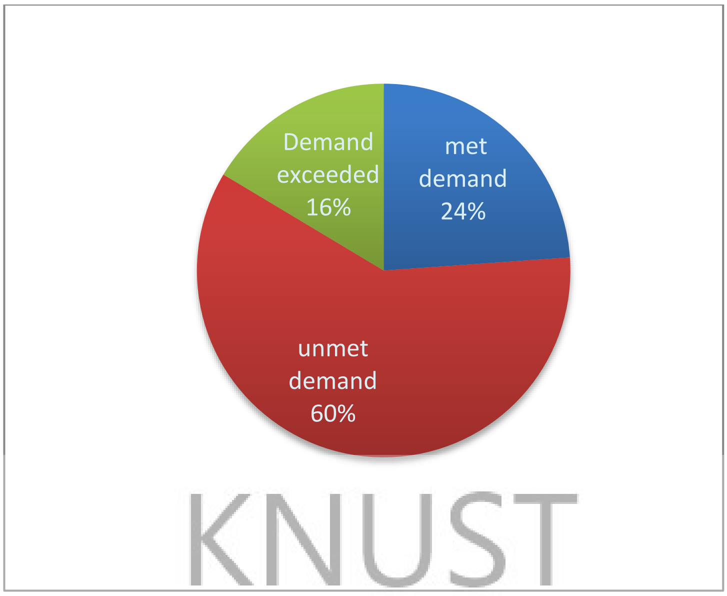

Figure 5.1. Percentage of water requirement met or unmet in the sub-basin

5.2 Boreholes in the geological formations

The study showed that the River Tain sub-basin of the Black Volta is underlain by five geological formations; Birimian sedimentary, Birimian Volcanic, Tarkwaian, Dahomeyan and Upper Voltaian. The Birimian Sedimentary forms 66.4 % of the entire geological formation in the sub-basin. Figure 5.2 indicates the distribution of boreholes in the various geological formations of the sub-basin. Available data indicates that there are about 742 boreholes in the sub-basin. Out of this number, 323 boreholes are found in the Birimian Sedimentary, 121, 134, 72 and 92 in the Birimian Volcanic, Upper Voltaian, Dahomeyan and Tarkwaian respectively. The areal extent of the various geological formations indicates that the boreholes are fairly distributed. Appendix IV and Figure 5.2 are the location of borehole point sources in the river Tain sub-basin.

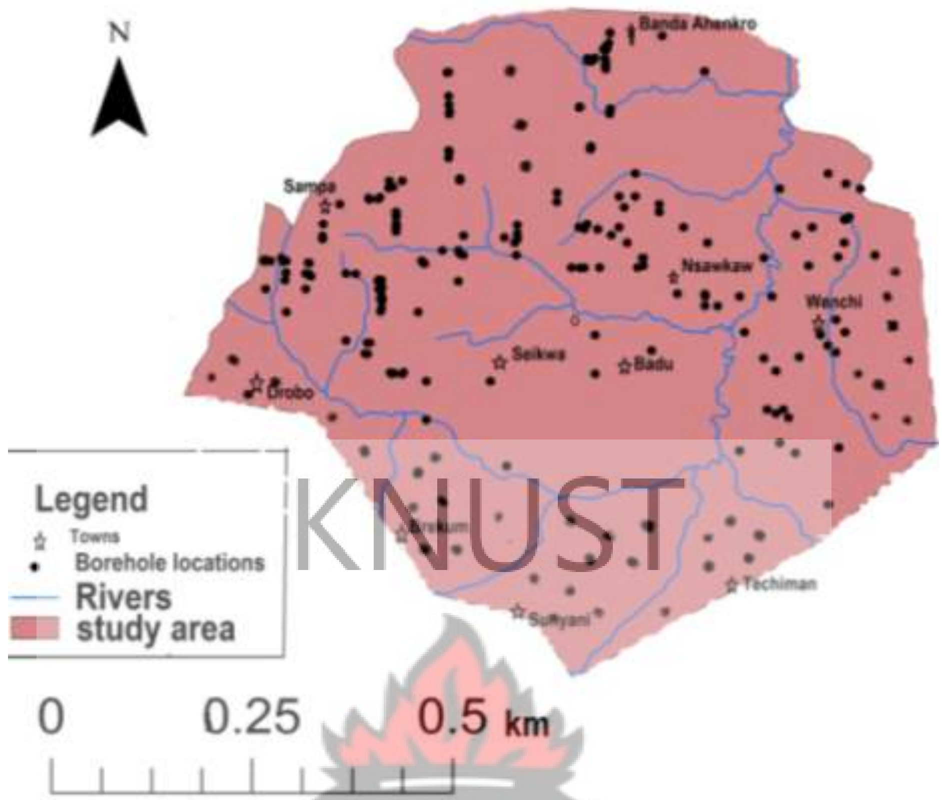

Figure 5.2 Groundwater point sources in the sub-basin

5.3 Aquifer characteristics

The depths to aquifer in the river Tain sub-basin vary widely from 13-52 m with a mean value of 30.5 m. Birimian Sedimentary which covers 66.4 % of the river Tain sub-basin has depth to aquifer ranging from 16-43 m with a mean value of 27 m while Birimian Volcanic, Upper Voltaian and Tarkwaian formations, the depth to Aquifer varies from 22-52 m, 19-43 m and 25-35 m respectively. However, most of the aquifers occur within the depth of 43m which indicates that the probability of striking substantial amount of water below the depth of 43 m is very low. The deepest depth to aquifer values occurs in the areas where the regolith is thickest such as Botenso, Nchiraa, Seketia, Akete among others while areas with thin regolith record the shallowest depth to aquifer.

The mean value of static water level in the study area of 17.6 m and the mean depth to aquifer of 30.5 m indicates that the water level in boreholes in the area rises several meters above the level at which water was struck. This is an indication that the groundwater in the study area exist under confined conditions especially towards the northern sector of the sub-basin. Some of the aquifers in the sub-basin are localized. This is justified by the fact that boreholes drilled closed to each other at distances ranging between 5 and10 m apart at Banda Nyire, Adadiem, Banda Sangma and Menji and many communities have varying yields. No phreatic aquifers were encountered during the study.

In the sub-basin, the aquifer materials encountered in the Birimian Sedimentary include laterite with quartz veins, deep brown clay, and dry fine clay at a depth of between 0-55 m with high to moderately weathered black shale between the depths of 55-70 m. In the Upper Voltaian sandstone, fine-textured dry sand with clay was encountered at the depth of 0 -55 m with highly weathered moist sandstone struck at the depth between 55-70 m. The data analyzed indicates that boreholes in the five geological formations ended in shale, sandstone or phyllite geological units. At the north-eastern part of the Upper Voltaian formation, clay layers were missing which suggest a possible recharge area for the aquifers.

Borehole yields in the sub-basin are highly variable. The yield values range between 7 l/min and 113 l/min with a mean value of 25.5 l/min suggesting that majority of the boreholes are low yielding as illustrated in Table 5.1. About 99 % of the boreholes sampled in the sub-basin were drilled for rural water supply scheme and therefore were fitted with hand pump. As a result of this, short duration of six (6) hour pumping test with a three hour recovery period was performed in all the data analysed. Data for the few mechanized boreholes were however not available during the study period for analysis.

Aquifer transmissivity was computed using the available six (6) hour duration pumping test data. The transmissivity values for the Birimian sedimentary range between 1.32 and 25.61 m^2/day while in the Birimian Volcanic, Upper Voltaian and Tarkwaian formations, transmissivity values range between 1.019 and 16.6 m^2/day, 3.14 and 40.58 m^2/day and 1.54 and 20.34 m^2/day respectively. For the two boreholes drilled in the Dahomeyan formation one was unsuccessful, however, pumping test was not performed on the wet well during the period of study.

5.4 Hydrogeological data analysis

Appendix III is the well inventory data compiled as basis for this study. The common borehole parameters such as well depths, discharge, static water level, dynamic water level, screen position, pump installation depth and the geological logs were considered. Table 5.1 summarises the important borehole parameters considered in the study.

Table 5.1. Summary of boreholes parameters in the Tain sub-basin of the Black Volta

Geological formation	Number of BHs	Depth (m)		Yield (l/min)		SWL(m)		Transmissivity (m^2/day)	
		range	mean	range	mean	range	mean	range	mean
Birimian Sedimentary	25	30-75	48.9	7-113	26.6	4.8-24.7	14.4	1.32-25.61	10.63
Birimian Volcanic	16	39-69	45.8	9-21	15	12.6-38.2	26.1	1.019-16.6	10.44
Dahomeyan*	2	40-70	55	**	**	**	**	**	**
Tarkwaian	6	40-56	47.2	12-20	16	4.9-27.8	16.4	1.54-20.34	7.29
Upper Voltaian	11	30-60	49.3	12-55	26.7	2.4-34.2	15.3	3.14-40.58	20.15

*pumping test had not been performed on the boreholes in the formation

5.4.1 Borehole Depths

Borehole depths in the river Tain sub-basin generally vary from 30 to 75 m with a mean value of 48.2 m. In the Birimian Sedimentary formation borehole depth are within the range of 30-75 m with a mean value of 48.9 m while the areas underlain by the Upper Voltaian, Birimian Volcanic, Dahomeyan and Tarkwaian formations, the boreholes recorded the depths ranging between 30 and 60 m, 39 and 69 m, 40 and 70 m and 40 and 56 m respectively. It should be noted that most of the boreholes in the sub-basin are partially penetrating.

Upper Voltaian however, has the highest mean depth of 49.3 m with the Birimian Volcanic recording the lowest mean value of 45.8 m. The mean depths of dry wells in the sub-basin are 50.4, 66, 59.5, 45 and 70 m for Birimian Sedimetary, Upper Voltaian, Birimian Volcanic, Tarkwaian and Dahomeyan geological formations respectively.

Available data indicates that apart from a borehole at Adadiem in the Birimian Sedimentary which is the deepest with a value of 75 m among all the wet boreholes in the sub-basin, other boreholes which are of the depth up to 70 m are mostly dry and are located on highlands. It is my conviction that the boreholes declared unsuccessful in the sub-basin rather ended prematurely and further drilling depth might have intercepted good aquifer zones. Figure 5.3 below illustrates borehole depth in the various geological zones in the sub-basin.

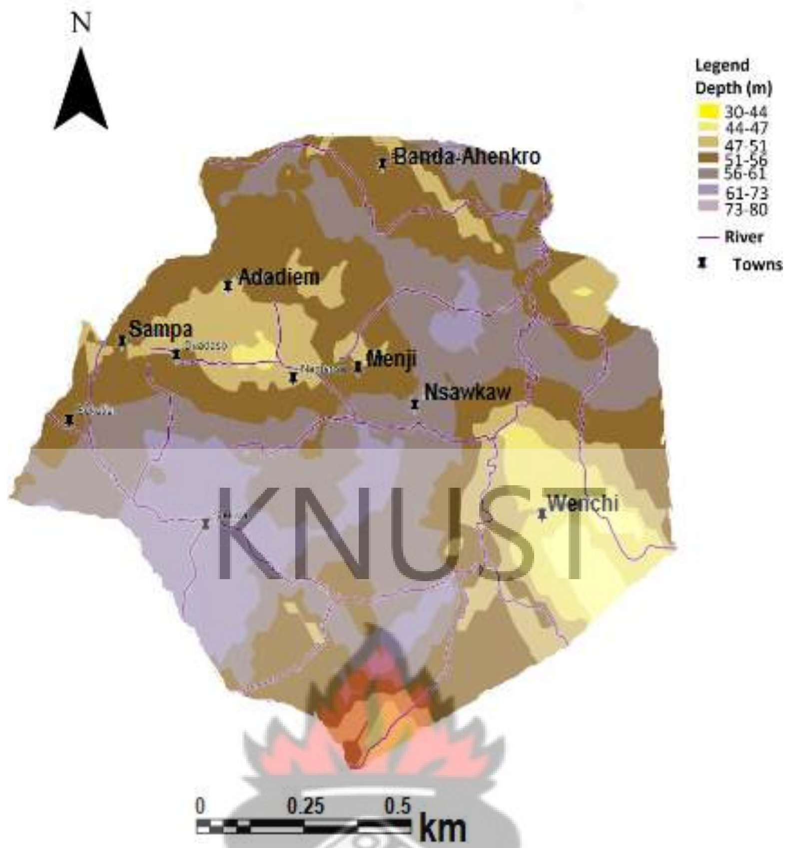

Figure 5.3. Borehole depths in the study area

5.4.2 Borehole Yields

According to Freeze and Cherry, 1979, a well yield is interpreted as the maximum possible sustainable pumping rate compatible with the stability of the supply from the aquifer. In order to determine the groundwater potential in an area, borehole yield plays an important role in addition to other aquifer parameters. Table 5.1 shows the ranges of borehole yields in the various geological formations in the study area. It is revealed from the table that Upper voltaian recorded the highest average yield of 26.7 l/min followed by Birimian Sedimetary with a mean value of 26.6 l/min while Birimian Volcanic and Tarkwaian formations recording the mean values of 15 and 16 l/min respectively. The values suggest that most of the boreholes in the sub-basin are low yielding. It is however important to note that most of the boreholes were drilled purposely for rural water supply and therefore boreholes were completed anytime adequate yield to meet rural supply was struck. As a result, the boreholes from which data was generated for the analysis were only partially penetrating the saturated aquifer thickness which may justify the reason for low yielding wells. Figure 5.4 is a borehole yield map in the study area.

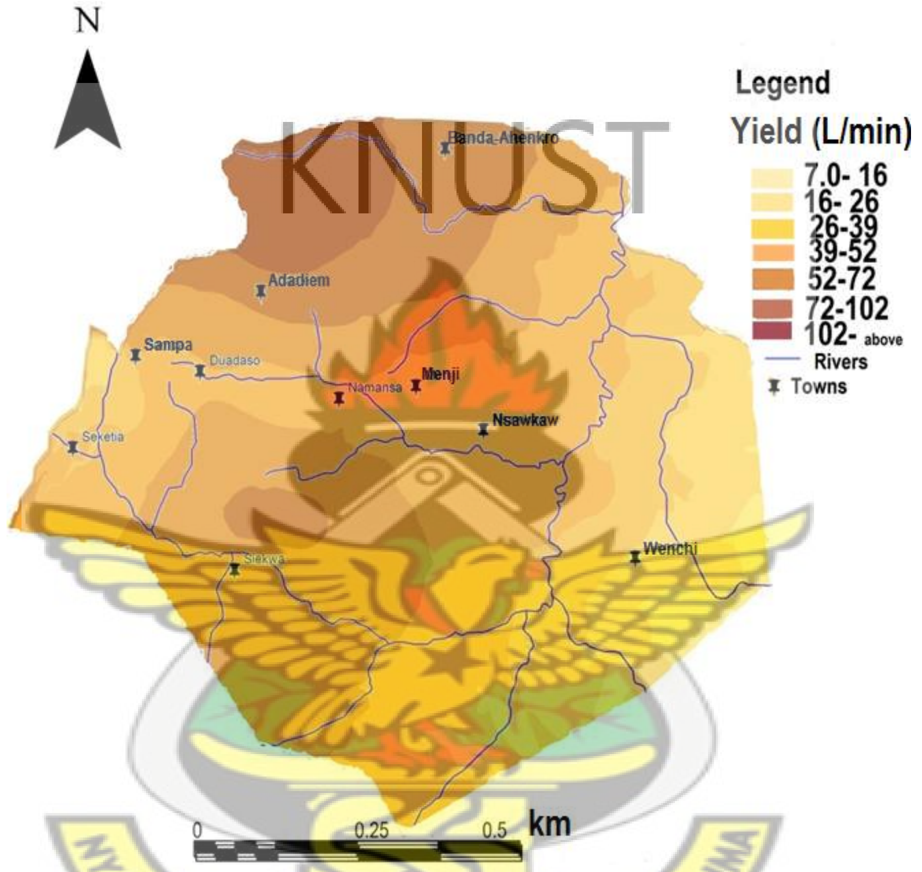

Figure 5.4 Borehole yield in the study area

5.4.3 Static water level

The static water level is the level of water in a well when no water is being withdrawn or added to an aquifer. In the River Tain sub-basin of the Black Volta, static water levels (SWL) generally vary based on the type of the geological formation. Available data for the four geological formations analysed indicates that Birimian Volcanic recorded the highest mean static water level of 26.1 m while the Tarkwain, Birimian Sedimetary and Upper Voltaian recorded the mean values of 16.4, 14.4 and 15.3 m respectively. Data on the Dahomeyan formation was not available for analysis during the study period. The shallowest static water level of 1.4 m occurred at Gedenge Newsite in the Birimian Volcanic with the deepest of 40.1 m occurred at Okyerekrom in the Birimian Sedimentary formation. Figure 5.5 below illustrates the static water levels of boreholes in the sub-basin.

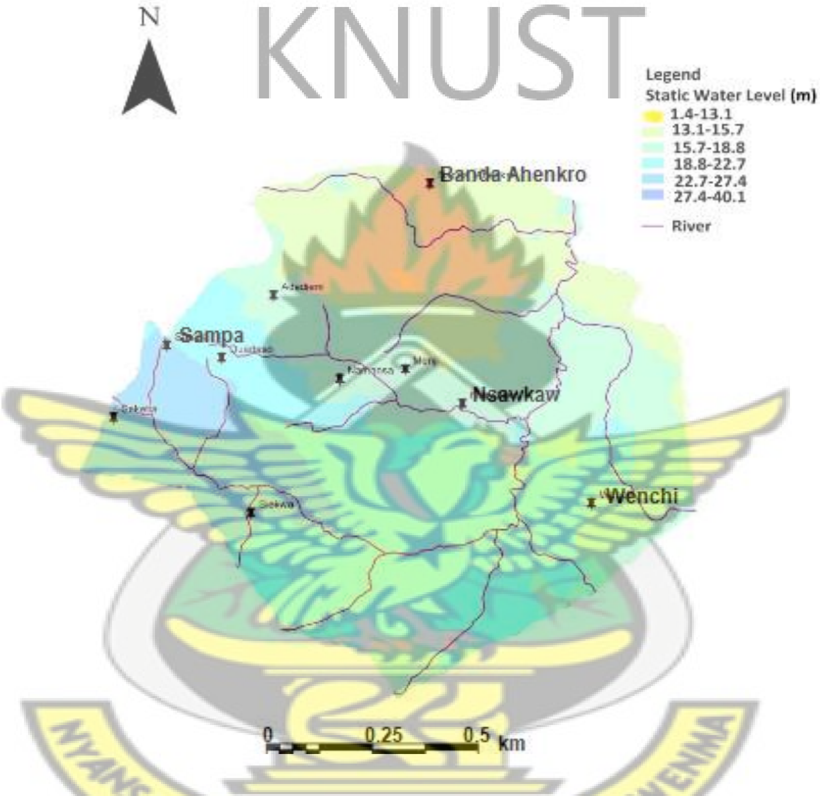

Figure 5.5. Static Water Level (SWL) in the sub-basin.

5.4.4 Specific Capacity

The specific capacity is an aquifer parameter which is used to determine whether a borehole will provide adequate water supply or not. It is defined as the discharge per unit time per drawdown (Karanth, 1987). Specific capacity depends on factors such as storativity, screen perforation size, aquifer transmissivity, duration of pumping as well as well development method. Figure 5.6 shows the specific capacity of boreholes in the sub-basin.

Birimian Sedimentary has a specific capacity range of 0.37-7.23 l/min/m with a mean value of 2.44 l/min/m while the specific capacities of the Tarkwaian, Birimian Volcanic and Upper Voltaian range from 1.89-2.33, 0.8-1.57 and 0.61-22.82 l/min/m respectively for a period of six (6) hour pumping and three (3) hour recovery periods. The low value of specific capacity in the sub-basin indicates that transmissivities in the various geological formations are generally low. However, the low values may be the effect of losses in the wells, geological boundaries and partial penetration of the aquifers by the boreholes. Figure 5.6 is the specific capacity of boreholes in the study area.

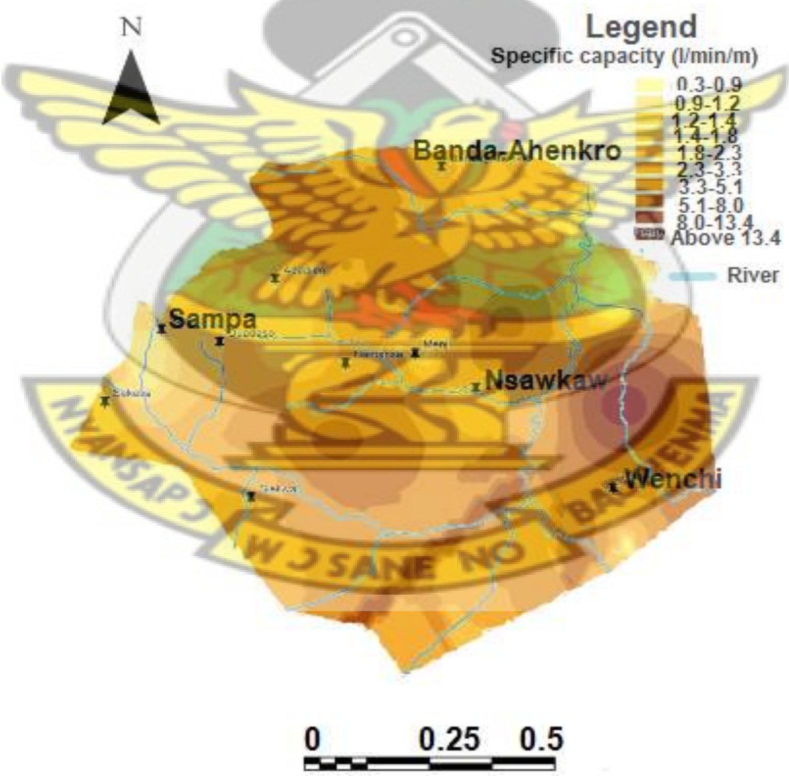

Figure 5.6. Specific capacity of boreholes in the sub-basin

5.4.5 Borehole success rate

Figure 5.7 indicates the borehole success rates in the various geological formations in the river Tain sub-basin. The above illustration could be taken as the groundwater potential of the individual geological units which form the sub-basin. Based on this assumption, then Tarkwaian formation which records 94 % success rate is the richest in terms of groundwater in the study area. The rock units that form this formation are quartzite, phyllite, schist, grit and conglomerate. Birimian volcanic is next with 88.9 % success rate and it is composed of phyllite, greywacke, metamorphosed lava and pyroclasic rock geological units. Birimian sedimentary which forms the largest formation in the sub-basin records 69.6 % success rate. This is a bit worrying situation because majority of the communities in the study area abstract groundwater from this formation. On the contrary to this finding, most of the high yielding boreholes are found in the formation, hence making it quite complex to conclude that it contains low yielding aquifers. The relatively low success rates in the formation could be attributed to the large variations in the transmissivity, variabl aquifers, groundwater exploration method employed in locating borehole sites, depth of boreholes and drilling practices.

Upper Voltaian which is composed mainly of sandstone has a success rate of 68.8 %. From the figure above, Dahomeyan formation which is made up of granitoid undifferentiated geological unit has the highest failure rate of 50 % and the least success rate. This is due to the fact that Dahomeyan formation has generally impervious weathered zone and massive crystalline structure which limit its groundwater yielding capacity. However, it is not much of interest in the sub-basin because it rarely occurs.

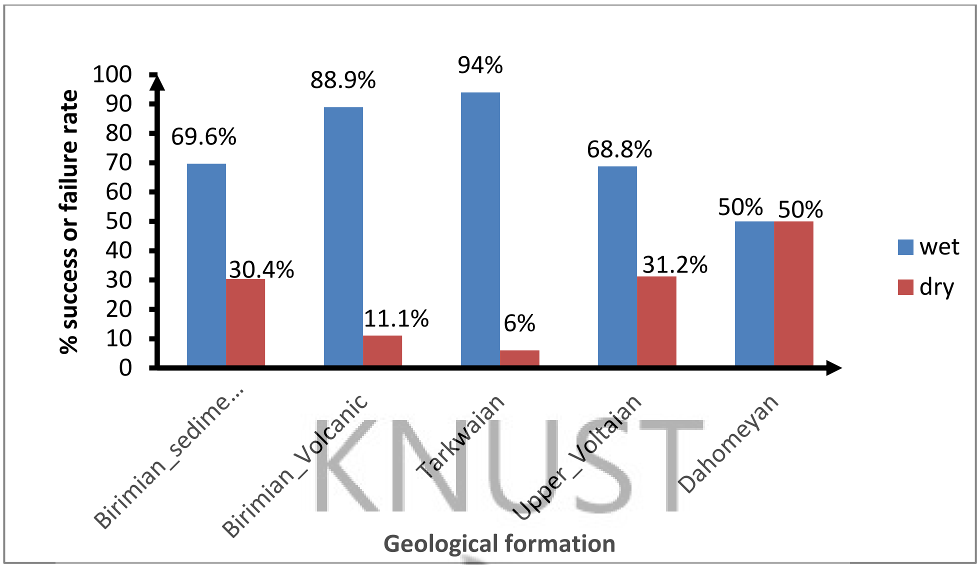

Figure 5.7 Borehole success and failure rate in the sub-basin

5.4.6 The relationship between borehole depth and yield

The research aims at establishing the relationship between the borehole yield and depth in the study area. It was observed in the research that the hydrogeology of the River Tain Sub-basin of the Black Volta is dependent on secondary porosity. As a result, it was assumed that the deeper the well, the higher the probability of encountering many fractured zones and invariably higher yielding zones. Figures 5.8 (a, b, c, and d) are plots of depths of boreholes against yield. Results from the plots indicate that there is poor correlations between yield and depth of the boreholes in the Birimian Sedimentary as well as all other geological formations since the highest yielding borehole of 47 m deep at Adadiem clinic has a yield of 113 l/min with others as shallow as 30 m at Agubie Kenasi and Ampieni have yields above 30 l/min and others as deep as 75 m at Adadiem, Kodua, Kwabena Suo, Damaabi have yields less than 10 l/min.

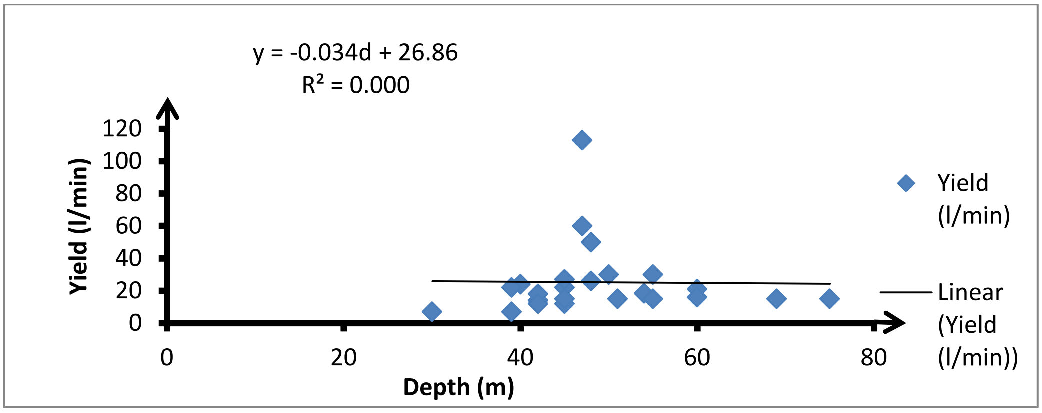

Figure 5.8a Borehole depth against yield in the Birimian Sedimentary

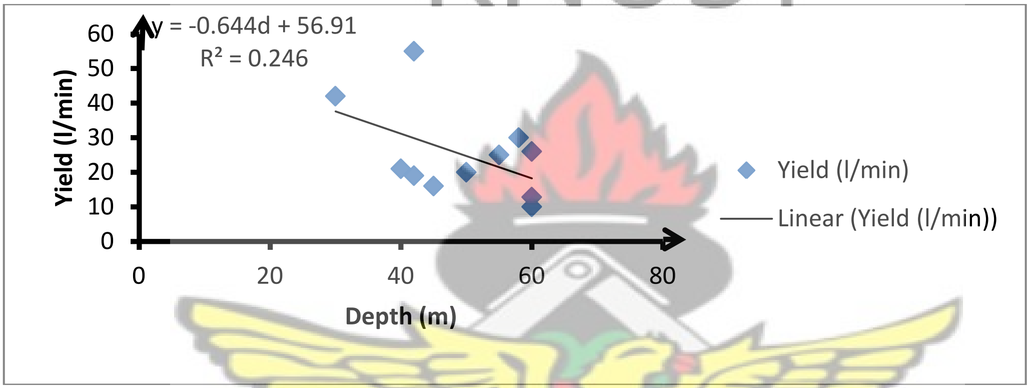

Figure 5.8b Borehole depth against yield in the Upper Voltaian

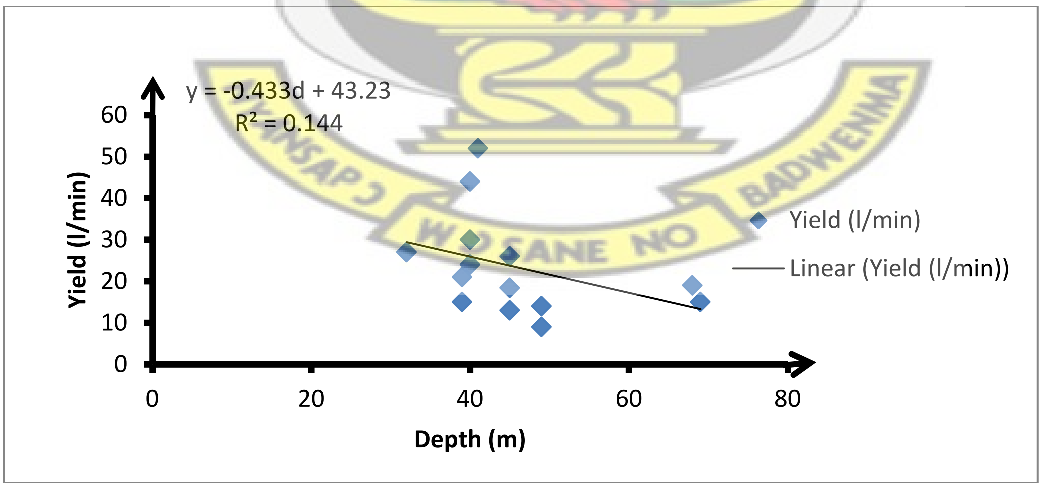

Figure 5.8c Borehole yield against depth in the Birimian Volcanic

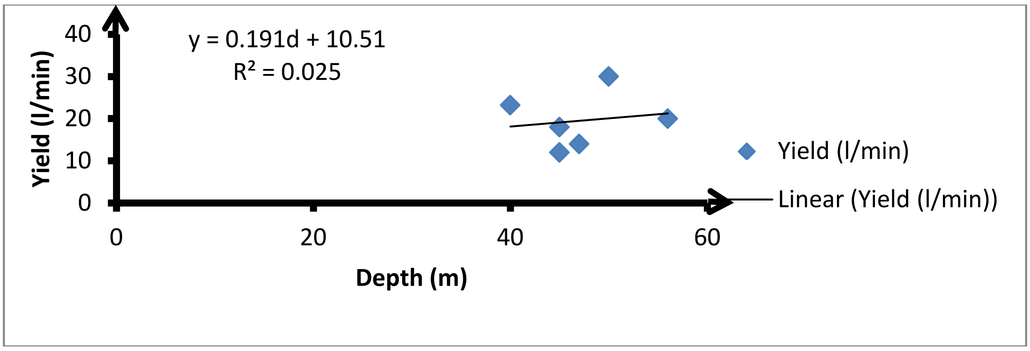

Figure 5.8d Borehole yield against depth in the Tarkwaian formation

5.4.7 The relationship between well depth and the topography in the sub-basin

The study revealed that topography plays a major role in the location of boreholes in the river Tain sub-basin. The number of boreholes sampled indicates that the groundwater recharge areas have higher yielding boreholes than in the discharge areas. Figure 5.9 below illustrates the correlation between borehole depth and height above sea level in the sub-basin. Valleys represent the recharge areas whiles highlands represent the discharge areas. This observation confirms the report by LeGrand (1954), that well success rate varies with topography in crystalline rocks in the Piedmont region of North Carolina. It is clear from the study that most deepest successful boreholes are found on the highlands indicating that with good groundwater exploration and drilling methods, uplands can also be good groundwater potential zones.

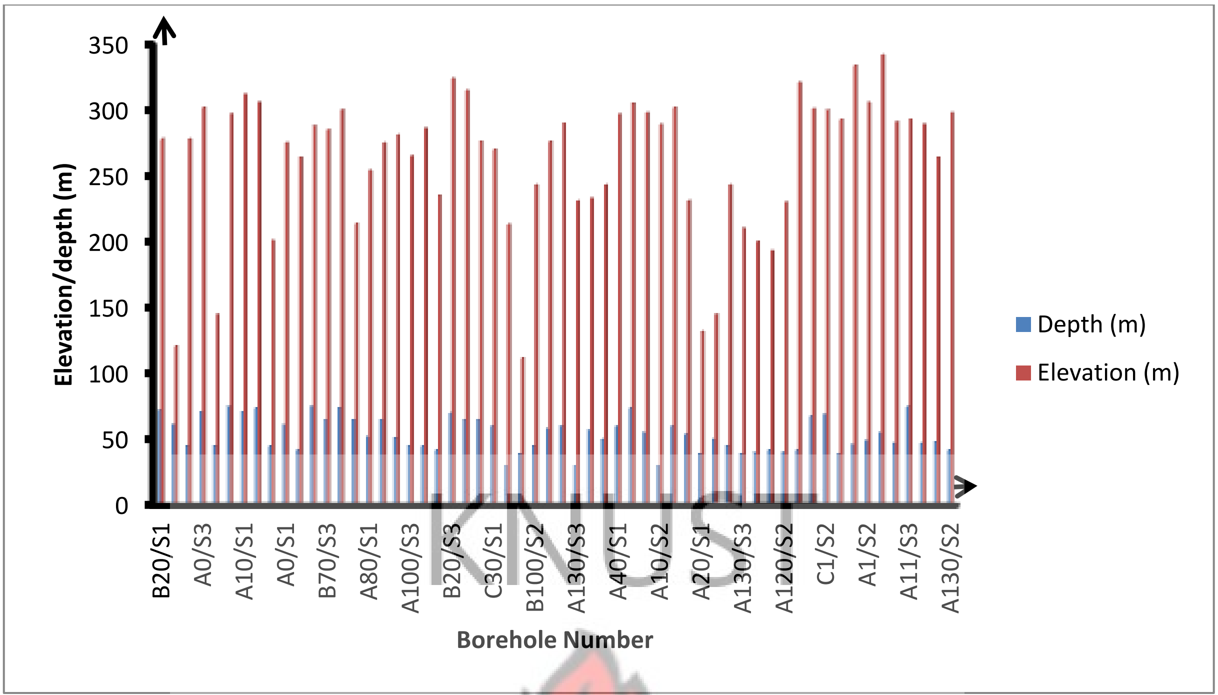

Figure 5.9 Relationship between well depth and topography

5.5 Groundwater occurrences

The aquifers of the river Tain sub-basin are crystalline in nature and therefore impermeable and virtually lack primary porosity. Groundwater occurrence therefore depends on secondary porosity through weathering, fracturing and fissuring. The main sources of groundwater supply to the aquifers are through the weathered layer or regolith developed on the crystalline basement rocks and fractures within the underlining bedrock. Factors such as topography, lithology and climatic conditions play a role in the variation of thickness in weathered zones, aquifer recharge and weathering of the underlying rocks. Basically, two types of aquifers were identified; they include fractured zone and weathered zone aquifers.

5.5.1 Fractured zone aquifer

Fractured aquifers were encountered at Adadiem, Arkokrom, Abekwai, Wala Nkwanta and Amoakokrom. The respective yields of the boreholes are 14, 15, 22, 52 and 16 l/min. The zones are composed of aplite veins, pegmatite, and quartz with some fissures.

Water bearing zones in the Upper Voltaian are made up of fractured decomposed rocks and fractured quartz veins in fresh rocks. Groundwater potential in the Upper Voltaian zone is very low. However, there is significant increase in groundwater where joints and fractures intercept stream courses. This explains why the boreholes at Amponsakrom, Botenso, Awisa and many communities in the formation were drilled near streams, although it is very difficult to locate such zones during water exploration. The wells developed in the fractured zones are mostly successful but low yielding due to low porosity.

In the Birimian Sedimentary and Volcanic formations, fissures zones were encountered underneath the thick regolith at Kwabena Suo, Kogua, Tadeakwae and Abekwai. The depth of the boreholes were, 74, 76, 68 and 72 m respectively and their respective yields were 26, 15, 22 and 22 l/min. Boreholes in the fissure zones are deeper than those drilled in the weathered layer. Also, they are very successful and fall between moderately to high yielding. It is my conviction that boreholes declared unsuccessful in weathered zones at the depths between 35 and 65 m at Yoomu, Obuasi Nchiraa, Amoakrom, Kwadwo Arko, Babakrom and Gedenga Newsite would have struck water if they were drilled further beyond the weathered zones.

5.5.2 Weathered Zone Aquifers

The weathered zone aquifers in the sub-basin cover the major aquifer zones and Birimian Sedimentary falls within these zones. The zones are either slightly, moderately, or highly decomposed rocks of quartz, shale, sandstone, mudstone, phyllite and granite. There is an outcrop of weathered zones at Agubie Kenase, Ohiampeanika, Droboso, Yoyoano and Suhum and extends to a depth of about 70 m at Okyerekrom, Damaabi, and Arkokrom with an average depth of about 25 m. The variation in thickness of the weathered zone depends on the geological formation, topography and the vegetation cover in the sub-basin.

The weathered zone recorded the highest percentage of failure rate and drying of boreholes in the sub-basin. These were recorded at Amoakrom, Atomfourso, Awiakrom, Mframaso, Aboabo and Yoomu at a depth of 60, 70, 75, 39, 70 and 80 m respectively. These boreholes were drilled during the dry season. However, if these boreholes were drilled further than their respective depths, they might have encountered rich aquifers. Also some boreholes at Banda Ahenkro, Buni, Seketia Town, Goka, Debibi, Namasa and many more were found dried after a short period of use. These were drilled in the wet season. This may be due to the fact that such boreholes ended in the weathered layer which retains percolated rain water when it encounters impermeable rock or clay layers. Such aquifers do not retain water for a long time and only supply water for hand-dug wells during the wet season and dry up during the dry season. Cave in and other construction materials such as the filter media sometimes also influence the drying of some boreholes. To strike substantial amount of water in the weathered zone in the sub-basin, boreholes drilled must not be below the depth of 45 m.

5.6 Groundwater Potential

The groundwater potential of the river Tain sub-basin was determined from the available data from boreholes drilled. Based on these data, total and recoverable quantities of groundwater storage were computed. The various borehole parameters such as specific capacity, static water level, and borehole logs were studied to identify the weathering front, groundwater zones, saturated thickness and unsaturated zones. Table 5.2 summarises the data used for the analysis. A borehole is considered unsuccessful when the yield is less than 7 l/min.

Available data shows that the aquifers in the sub-basin are produced in highly to slightly weathered rocks. The mean thickness of the weathered zones in the various geological formations forming the sub-basin is: 35, 49.3, 31.7, 40 and 15.3 m for Birimian Sedimentary, Upper Voltaian, Birimian Volcanic, Dahomeyan and Tarkwaian respectively.

Assuming the porosity of the aquifer materials (the poorly to moderately decomposed rocks) is 10 % (Freeze & Cherry, 1979) and the mean specific capacity of the sub-basin of 3.76 % with the area covered by the sub-basin of 5823.16 km^2, permanent groundwater reserves Q_t and the recoverable groundwater in storage Q_r are computed.

The total permanent groundwater reserve in the river Tain sub-basin is 6.89×10^7 m^3 whiles the total recoverable groundwater is 2.59×10^7 m^3. The latter value forms 38 % of the total permanent groundwater reserve in the sub-basin and it is the water which is available for abstraction by wells, recharging of streams and sometimes gush out as springs under favourable topographic conditions. The permanent groundwater reserves and recoverable groundwater storage for the various geological formations is summarized in Table 5.2 with other important parameters for the computations.

Table 5.2. Total and recoverable groundwater reserves in the five geological formationsin the river Tain sub-basin

Geological formation	Area covered (Km^2)	Mean Specific capacity (m3/min/m)	Percentage of saturated zone in the formation	Mean Saturated Thickness (m)	Total groundwater reserves (m^3)	Total recoverable groundwater reserves (m^3)	Percentage of recoverable groundwater as the total groundwater vol. (m^3)
Birimian Sedimentary	3865	2.44	75.9	17.32	5.08×10^7	1.2×10^7	23.6
Birimian Volcanic	731.9	1.3	88.2	15.71	1.01×10^7	1.3×10^6	12.9
Upper Voltaian	217.2	3.62	68.8	18.42	2.7×10^6	9.96×10^5	36.9
Dahomeyan	342.4	**	**	**	**	**	**
Tarkwaian	667.1	2.14	66.7	14.75	6.56×10^6	1.40×10^6	21.3

**pumping test had not been done during the period of study

5.7 Water Quality Analysis

Available data from sampled boreholes in the river Tain sub-basin indicates that the quality of groundwater abstracted through boreholes is generally of good physicochemical quality and therefore suitable for domestic including drinking, agriculture and industrial uses. The water quality standard is within WHO (2004) guidelines limits. Table 5.3 and Appendix VII present the various water quality parameters that were measured.

Table 5.3. Water quality ranges in the various geological formations in the sub-basin

Parameter	Unit	Geological formation/Quality range				WHO Standard
		UV	BS	BV	TARK	
Calcium	ppm	12-28	21-108	4-14	9.6	-
Magnesium	ppm	1.5-8.5	2.7-12.2	8.5-9.6	3.9	-
Sodium	ppm	4.0-23	5.0-30	10-17	3.0	300
Nitrate	ppm	0.2-12	0.3-3.0	0.4-7.0	0.3	50
Iron	Ppm	0.01-0.2	0.003-0.15	0.003-0.01	0.03	0.3
Nitrite	ppm	0.001-0.9	0.003-0.14	0.01-0.3	0.14	3.0
Sulphate	ppm	0.0-15.0	0.5-20.0	0.5-9.0	0.0	250
Manganese	ppm	0.0-0.5	0.0-0.001	0.0-0.1	0.00	-
Potassium	ppm	2.0-13.0	0.0-5.0	0.0-6.5	1.0	30

5.7.1 The pH

WHO recommended pH value for domestic drinking water is in the range of 6.5-8.5. Water sampled from the boreholes in the river Tain sub-basin indicates that their pH values fall within the recommended WHO value except a borehole at Wurumpo with a borehole number A30/S2 which has a value of 6.4. It falls within the Upper Voltaian formation.

5.7.2 Bacteriological quality analysis

Out of seventeen boreholes sampled in the sub-basin indicates that seven (7) contain coliforms beyond the WHO recommended limit of 0.0 MPN Index/100 mL each of Total Coliforms, Interococci, Faecal coliform and 0-3 CFU Total Meterotrophic Bacteria. The boreholes with microbiological problems include the following; Droboso (BH. No. A140/S3), Atomfourso (BH. No. A/10/S2), Faaman (BH No. Not Available), Ampieni (BH. No. A/130/S3), Bonkuro No1 (BH. No. A/10/S1), Subinso (BH. No. B/70/S3 and Adwee (BH. No. B/100/S2). Their depths range between 39 and 50 m. These are mostly found near communities and could have been originated from anthropogenic sources including improper sitting of sanitation facilities and percolation of remains of animal dropping in the shallow aquifers since the boreholes are shallow.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

Based on the research undertaken on baseline study into groundwater resources in the river Tain sub-basin of the Black Volta, the following conclusions were drawn from the findings:

- Borehole yield in the sub-basin does not depend on the depth since boreholes with depth range between 20 and 30 m at Ampieni Agubie Kenasi, Abotereye, Ohiampeanika among others gave average yield of 40 l/ min whiles boreholes with depth range between 50 and 80 m at Adadiem, Kodua and Damaabi gave average yield of 8 l / min.
- The aquifers in the sub-basin are low yielding because average aquifer yield is 32 l/ min with a range between 7 and 113 l/ min and it varies from one geological zone to another.
- About 60 % of the communities forming the river Tain sub-basin did not have the required number of boreholes based on the WHO recommendation of 300 persons per a borehole leading to perennial water problems in such communities.
- Groundwater quality in the sub-basin falls within the WHO (2004) guideline limits for domestic water use, except a few areas which form 30 % of the sampled communities

6.2 Recommendations

The following recommendations were made based on the outcome of the research on baseline studies into the groundwater resources in the Tain Sub-basin of the Black Volta:

- Borehole depths should go beyond the weathered zones where there is the likelihood of striking rich and sustainable water bearing aquifers.

- More research should be conducted into areas where aquifer protective capacities fall between poor to weak owing to high content of sand in the overburden layer so that good measures could be taken to reduce the underground water vulnerability to surface contamination.
- Due to the inadequacy of the groundwater resources in the sub-basin, high yielding boreholes should be mechanized for community water supply to increase water accessibility and reduce drilling of more boreholes.

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APPENDIX

Appendix I: Sample Check List

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<tr><td colspan="10">Date of mapping</td></tr>
<tr><td colspan="10">Loction</td></tr>
<tr><td>Name of comm’ty</td><td>Pop.</td><td>Elevation</td><td>Type of pump</td><td>ID</td><td>Accuracy</td><td>No. of water points</td><td>Long</td><td>Lat</td><td>Date of construction</td></tr>
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Appendix II: Rainfall (mm) in the sub-basin

Year	Jan	Feb	Mar	April	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Total	Mean
1975	0.0	35.3	162.6	100.8	162.6	93.0	260.3	61.0	84.1	186.7	31.0	1.8	**1179.2**	**98.3**
1976	0.0	110.0	97.3	198.7	134.5	235.7	61.3	56.7	128.0	169.3	94.0	0.0	**1285.5**	**107.1**
1977	38.0	23.1	13.3	120.0	159.3	82.1	99.3	146.8	196.3	272.7	4.2	3.6	**1158.7**	**96.6**
1978	0.0	19.1	144.1	108.2	110.0	221.6	154.9	21.8	151.7	153.0	52.6	3.3	**1140.3**	**95.0**
1979	8.4	0.0	65.5	113.5	91.8	160.5	244.8	69.4	192.1	284.8	45.7	0.3	**1276.8**	**106.4**
1980	27.8	31.1	37.2	195.4	78.2	138.5	191.2	45.0	222.4	193.2	97.3	2.3	**1259.5**	**105**
1981	0.0	3.8	229.7	106.4	123.1	50.9	141.7	147.4	238.7	251.3	12.6	Trace	**1305.6**	**108.8**
1982	0.0	23.0	29.7	179.4	118.7	63.1	144.2	67.0	103.2	153.8	9.2	0.0	**891.3**	**74.3**
1983	0.0	7.9	12.6	137.2	264.4	112.5	19.0	4.3	142.4	124.7	0.3	21.3	**846.6**	**70.6**
1984	0.0	0.5	205.5	213.4	186.0	143.4	224.1	214.0	148.6	112.4	53.1	0.0	**1501**	**125.1**
1985	9.9	1.9	131.6	176.4	141.3	131.1	237.0	186.1	243.3	167.8	70.1	0.0	**1396.5**	**116.4**
1986	4.2	11.0	116.8	164.7	102.6	114.4	100.3	109.9	178.3	219.8	47.5	0.0	**1173.3**	**97.8**
1987	0.0	24.2	132.4	34.1	144.4	116.6	134.0	156.9	297.8	201.5	8.8	0.4	**1251.1**	**104.3**
1988	10.4	54.5	179.8	96.6	107.4	155.7	166.5	77.7	225.2	121.2	14.6	0.0	**1209.6**	**100.8**
1989	0.0	0.00	166.7	159.0	158.2	347.6	241.5	157.5	214.9	274.4	20.1	20.3	**1759.6**	**146.6**
1990	3.0	29.0	Trace	124.5	101.5	156.8	35.3	93.8	284.2	144.9	89.8	96.5	**1159.3**	**96.6**
1991	0.0	42.9	118.5	189.6	344.1	92.3	170.6	158.0	116.8	119.7	35.3	20.4	**1408.2**	**117.4**
1992	3.2	21.6	33.8	184.4	250.7	154.8	103.1	13.5	267.5	110.3	142.8	0.0	**1285.7**	**107.1**
1993	0.0	19.1	283.0	92.7	186.4	139.2	73.0	28.6	247.9	75.0	53.3	14.2	**1212.4**	**101.0**
1994	0.0	2.0	103.7	80.9	116.2	119.3	19.7	87.7	90.8	260.6	37.7	0.0	**918.6**	**76.6**
1995	0.0	1.9	76.8	232.3	163.5	177.9	115.8	117.6	290.6	145.6	16.9	33.7	**1372.6**	**114.4**
1996	0.0	94.4	66.8	202.4	198.1	177.8	90.8	138.6	82.5	74.5	1.8	28.0	**1155.6**	**96.3**
1997	0.3	0.0	121.8	93.2	183.7	153.0	74.2	78.0	99.7	197.6	18.3	0.0	**1019.8**	**85.0**
1998	2.1	10.4	2.0	207.5	156.3	205.8	25.7	57.7	174.4	157.0	40.1	13.5	**1052.5**	**87.7**
1999	2.4	37.2	193.7	192.5	160.5	111.0	113.0	105.8	101.5	188.3	82.9	0.0	**1288.8**	**107.4**
2000	49.2	0.0	31.8	153.2	135.9	294.0	170.6	73.6	90.4	138.6	49.7	0.0	**1159.2**	**96.6**

Appendix III: Data on existing successful and unsuccessful boreholes

a. Successful boreholes

BIRIMIAN SEDIMENTARY

No.	Community	BH No.	Drilling date	Airlift Yield (L/min)	Depth (m)	Geo. unit	Screen position (m)	Pumping test results				Specific capacity (l/min/m)
								Discharge (L/min)	SWL (m)	DWL (m)	Draw-down	
1	Adadiem	A1	2012	18.0	75	Shale	53-56, 68-74	14	15.46	53.22	37.76	0.37
2	Adadiem Clinic	C1	2012	150	47	Shale	25.31, 43-46	113	5.79	23.38	17.50	6.46
3	Agubie Akroma	A10/S1	2011	30	42	Shale	25-33,39-41	24.0	23.42	34.98	11.56	2.08
4	Agubie Kenasi	A30/S2	2011	60	33	Shale	21-32	42.0	7.67	19.81	12.14	3.46
5	Arkokrom	A0/S3	2012	38	71	Sandstone	55-57,61-70	16	37.25	44.24	6.99	2.29
6	Atomfourso	AO/S1	2011	15	45	Shale	36-44	12	20.25	30.85	10.6	1.13
7	Bonakire	A1	2012	50	48	Shale	29-35, 41-47	50	11.67	33.21	21.54	2.32
8	Damaabi	B100/S1	2012	14	74	Shale	51-53,71-73	20	31.47	40.25	8.78	2.28
9	Droboso	A140/S3	2011	40	39	Shale	26-38	22	7.7	14.25	6.55	3.36
10	Hiamakyene	A10/S2	2011	30	42	Shale	29-35,39-41	18	7.1	17.23	10.13	1.78
11	Jenini	A1	2012	80	47	Shale	35-38, 41-44	60	16.36	24.56	8.30	7.23
12	Kodua	A10/S1	2012	20	76	Sandstone	59-64,69-74	15	35.77	43.55	7.78	1.93
13	Kwabena Suo	B50/S1	2012	32	74	Sandstone	52-54,64-73	26	17.58	25.01	7.43	3.50
14	Mayera	B1	2012	40	55	Shale	41.5-53.5	30	13.28	34.03	20.75	1.45
15	Mother Care	A70/S1	2012	20	51	Sandstone	37-44,48-50	15	24.23	32.4	8.17	1.84
16	New Site	A100/S3	2011	30	45	Shale	26-31, 39-44	22	4,82	12.83	8.01	2.75
17	Nkona	B100/S3	2011	32	45	Sandstone	26-32, 37-44	27	5.42	15.95	10.53	2.56
18	Nyamebekyere	A40/S3	2011	33	50	Sandstone	37-49	30	10.26	22.02	11.94	2.51
19	Nyamponase	A30/S3	2011	20	45	Shale	26-32, 38-44	15.0	23.49	31.95	8.46	1.77
20	Ohiampeanika	A20/S1	2011	20	42	sandstone	26-35, 38-40	14	19.88	29.62	9.74	1.44
21	Okyerekrom	B20/S1	2012	23	70	Sandstone	54-59,64-69	14	40.12	49.95	9.83	1.42

22	Suhum	A120/S3	2011	20	40	shale	27-29, 34-39	24.0	9.84	20.88	11.04	2.17
23	Yoyoano	A130/S2	2011	30	42	Shale	22-34, 37-41	12	25.5	38.49	10.99	1.09

BIRIMIAN VOCANIC GEOLOGICAL FORMATION

No.	Community	BH No.	Drilling date	Airlift Yield (L/min)	Depth (m)	Geo. unit	Screen position (m)	Pumping test results				Specific capacity (l/min/m)
								Discharge (L/min)	SWL (m)	DWL (m)	Draw-down	
1	Abekwai	B20/S1	2012	23	72	Shale	50-52,69-71	22	20.33	29.94	9.61	2.29
2	Agblekama	A160/S1	2012	21	61	Sandstone	45-51,54-60	13	9.62	20.21	10.59	1.23
3	Amanfoso	B1	2011	12	46	Sandstone	33-45	9	38.15	44.17	6.02	1.50
4	Antwikrom	B30/S1	2011	20	45	Shale	29-35,39-44	13	12.56	20.83	8.27	1.57
6	Gedenge Newsite	A130/S2	2012	37	61	Sandstone	45-60	42	1.4	13.61	12.21	3.44
7	Kokosu DA	A1	2011	20	39	Sandstone	23-29, 32-38	15	14.33	28.32	13.99	1.07
8	Komasu	A0/S1	2012	Dry	54	Sandstone	38-44,47-53	16	29.35	36.73	7.38	2.17
9	Kwaku Donkor	A80/S1	2012	55	52	Sandstone	38-46,46-51	18	17.82	24.02	6.2	2.90
11	Old Drobo	A1	2011	18	49	Shale	33-48	14	24.89	35.58	10.09	1.39
12	Pentecost Newsite	A90/S1	2012	43	55	Sandstone	38-46,48-54	33	10.82	6.84	3.98	8.29
13	Seikrom	A130/S3	2012	29	39	Shale	29-38	21	20.23	34.21	13.98	1.50
14	Seketia Clinic	A1	2011	25	68.0	Sandstone	52-67	19	34.32	51.67	17.35	1.10
15	Seketia Town	A1	2011	25	68.0	Sandstone	52-67	19	34.32	51.67	17.35	1.10
16	Tadeakwae	B120/S1	2012	27	65	Phyllite	49-55,59-64	22	5.75	18.29	12.54	1.75
17	Wala Nkwanta	A60/S1	2012	65	65	Shale	49-52,55-64	52	8.8	14.52	5.72	9.09

UPPER VOLTAIAN GEOLOGICAL FORMATION

No.	Community	BH No.	Drilling date	Airlift Yield (L/min)	Depth (m)	Geo. unit	Screen position (m)	Pumping test results				Specific capacity (l/min/m)
								Discharge (L/min)	SWL (m)	DWL (m)	Draw-down	
1	Aboabo	B130/S3	2012	15	60	Sandstone	44-47, 51-60	14	24.66	43.1	18.44	0.76
2	Abotereye	B110/S2	2011	30	30	Shale	17-28	7	7.8	27.25	19.45	0.36
3	Abotereye	B10/S1	2011	14	39	Shale	26-38	7.0	9.85	30.6	20.75	0.34
4	Adwee	B100/S2	2011	120	45	Sandstone	26-31, 38-44	16	11.8	21.1	9.30	1.72
5	Akete	A50/S1	2011	33	58	Sandstone	44-56	30	34.23	46.8	12.57	2.39
6	Amoakokrom	A70/S3	2012	19	73	Sandstone	57-63,67-72	16	29.35	36.73	7.38	2.17
7	Ampieni	A130/S3	2011	80	30	Shale	24-29	42	2.35	21.70	19.35	2.17
8	Bonkro No 1	A10/S1	2011	25	50	Sandstone	37-49	20	8.7	16.79	8.09	2.47
9	Botenso	Ao/S1	2012	18	60	Shale	44-46, 51-59	12.8	9.8	30.85	21.05	0.61
10	Buasu	AD/S1	2011	20	60	Sandstone	30-39	26	7.74	20.24	12.50	2.08
11	Congo	B270/S2	2011	30	55	Sandstone	36-38, 42-54	25	30	38.44	8.44	2.96
12	Subinso No1	A40/S2	2012	20	40	Shale	27-29, 33-39	21	15.3	33.71	18.41	1.14
13	Subinso No1	B70/S3	2012	11	42	Shale	20-41	10	8.65	24.4	15.75	0.63
14	Wurompo	A30/S2	2011	18	42	Shale	27-32,36-38	55	21.93	24.34	2.41	22.82

TARKWAIAN GEOLOGICAL FORMATION

No.	Community	BH No.	Drilling date	Airlift Yield (L/min)	Depth (m)	Geo. unit	Screen position (m)	Pumping test results				Specific capacity (l/min/m)
								Discharge (L/min)	SWL (m)	DWL (m)	Draw-down	
1	Faaman	A20/S2	2012	23	64	Shale	55-63	20	27.83	36.22	8.39	2.38
2	Fawoman	A10/S1	2012	20	40	Sandstone	27-29,33-39	18	4.87	14.38	9.51	1.89

3	Fula	A10/S1	2012	20	45	Sandstone	36-44	18	7.34	25.23	17.89	1.01
4	Kojo Arko	B70/S3	2012	65	65	Shale	49-51,56-64	22	25.1	31.17	6.07	3.62

DAHOMEYAN FORMATION

No.	Community	BH No.	Drilling date	Airlift Yield (L/min)	Depth (m)	Geo. Unit	Screen position (m)	Pumping test results				Specific capacity (l/min/m)
								Discharge (L/min)	SWL (m)	DWL (m)	Draw-down	
1	Kwaekesim	A20/S1	2012	42	65	Phyllite	**	**	**	**	**	**

**Pumping Test had not been performed on the borehole

b. Unsuccessful boreholes

No.	Community	BH No.	Drilling date	Airlift Yield (L/min)	Depth (m)	Geo. Unit	GEOLOGICAL FORMATION
1	Babakrom	A10/S1	2012	Dry	77	Granitoids	Dahomeyan
2	Bandawai	A10/S1	2012	Dry	71	Shale	Tarkwain
3	Kojo Arko	A80/S1	2012	Dry	76	Shale	Tarkwain
4	Congo	A10/S3	2012	Dry	70	sandstone	Upper Voltaian
5	Oboase Nchiraa	A10S2	2012	Dry	80	Shale	Upper Voltaian
6	Botenso	A40/S1	2012	Dry	70	Shale	Upper Voltaian
7	Boase Kwadom	B20/S2	2012	Dry	67	Shale	Upper Voltain
8	Amoakokrom	A10/S1	2012	Dry	80	Sandstone	Upper Voltaian
9	Abotereye	A60/S3	2011	Dry	70	Shale	Upper Voltaian
10	Aboabo	C30/S1	2012	Dry	70	Sandstone	Upper Voltaian
11	Mframaso Landry	A20/S1	2012	Dry	39	Sandstone	Birimian Volcanic
12	Gedenge Newsite	A0/S1	2012	Dry	75	Sandstone	Birimian Volcanic
13	Amoakrom	B30/S1	2012	Dry	60	Sandstone	Birimian Sedimentary
24	Atomfourso	A60/S2	2012	Dry	70	Shale	Birimian Sedimentary

15	Awiakrom	B10/S2	2012	Dry	75	Shale	Birimian Sedimentary
16	Droboso	A10/S2	2011	Dry	65	Shale	Birimian Sedimentary
17	Droboso	A10/S1	2012	Dry	30	Shale	Birimian Sedimentary
18	Hiamakyene	A30/32	2012	Dry	60	Sandstone	Birimian Sedimentary
19	Yoomu	A30/S1	2012	Dry	80	Shale	Birimian Dedimentary
20	yoomu	A80/S2	2012	Dry	90	Shale	Birimian Sedimentary

Appendix IV: Location of borehole point sources

No	community	BH. No	Geographical location		Elevation (m)	Year Drilled	Geological formation
			Longitude	Latitude			
1	Adadiem	234F874BH2	2^{o}33’09.8”	8^{o}04’54.4”	296	2000	Birimian Sedimentary
2	Adadiem	544F844BH3	2^{o}33’09.6”	8^{o}04’54.6”	297	2005	Birimian Sedimentary
3	Adadiem	2004F374BH1	2^{o}33’10.7”	8^{o}04’54.7”	297	1999	Birimian Sedimentary
4	Adadiem	304F8BH4	2^{o}33’07.4”	8^{o}04’43.7”	293	2012	Birimian Sedimentary
5	Adadiem	AS/BH1	2^{o}33’12.9”	8^{o}04’57.8”	295	2004	Birimian Sedimentary
6	Adadiem	DDA/BH4	2^{o}33’13.8”	8^{o}04’58.1”	302	1998	Birimian Sedimentary
7	Adadiem	BHS/BH3	2^{o}33’13.7”	8^{o}05’00.8”	398	1996	Birimian Sedimentary
8	Adadiem	205FBH5	2^{o}33’04.7”	8^{o}05’01.9”	291	2012	Birimian Sedimentary
9	Akete	A56/S2	2^{o}03’56”	7^{o}47’56.7”	287	2011	Upper Voltaian
10	Akete	A56/S1	2^{o}03’52.2”	7^{o}47’58.4”	283	2011	Upper Voltaian
11	Amanfoso	BT/204/BH2	2^{o}43’32.7”	7^{o}51’56.6”	334	2012	Birimian Sedimentary
12	Amanfoso	FE/22/BH1	2^{o}43’27.1”	7^{o}51’47.5”	339	1990	Birimian Sedimentary
13	Amanfoso	B/44/BH2	2^{o}43’24.4”	7^{o}51’40.1”	338	2001	Birimian Sedimentary
14	Amanfoso	NB/HE4/BH2	2^{o}43’20.4”	7^{o}51’38,1”	335	1994	Birimian Sedimentary
15	Amponsakrom	204F874BH1	2^{o}04’43”	7^{o}52’69”	264	2004	Upper Voltaian
16	Asuokor	214/F75/BH3	2^{o}37’29.2”	7^{o}44’08.8”	289	1995	Birimian Sedimentary
17	Asuokor	H4/F573/BH4	2^{o}37’14.7”	7^{o}43’57.2”	323	1986	Birimian Sedimentary
18	Asuokor	AS/23/BH2	2^{o}33’00.7”	7^{o}44’04.9”	317	2001	Birimian Sedimentary
19	Asuokor	DS7/K3/BH3	2^{o}36’48.1”	7^{o}44’10.7”	312	2004	Birimian Sedimentary
20	Asuokor	NH/M23/BH4	2^{o}36’58.7”	7^{o}43’56.1”	311	2004	Birimian Sedimentary
21	Asuono	R23/Y2S/BH3	2^{o}6’21.4”	7^{o}41’17.4	296	1994	Upper Voltaian
22	Asuono	R4/F87/BH3	2^{o}6’18.3”	7^{o}41’19”	294	1995	Upper Voltaian
23	Asuono	2T/R74/BH2	2^{o}6’24’	7^{o}41’23.2”	293	2005	Upper Voltaian
24	Attakrom	BN/30W/BH4	2^{o}16’36.3”	7^{o}50’50”	244	2004	Birimian Sedimentary

25	Awisa	AW/02T/BH1	2^o6’2.5”	7^o48’42”	315	2008	Upper Voltaian
26	Awisa	304/F84/BH2	2^o6’4.9”	7^o48’47.2”	303	1995	Upper Voltaian
27	Awisa	20K/F8/BH4	2^o6’6.1”	7^o48’28.8”	309	2006	Upper Voltaian
28	Ayayor	208/F/BH2	2^o7’6”	7^o37’41.1”	289	2008	Dahomeyan
29	Ayayor	208/F8/BH1	2^o7’19.7”	7^o37’35.4”	282	2008	Dahomeyan
30	Ayayor	20T/4F/BH3	2^o7’6.8”	7^o37’42.5”	285	2006	Dahomeyan
31	Banda_Ahenkro	BM/804/BH1	2^o21’19.4”	8^o9’54.2”	276	1985	Birimian Volcanic
32	Banda_Ahenkro	WDA/20/BH 2	2^o21’21.9”	8^o9’48.5”	265	1988	Birimian Volcanic
33	Banda_Ahenkro	BA/30W/BH 1	2^o21’20.4”	8^o9’46.7”	269	2011	Birimian Volcanic
34	Banda_Ahenkro	B/RE4/BH3	2^o21’9.3”	8^o10’9.3”	296	1990	Birimian Volcanic
35	Banda_Ahenkro	BH2/204/H	2^o21’08.4”	8^o10’16.6”	287	2004	Birimian Volcanic
36	Banda_Bofie	MG/ET4/BH 4	2^o22’30.6”	8^o01’04.9”	257	1988	Birimian Volcanic
37	Banda_Bofie	BB/204/H/87	2^o22’33.1’	8^o01’07.3”	250	2008	Birimian Volcanic
38	Banda_Bofie	NE/TY02/BH 3	2^o22’34.1’	8^o01’07.9”	245	2012	Birimian Volcanic
39	Banda_Bofie	HF/096/BH	2^o22’31.6’	8^o01’11.2”	253	2008	Birimian Volcanic
40	Banda_Bofie	TT/302/BH2	2^o22’31”	8^o01’13’	263	1985	Birimian Volcanic
41	Banda_Bofie	BH2/204/H	2^o22’29.9’	8^o01’14.7’	265	2008	Birimian Volcanic
42	Banda_Bofie	BB/204/BH2	2^o22’30.3”	8^o01’08.4”	251	1985	Birimian Volcanic
43	Banda_Dompofi e	83D3/ET/34	2^o22’01’	8^o08’58.1”	262	2001	Birimian Volcanic
44	Banda_Dompofi e	0803D3/E/04 6-1	2^o21’57.5”	8^o08’56.7”	265	1998	Birimian Volcanic
45	Banda_Dompofi e	204E046BH1	2^o22’03.7”	8^o08’53.8”	248	2004	Birimian Volcanic
46	Banda_Dompofi e	204E048BH2	2^o22’04”	8^o08’52.1”	262	2004	Birimian Volcanic
47	Banda_Gbao	204E049BH1	2^o21’39.9”	7^o	278	2004	Birimian Volcanic
48	Banda_Gbao	204F274BH1	2^o21’48.5”	8^o08’49.9”	251	1996	Birimian Volcanic
49	Banda_Gbao	204M049BH 2	2^o21’46.3”	8^o08’54.1	265	2001	Birimian Volcanic
50	Banda_Gbao	204Y042BH5	2^o21’45.6	8^o08’54.1”	271	1998	Birimian Volcanic
51	Banda_Kanka	204W49BH3	2^o21’32.6”	8^o09’04.8”	289	1985	Birimian Volcanic
52	Banda_Makala	204E047BH1	2^o22’50”	8^o08’32.7”	246	1989	Birimian Volcanic
53	Banda_Makala	224E9BH1	2^o22’50.7”	8^o08’33.1”	249	1985	Birimian Volcanic
54	Banda_Makala	234E349BH2	2^o22’54.3”	8^o08’33.8”	251	2009	Birimian Volcanic

55	Banda Nyire	204F07BH1	2°17’38’7”	8°06’40.9’	199	2004	Tarkwaian
56	Banda_Nyire	204BNBH1	2°17’49.4”	8°06’47.3”	198	2011	Tarkwaian
57	Banda_Nyire	204F07BH2	2°17’39.6”	8°06’43.2”	202	2004	Tarkwaian
58	Banda_Sabie	204T549BH4	2°21’11.8”	8°04’03.2’	204	2011	Tarkwaian
59	Banda_Sabie	194E049BH3	2°21’10”	8°04’05.9”	205	2012	Tarkwaian
60	Banda_Sabie	0803/4/038	2°21’05.2”	8°04’10.9”	214	1999	Tarkwaian
61	Banda_Sabie Clinic	0803D3/4/03 8-4	2°21’06.4”	8°04’23.4”	235	2005	Tarkwaian
62	Banda_Sangma	204/E/046/B H2	2°22’22”	8°08’34.7”	241	2004	Birimian Volcanic
63	Banda_Sangma	204/E048/BH 1	2°22’23.3”	8°08’34.5”	249	2004	Birimian Volcanic
64	Banda_Sangma	EO/M21/BH1	2°22’23.6”	8°08’34.4”	240	2008	Birimian Volcanic
65	Banda_Sase	EO/M21/BH2	2°21’42.9”	8°09’04.4”	281	2004	Tarkwaian
66	Bandaman_SHS	BH4/204/E/02 9	2°21’40.7”	8°07’30.3”	248	2004	Birimian Volcanic
67	Bandaman_SHS	EO/M21/BH3	2°21’42.3”	8°07’54.7”	253	2004	Birimian Volcanic
68	Beposo	204/E45/BH3	2°6’23.8”	7°41’30”	293	2011	Upper Voltaian
69	Beposo	S4/E048/BH1	2°6’29.9”	7°41’29.5”	300	1988	Upper Voltaian
70	Beposo	M04/E054/B H1	2°6’33.5”	7°41’26.9”	285	2004	Upper Voltaian
71	Bonakire	BB/E048/BH 1	2°32’51.7”	7°59’06.1”	278	1985	Upper Voltaian
72	Bonakire	BA/F048/BH 2	2°32’49.3”	7°59’08.8”	268	1986	Upper Voltaian
73	Bonakire	SW/M48/BH 1	2°32’44.7”	7°59’07.3”	258	2004	Upper Voltaian
74	Bonakire	P04/E8/BH5	2°32’47.7”	7°59’20.9”	264	1990	Upper Voltaian
75	Branam	BR/E04/BH1	2°03’50.9”	7°58’49.3”	194	2011	Upper Voltaian
76	Branam	ST/E0W/BH2	2°03’54.8”	7°58’42.7”	188	2011	Upper Voltaian
77	Branam	202/B08/BH1	2°03’55.7”	7°58’39.6”	185	2010	Upper Voltaian
78	Branam	204/B87/BH2	2°03’48.3”	7°58’38.1”	195	2012	Upper Voltaian
79	Brodi	RE/S087/BH 3	2°35’24.5”	7°52’39.8”	288	1998	Birimian Sedimentary
80	Brodi	506/098/BH1	2°35’29.7”	7°52’29.9”	283	1990	Birimian Sedimentary
81	Brodi	K2/B07/BH4	2°35’21.2”	7°52’27.2”	285	1985	Birimian Sedimentary
82	Brodi	204/B0/BH3	2°35’17.2”	7°52’18.6”	304	2004	Birimian Sedimentary
83	Brodi	IHE/E76/BH2	2°35’11.3”	7°52’18.1”	297	1985	Birimian Sedimentary
84	Buni	20T/B87/BH4	2°38’27.9”	7°48’25.2”	320	1985	Birimian Sedimentary
85	Buni	20/2B0/87/B H3	2°38’35.5”	7°48’19.1”	313	1983	Birimian Sedimentary
85	Buni	BW/B07/BH5	2°38’32.9”	7°48’17.4”	314	2004	Birimian Sedimentary

87	Buni	E203/E7/BH2	2°38’26.1”	7°48’15.9”	311	1985	Birimian Sedimentary
88	Buni	FB/30R/BH9	2°38’31.6”	7°48’14.2”	295	2008	Birimian Sedimentary
89	Buni	204/190/BH7	2°38’34.1”	7°48’09.2”	312	2004	Birimian Sedimentary
90	Buni	AS/103/BH2	2°38’40”	7°48’06.6”	296	2012	Birimian Sedimentary
91	Debibi	GA/40/BH3	2°32’23”	7°53’46.2”	272	1986	Birimian Sedimentary
92	Debibi	204/1T2/BH7	2°32’34.1”	7°53’48.1”	270	1985	Birimian Sedimentary
93	Debibi	BN1/RE7/BH 9	2°32’31”	7°53’47.6”	273	1999	Birimian Sedimentary
94	Debibi	202B087BH6	2°32’31.9”	7°53’44.2”	268	2001	Birimian Sedimentary
95	Debibi	201/B0T/BH4	2°32’31.7”	7°53’42.1”	270	2011	Birimian Sedimentary
96	Debibi	244/B07/BH1	2°32’35.8”	7°53’41.7”	279	1993	Birimian Sedimentary
97	Debibi	224/B7/BH4	2°32’44.7”	7°53’44.3”	270	1985	Birimian Sedimentary
98	Debibi	2R2/B07/BH 5	2°32’40.5”	7°53’54.9”	268	1982	Birimian Sedimentary
99	Debibi	SS/E092/BH3	2°32’38.5”	7°54’05.5”	280	1992	Birimian Sedimentary
100	Debibi	SE/05T/BH2	2°32’51.6”	7°53’34.6”	268	2004	Birimian Sedimentary
101	Domeabra	A230/BH1	2°06’0.6”	7°40’18.4”	321	2008	Dahomeyan
102	Droboso	A140/S3	2°06’21.7”	7°42’11.49 ”	289	2012	Birimian Sedimentary
103	Duadaso	AS/309/BH2	2°37’35.5”	7°54’09.8”	336	2004	Birimian Sedimentary
104	Duadaso	EW/TY9/BH 6	2°37’35”	7°54’19.9”	339	1985	Birimian Sedimentary
105	Duadaso	3T5/B07/BH1	2°37’28.8”	7°54’12.3”	324	1985	Birimian Sedimentary
106	Duadaso	NH/AS5/BH9	2°37’31.2”	7°54’08.7”	336	1990	Birimian Sedimentary
107	Duadaso	BB/09/BH7	2°37’24”	7°54’11.4”	322	1985	Birimian Sedimentary
108	Duadaso	F09/P35/BH2	2°37’24.7”	7°54’14.6”	322	2002	Birimian Sedimentary
109	Duadaso	NH2/E03/BH 8	2°37’23.1”	7°54’23.8”	352	2002	Birimian Sedimentary
110	Duadaso	T28/ER9/BH 2	2°37’23.1”	7°54’23.8”	315	1985	Birimian Sedimentary
111	Duadaso	DD/RT8/BH2	2°37’13.7”	7°54’21.7	333	1986	Birimian Sedimentary
112	Duadaso	4E4/F4/BH1	2°37’12.8”	7°54’11.7”	261	1985	Birimian Sedimentary
113	Faaman	204/F56/BH1	2°14’22.9”	8°07’15.6”	199	2004	Tarkwaian
114	Faaman	AS/07/BH1	2°14’23”	8°07’15.8”	155	2011	Tarkwaian
115	Goka	201/B08/BH1	2°38’57.7”	7°51’04.7”	321	2001	Birimian Sedimentary
116	Goka	87K/B8/BH9	2°38’52”	7°51’02.2”	319	1987	Birimian

							Sedimentary
117	Goka	209/B05/BH3	2°38’53.2”	7°50’59.9”	323	1990	Birimian Sedimentary
118	Goka	D0T/802/BH 2	2°38’56.6”	7°50’59”	317	2003	Birimian Sedimentary
119	Jamera	YT/903/BH3	2°37’40.8”	7°58’04.6”	355	2012	Birimian Sedimentary
120	Jamera	E02/B087/BH 4	2°37’35”	7°58’59.7”	350	1992	Birimian Sedimentary
121	Jamera	201/BD89/B H3	2°37’07”	7°58’11.4”	336	2001	Birimian Sedimentary
122	Jamera	204/B87/BH4	2°37’32.9”	7°58’07.4”	349	2008	Birimian Sedimentary
123	Jamera	G02/B078/B H9	2°37’27.3”	7°58’10.6”	344	2000	Birimian Sedimentary
124	Jamera	P02/B/BH8	2°37’30”	7°58’09”	350	1995	Birimian Sedimentary
125	Jamera	Y02/B07/BH 2	2°37’24:	7°58’17”	338	1997	Birimian Sedimentary
126	Jankufa	KE9/28P/BH 4	2°40’59.1”	7°46’18.3”	300	1996	Birimian Sedimentary
127	Jenini	E92/B7/BH1	2°33’13.4”	8°07’06.8”	284	1992	Birimian Sedimentary
128	Jenini	211E/R7/BH2	2°33’17.8”	8°07’06.8”	282	2011	Birimian Sedimentary
129	Jenini	402/B7/BH8	2°33’24.8”	8°07’05.1”	282	2001	Birimian Sedimentary
130	Jenini	F03/KH2/BH 3	2°33’16”	8°06’59”	274	1998	Birimian Sedimentary
131	Jenini	K01/NH2/BH 4	2°33’12.4”	8°06’50.9”	289	1992	Birimian Sedimentary
132	Jinago	NH7/045/BH 1	2°38’39.5”	7°49’44.2”	292	1985	Birimian Sedimentary
133	Jinago	BH2/204/RH	2°38’41.5”	7°49’37.2’	292	2004	Birimian Sedimentary
134	Jinago	ST1/091/BH2	2°38’41.9”	7°49’34.6”	287	1986	Birimian Sedimentary
135	Kabile	202/EW/BH5	2°38’57.1”	7°57’40.7”	261	2002	Birimian Sedimentary
136	Kabile	R80/221/BH1	2°39’07.1”	7°57’37.9”	368	1985	Birimian Sedimentary
137	Kabile	KB/09E/BH2	2°39’00.4”	7°57’37.5”	366	1985	Birimian Sedimentary
138	Kabile	AS208/R2	2°39’10.5”	7°57’47.1”	363	1992	Birimian Sedimentary
139	Kabile	AR0/23T/BH 2	2°38’46.8”	7°57’52”	372	2008	Birimian Sedimentary
140	Kabrano	BH4/ER/M09	2°21’33.4”	8°9’13.2”	286	1992	Birimian Volcanic
141	Kabrano	K02/S07/BH4	2°21’36.1”	8°9’14.4”	285	2004	Birimian Volcanic
142	Kabrano	E02/T87/BH7	2°21’43.5”	8°9’26.2”	275	2004	Birimian Volcanic
143	Koase	202B087BH1	2°06’27”	7°40’49.8”	298	2002	Upper Voltaian
144	Koase	SA/T09/N/B H1	2°06’22.4”	7°40’52.1”	297	1992	Upper Voltaian

145	Koase	ER/706/BH2	2^o06’25.1”	7^o40’53.1”	302	2008	Upper Voltaian
146	Kokoa	R07/209/BH1	2^o38’43”	7^o51’10.7”	337	2001	Birimian Sedimentary
147	Kokoa	T02/B7/BH7	2^o38’48.8”	7^o51’06.4”	324	1995	Birimian Sedimentary
148	Kokoa	JH09/B20/BH 2	2^o38’54.9”	7^o51’10.8”	327	1996	Birimian Sedimentary
149	Kokoa	BN1/SH0/BH 3	2^o38’57.7”	7^o51’04.7”	321	2001	Birimian Sedimentary
150	Kokoa	NH1/BO3/B H4	2^o38’52”	7^o51’02.2”	319	2006	Birimian Sedimentary
151	Kokoa	NN/OH3/BH 9	2^o38’53.2”	7^o50’59.9”	323	2011	Birimian Sedimentary
152	Kokoa	RH/09E/BH7	2^o38’56.6”	7^o50’59”	317	2003	Birimian Sedimentary
153	Kokoa	AS/T9/BH2	2^o38’34.3”	7^o51’10.3”	322	1997	Birimian Sedimentary
154	Kokosua No. 1	RL8/WH/BH 8	2^o45’48.1”	7^o52’31.5”	298	1994	Birimian Volcanic
155	Kokosua No. 1	BO7/09T/BH 1	2^o45’47.6”	7^o52’32.5”	290	1986	Birimian Volcanic
156	Kokosua No. 1	N02/NT/BH2	2^o45’42.5”	7^o52’34.5”	287	1985	Birimian Volcanic
157	Kokosua No. 1	RH/T20/BH1	2^o45’39.9”	7^o52’36.5”	291	1988	Birimian Volcanic
158	Kokosua No. 2	RST/206/BH 2	2^o47’00.9”	7^o52’45.4”	300	2004	Birimian Volcanic
159	Kokosua No. 2	TS/213/BH4	2^o47’07.3”	7^o52’45.3”	295	2008	Birimian Volcanic
160	Kokosua No. 2	204C100BH2	2^o47’12.1”	7^o52’41.7”	292	2005	Birimian Volcanic
161	Kokosua No. 2	GS/OT90/BH 3	2^o47’07.1”	7^o52’34.5”	289	1990	Birimian Volcanic
162	Kokosua_DA Sch.	DX/3E3BH2	2^o46’23.6”	7^o52’37.9”	293	2012	Birimian Volcanic
163	Kuti	127/P/82-1	2^o42’53.4”	7^o54’32”	328	1982	Birimian Sedimentary
164	Kuti	134/H/BH2	2^o42’53.2”	7^o54’28.9”	325	1985	Birimian Sedimentary
165	Kwame_Tenten	204/R10/BH3	2^o25’14.2”	7^o54’38.9”	285	2004	Tarkwaian
166	Kwame_Tenten	10E/30T/BH2	2^o25’21”	7^o54’31.8”	284	2004	Tarkwaian
167	Kyingakrom	135/39R/BH1	2^o03’32.4”	8^o06’2.8”	135	2002	Birimian Sedimentary
168	Kyingakrom	202/T14/BH1	2^o03’32.4”	8^o06’5.4”	146	2002	Birimian Sedimentary
169	Kyingakrom	Y67/4T3/BH 1	2^o03’33.8”	7^o06’8.7”	128	2012	Birimian Sedimentary
170	Manji	204/E10/BH4	2^o22’33.1”	7^o55’22.3”	232	2004	Tarkwaian
171	Manji	202TMBH2	2^o22’40.9”	7^o55’25.5”	243	2002	Tarkwaian
172	Manji	208/H10/BH1	2^o22’39.8”	7^o55’26.6”	264	2008	Tarkwaian
173	Manji	F09/9T/BH2	2^o22’54”	7^o55’37.9”	251	1985	Tarkwaian
174	Manji	2T4C10BH4	2^o23’04.8”	7^o55’37”	232	1992	Tarkwaian
175	Mayera	204/Y104/BH 5	2^o41’04.5”	7^o51’48.2”	339	2004	Birimian Sedimentary
176	Mayera	07T/AS/BH5	2^o40’59.7’	7^o51’57.9”	342	2012	Birimian Sedimentary

177	Moli	T04/W154/BH6	2^{o}43’39.7”	7^{o}52’24.6”	317	1992	Birimian Sedimentary
178	Moli	P05/TH/BH1	2^{o}43’38.1”	7^{o}52’21.0”	324	1985	Birimian Sedimentary
179	Moli	012/HH/BH2	2^{o}43’33.3”	7^{o}52’21.1”	328	2004	Birimian Sedimentary
180	Namansa	GH0/FI/BH9	2^{o}28’45.5”	7^{o}54’04.9”	274	1987	Tarkwaian
181	Namansa	E92/E54/BH2	2^{o}28’55.4”	7^{o}54’02.5”	275	1995	Tarkwaian
182	Namansa	H/NH12/BH4	2^{o}28’55”	7^{o}54’58.4”	281	2008	Tarkwaian
183	Namansa	ASO/M9/BH2	2^{o}28’51.3”	7^{o}54’02.7”	287	2004	Tarkwaian
184	Namansa	28E/DOJ/BH1	2^{o}28’53”	7^{o}54’07”	282	1985	Tarkwaian
185	Namansa	132/E04/BH3	2^{o}28’48.5”	7^{o}54’13.7”	283	1987	Tarkwaian
186	Namansa	AS120/SBH1	2^{o}29’01.9”	7^{o}54’04.1”	284	1990	Tarkwaian
187	Nipanikro	AS132/S3	2^{o}07’8.8”	8^{o}06’9.6”	111	2012	Birimian Sedimentary
188	Nkona	AD/TS/BH2	2^{o}19’01.3”	7^{o}52’42.2”	286	1985	Birimian Sedimentary
189	Nkona	BH3/923/M	2^{o}19’59.7”	7^{o}52’45.4”	274	2008	Birimian Sedimentary
190	Nkona	T01/92/BH3	2^{o}19’07.4”	7^{o}52’50”	292	1992	Birimian Sedimentary
191	Nkona	B100/S2	2^{o}20’49”	7^{o}52’27.5”	198	2012	Birimian Sedimentary
192	Nkonsia	124/T03/BH2	2^{o}06’17.7”	7^{o}40’17.1”	318	2004	Dahomeyan
193	Nkonsia	129/H/BH2	2^{o}06’10.7”	7^{o}40’15.7”	322	2002	Dahomeyan
194	Nsawkaw	132/OH/BH3	2^{o}18’44.3”	7^{o}52’31.4”	279	1985	Birimian Sedimentary
195	Nsawkaw	0982/UH/BH4	2^{o}18’38.5”	7^{o}52’32.1”	274	1985	Birimian Sedimentary
196	Nsawkaw	271/HE/BH2	2^{o}18’53.1”	7^{o}52’16.4”	283	1992	Birimian Sedimentary
197	Nsawkaw	204/T11/BH3	2^{o}18’50.1”	7^{o}52’07.5”	277	2004	Birimian Sedimentary
198	Old_Drobo	23E/08F/BH4	2^{o}44’01.5”	7^{o}50’55.9”	306	2012	Birimian Volcanic
199	Old_Drobo	132/BH2/RT	2^{o}44’03.9”	7^{o}50’50”	361	1982	Birimian Volcanic
200	Old_Drobo	204/R12/BH3	2^{o}44’05.9”	7^{o}50’53.9”	313	2004	Birimian Volcanic
201	Papakyeai	208/H10/BH5	2^{o}13’24.7”	7^{o}49’44”	222	2008	Birimian Sedimentary
202	Sase_Banda	202/T14/BH5	2^{o}21’56.3”	7^{o}090’04.4”	268	1992	Birimian Volcanic
203	Seketia	202/S10/BH4	2^{o}45’33.7”	7^{o}48’30.6”	301	2012	Birimian Volcanic
204	Seketia	DA/P23/BH3	2^{o}45’25.2”	7^{o}48’45.6”	324	2012	Birimian Volcanic
205	Seketia_Clinic	RH/023/BH9	2^{o}45’27.5”	7^{o}48’36.7”	300	2012	Birimian Volcanic
206	Subinso	204C100BH1	2^{o}02’58.4”	7^{o}56’33.2”	191	2008	Upper Voltaian
207	Subinso_No1	B70/S3	2^{o}03’24.5”	7^{o}55’40.1”	200	2012	Upper Voltaian
208	Subinso_No1	A40/S2	2^{o}03’28.5”	7^{o}55’39.3”	193	2012	Upper Voltaian

209	Subinso_No1	202/B08/BH4	2^o03’32.4”	7^o55’29.5”	214	2012	Upper Voltaian
210	Suma_Ahenkro	212/C00/BH3	2^o42’47.7”	7^o55’25.7”	347	1982	Birimian Sedimentary
211	Suma_Ahenkro	124/R20/BH2	2^o42’54.8”	7^o54’50.8”	325	1982	Birimian Sedimentary
212	Surugbokrom	201/W3/BH4	2^o11’8.8”	8^o05’51.5”	138	2011	Tarkwaian
213	Tainso	BA32/S5/BH 3	2^o11’59.4”	7^o47’51.4”	212	2001	Birimian Sedimentary
214	Tainso	W30/K2/BH2	2^o11’57.4”	7^o47’42.7”	168	1986	Birimian Sedimentary
215	Weiwa	EA30/T1/BH 2	2^o23’51.9”	7^o04’35.7”	245	1985	Birimian Volcanic
216	Weiwa	BA30/S2/BH2	2^o23’54.9”	7^o04’37.5”	243	1985	Birimian Volcanic
217	Weiwa	A33/S2/BH1	2^o23’57.3”	7^o04’31.2”	246	1985	Birimian Volcanic
218	Wurompo	A30/S2	2^o05’04.2”	7^o46’43.1”		2012	Upper Voltaian
219	Wurompo	A31/S3	2^o05’01”	7^o46’42.1”		2011	Upper Voltaian
220	Yabraso	205/E48/BH2	2^o14’14.3”	7^o50’02.5”	234	2004	Birimian Sedimentary
221	Yabraso	E3/E044/BH1	2^o14’11.4”	7o50’00.1”	238	1985	Birimian Sedimentary
222	Yabraso	YS/04/BH1	2^o14’20.3”	7^o49’54.7”	241	2002	Birimian Sedimentary
223	Yabraso	205/N09/BH2	2^o14’25”	7^o49’58.5”	238	2012	Birimian Sedimentary
224	Yabraso	AS/ER78/BH 1	2^o14’19”	7^o50’02.9”	240	2004	Birimian Sedimentary

Appendix V: Number of water points in communities

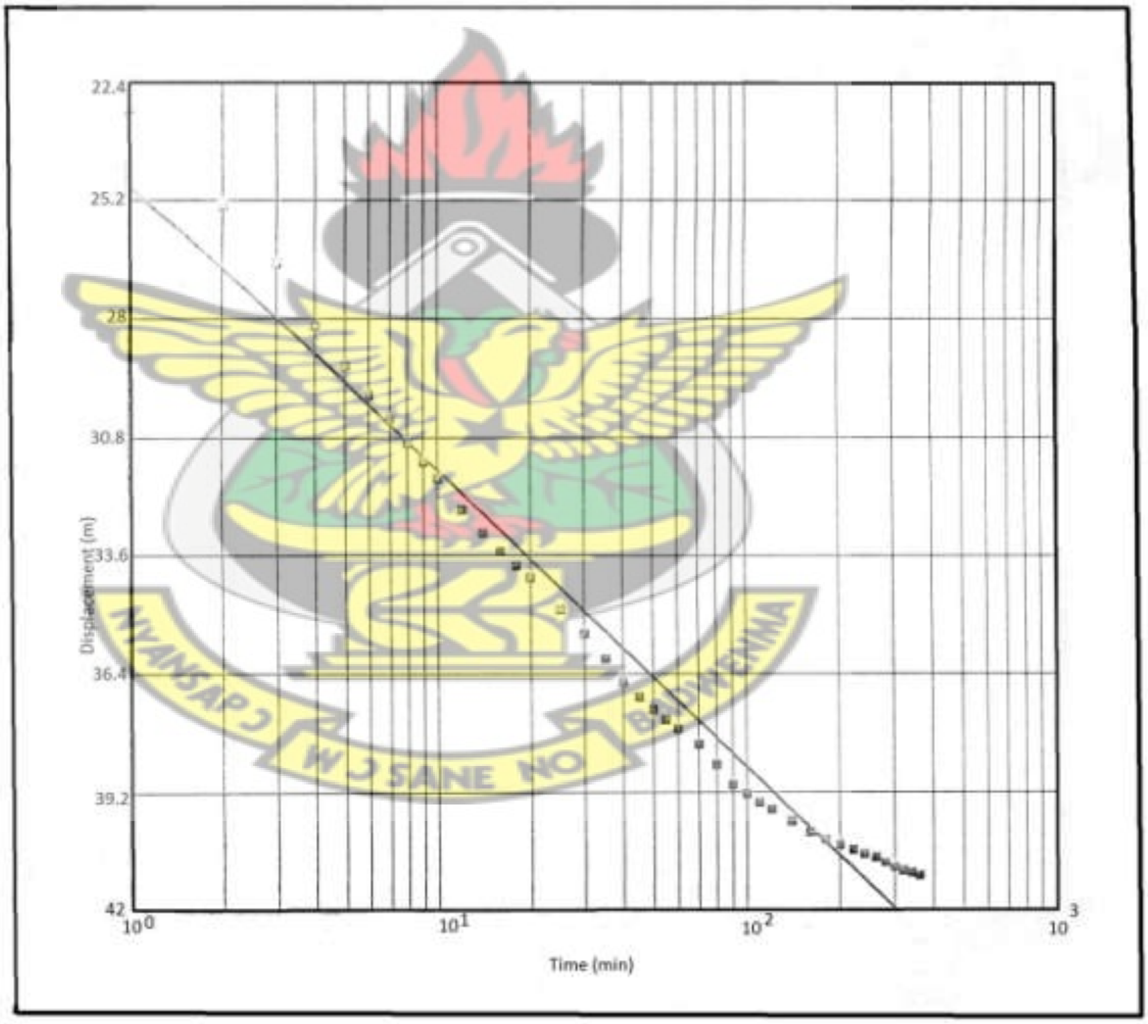
No	Community	Population 2012	No of BHs Required	No of BHs present	No of additional BHs to be provided	% of Requirement met
1	Adadiem	2,586	8	8	0	75
2	Akete	1,008	3	2	1	33
3	Amanfoso	586	2	4	0	100
4	Amponsakrom	2,496	7	1	6	14
5	Asuokor	3,290	9	5	4	44
6	Asuono	1,077	3	3	0	100
7	Attakrom	249	1	1	0	100
8	Awisa	3,326	10	3	7	20
9	Ayayor	252	1	3	0	100
10	Banda Ahenkro	2,396	7	5	2	57
11	Banda Bofie	1,235	4	8	0	100
12	Banda_Bongase	2,475	7	5	2	43
13	Banda Dompofie	863	3	4	0	100

14	Banda_Gbao	758	2	4	0	100
15	Banda Kanka	375	1	1	0	100
16	Banda Makala	370	1	3	0	100
17	Banda Nyire	785	3	3	0	67
18	Banda Sabie	2,675	8	4	4	50
19	Banda_Sangma	638	2	3	0	100
20	Banda Sase	477	2	2	0	100
21	Bandaman_SHS	300	1	2	0	100
22	Beposo	1,674	5	3	2	40
23	Bonakire	2,261	7	4	3	57
24	Branam	1,219	4	4	0	75
25	Brodi	4,415	13	5	8	31
26	Buni	3,136	9	6	3	67
27	Debibi	7,006	20	9	11	45
28	Domeabra	403	1	1	0	100
29	Droboso	2,160	6	2	4	33
30	Duadaso No 2	9,148	26	10	16	38
31	Faaman	2,526	7	2	5	29
32	Goka	7,737	22	4	18	18
33	Jamera	4,246	12	7	5	50
34	Jankufa	2,667	8	5	3	63
35	Jenini	1,359	4	5	0	100
36	Jinago	728	2	3	0	100
37	Kabile	4,234	12	5	7	42
38	Kabrano	1,087	3	3	0	100
39	Koase	2,073	6	3	3	50
40	Kokoa	5,171	15	8	7	53
41	Kokosua No 1	750	2	4	0	100
42	Kokosua No. 2	1,083	3	4	0	100
43	Kokosua DA Sch	209	1	1	0	100
44	Kuti	1,024	3	2	1	67
45	Kwame Tenten	989	3	2	1	67
46	Kyingakrom	11	1	3	0	100
47	Manji	3,097	9	5	4	56
48	Mayera	2,551	7	4	3	57
49	Moli	1,997	6	3	3	33
50	Namasa	2,628	8	7	1	88
51	Nipanikro	21	1	1	0	100
52	Nkona	1,416	4	4	0	100
53	Nkonsia	2,342	7	2	5	29
54	Nsawkaw	6,070	17	4	13	24
55	Old_Drobo	495	2	3	0	100
56	Papakyeaye	119	1	1	0	100
57	Sase_Banda	426	2	1	1	50
58	Seketia	2,275	7	3	4	43
59	Seketia Clinic		1	1	0	100
60	Subinso	3,796	11	1	10	9
61	Subinso No 1	3245	11	3	8	27
62	Suma_Ahenkro	8261	28	2	26	7
63	Surugbokrom	10	1	1	0	100

64	Tainso	1,257	4	2	2	50
65	Weiwa	996	3	3	0	100
66	Wurompo	771	2	2	0	50
67	Yabraso	1,139	3	5	0	100
68	Yoyoano	509	2	1	1	50

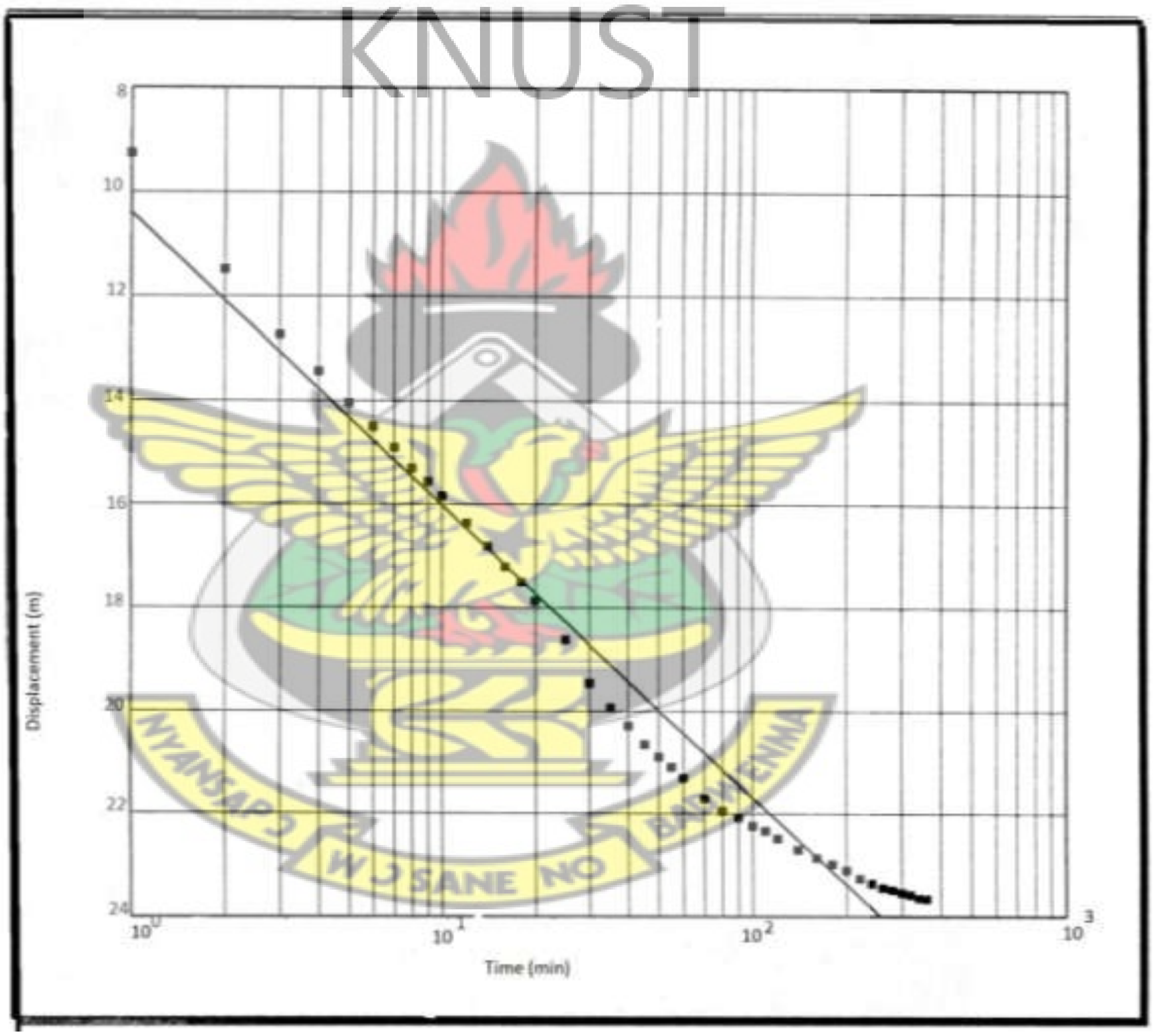
Appendix VI: Pumping test results

Pumping Test			
Client: Wenchi Municipal Assembly	Borehole Ref No. A30/S2	Community: Wurumpo	Analysis Date: 27/01/13 Time: 06:49:43
Well Depth: 42m	Anisotropy Ratio: Kz/Kr: 1	Observation Well No. A30/S2	Aquifer Saturation Thickness: 22.4m
Solution			
Transmissivity (m^2/day) 4.06	Aquifer Model: Confined	Duration of Pumping: 360min	Recovery Period: 180min
Method			Cooper and Jacob

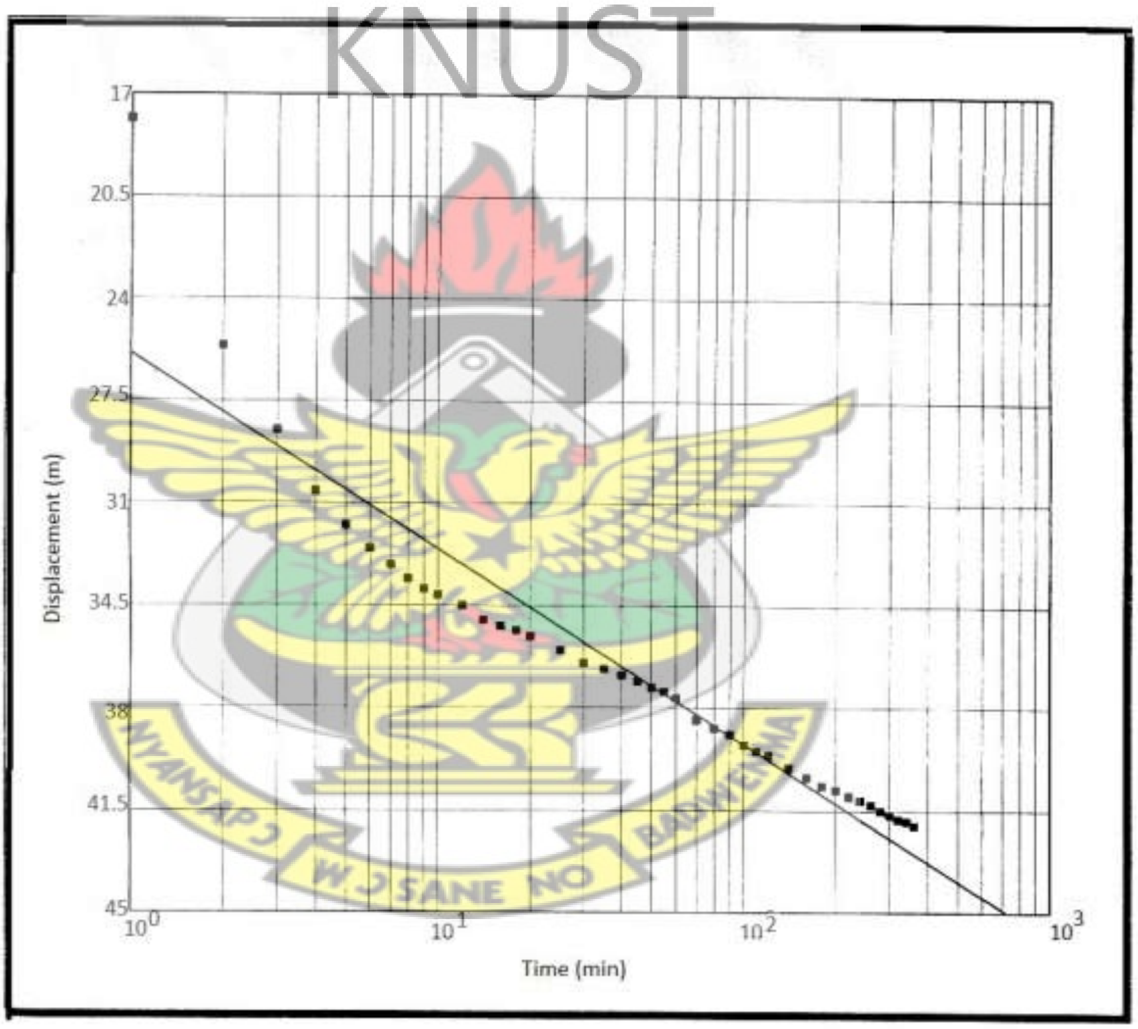


Pumping Test

Client: Wenchi Municipal Assembly	Borehole Ref No: A106/S1	Community: Droboso	Analysis Date: 27/01/13 Time: 09:47:41
Well Depth: 24m	Anisotropy Ratio: Kz/Kr:1	Observation Well No: A106/S1	Aquifer Saturated Thickness: 13.5m
SOLUTION			
Transmissivity (m2/day) 64.32	Aquifer model: Confined	Duration of Pumping: 360min	Recovery period: 180min
Method:	Cooper and Jacob method		

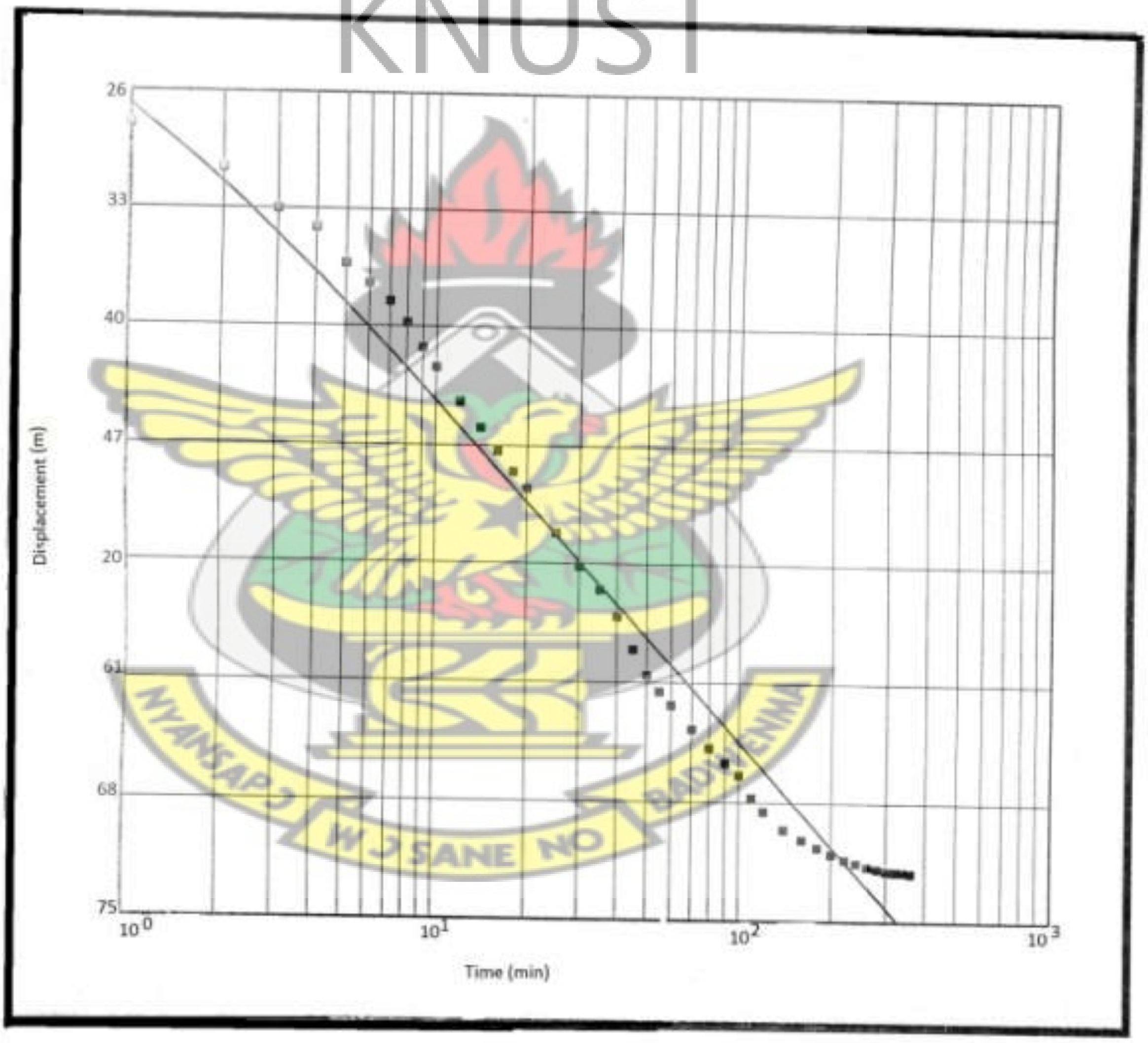


Pumping Test			
Client: Tain District Assembly	Borehole Ref No: A60/S1	Community: Atomfourso	Analysis Date: 27/01/13 Time: 12:32:45
Well Depth: 45m	Anisotropy Ratio: Kz/Kr: 1	Observation Well No: A60/S1	Aquifer Saturated Thickness: 28m
Solution			
Transmissity (m2/day): 40.58	Aquifer Model: Confined	Duration of Pumping: 360min	Recovery period: 180min
Method		Cooper and Jacob	



Pumping Test

Client: Jaman North District Assembly	Borehole Ref No. ADT2012	Community: Adadiem Town	Analysis Date: 27/01/2013 Time: 02:33:23
Well Depth: 75m	Anisotropy Ratio: Kz/Kr: 1	Observation Well No: ADT2012	Aquifer Saturation Thickness: 49m
Solution			
Transmissivity (m2/day) 22.82	Aquifer Model: Confined	Duration of Pumping: 360min.	Recovery Period: 180min
Method			Cooper and Jacob



Appendix VII: Physico-chemical water quality analysis results

PARAMETER	UNIT	GEOLOGICAL FORMATION/QUALITY RANGE				WHO STANDARD
		UV	BS	BV	TARK	
pH		6.4-7.8	6.6-8.0	6.8-7.1	6.8	6.5-8.5
Conductivity	p_s/cm	90-839	82.0-579.0	70.0-120.0	120.0	
Calcium (Ca^+)	ppm	12-28	20.8-107.6	3.8-13.6	9.6	-
Bicarbonates (CO_3^{2-})	ppm	5.0-50.0	5.0-79.0	5.0-52.0	5.0	-
Magnesium (Mg^{2+})	ppm	1.5-8.5	2.7-12.2	8.5-9.6	3.88	-
Sodium (Na^+)	ppm	4.0-23	5.0-30.0	10.0-17.0	3.0	200
Potassium (K^+)	ppm	2.0-13.0	0.0-5.0	0.0-6.5	1.0	30
Nitrate (NO_3-)	ppm	0.2-12.0	0.3-3.0	0.4-7.0	0.3	50
Nitrite (NO_2-)	ppm	0.001-0.9	0.003-0.14	0.01-0.3	0.140	3.0
Ammonia (Nitrogen) (NH_3)	ppm	0.01-0.2	0.0-0.1	0.0-0.01	0.00	1.5
Fluoride (F^{2-})	ppm	0.1-1.28	0.00-0.5	0.0-0.1	0.00	1.5
Total Iron (Fe)	ppm	0.01-0.2	0.003-0.15	0.003-0.01	0.03	0.3
Sulphate (SO_4^{2-})	ppm	0.0-15.0	0.5-20.0	0.5-9.0	0.0	250
Manganese (Mn)	ppm	0.0-0.5	0.0-0.001	0.0-0.1	0.00	0.0
Permanent Hardness	ppm	10.0-101.0	40.0-120.0	23.0-40.0	30.0	-
Temporary Hardness	Hardness ppm	15.0-147.0	83.0-280.0	40.0-69.0	40.0	500
Total Alkalinity	ppm	35.0-260.0	90.0-465.0	78.0	98.0	-

UV= Upper Voltaian BS= Birimian Sedimentary BV= Birimian Volcanic

TAR= Tarkwaian