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Hydrogeological and Hydrochemical Framework of Groundwater for Irrigation in the Atankwidi sub-basin of the White Volta Basin

Samuel Barnie

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Hydrogeological and Hydrochemical Framework of Groundwater for Irrigation in the Atankwidi sub-basin of the White Volta Basin

By

Samuel Barnie, BSc. (Hons)

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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.

Samuel Barnie **(20067588)**	Signature	21/04/10 Date

Certified by:

Dr. G.K. Anornu **(Supervisor)**	Signature	21/04/2010 Date
Dr. C. S. K. Kpordze **(Supervisor)**	Signature	21/04/10 Date
Prof. S. I. K. Ampadu **(Head of Department)**	Signature	04/05/2010 Date

Dedication

To the Almighty God, my family, friends and all loved ones.

Abstract

This study presents research findings on the hydrogeological and hydrochemical framework of groundwater for irrigation in Atankwidi sub-basin of the White Volta Basin. The potential use of shallow groundwater for small-scale dry season irrigation is a key issue for irrigation development in the arid zone of Ghana. Farmers within the Atankwidi sub-basin are increasingly using groundwater as a source of irrigation water due to the unavailability of surface water in the dry season, hence the need to investigate its availability and suitability in order to ensure sustainability in the application and possible expansion of groundwater irrigation in the area. The aquifer geometry in the Atankwidi sub-basin has therefore been successfully delineated using geophysical (VES and EM) techniques which revealed a shallow regional aquifer system with a mean saturation thickness of 6.3 m. The hydraulic conductivity values computed from grain-size analysis varied from 1.25×10^{-2} m/d to 1.52×10^{-2} m/d. Transmissivity values within the sub-basin were low with values ranging from 3.75×10^{-3} m^2/d to 5.32×10^{-1} m^2/d which is indicative of unconfined aquifer conditions. The estimated potential volume of groundwater storage of the aquifer within the sub-basin under the conditions of this research is 370,777,191.2 m^3. Two main water types (Ca-Mg-HCO_3 and Na-Mg-Ca-HCO_3) have been determined using the Piper diagram. The relative abundance of cations in the groundwater was found to be in the decreasing order of $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > Fe^{2+}$. Similarly, that of anions was found to have a decreasing order of $HCO_3^- > SO_4^{2-} > Cl^- > PO_4^{2-} > NO_3^- > F^-$. Groundwater in the area had low SAR and low to medium salinity hazard. However, magnesium hazard and alkalinity problems are likely to limit its use for irrigation. Dental decay have also been identified to be the main potential physiological problem associated with groundwater in some communities should it be used for drinking.

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List of Abbreviations and Acronyms

CWSA	Community Water and Sanitation Agency
EM	Electromagnetic
EPA	Environmental Protection Agency
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GMA	Ghana Meteorological Agency
GPS	Global Positioning System
GSB	Ghana Standards Board
GSS	Ghana Statistical Service
GVP	Glowa Volta Project
GWCL	Ghana Water Company Limited
MDGs	Millennium Development Goals
MH	Magnesium Hazard
SAR	Sodium Adsorption Ratio
SGI	Shallow Groundwater Irrigation
UER	Upper East Region
VES	Vertical Electrical depth Sounding
WHO	World Health Organisation
WRI	Water Research Institute
WVR	White Volta River

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1. INTRODUCTION

1.1 Background of the Study

Agriculture according to the Ghana Poverty Reduction Strategy I and II is the basis for economic growth and structural transformation. In other words, economic growth and structural transformation is propelled by the agricultural sector in order to maximize the benefits of accelerated growth. This prediction is based on a number of factors. First, agriculture is the highest contributor to GDP accounting for about 50% and provides employment for over 60% of the population. It also accounts for about 60% of export earnings. Consequently, growth in the sector will, therefore, impact directly on growth of the economy as well as employment. Therefore accelerated development in small-scale agriculture which is persistent in the rural areas will have direct benefit on poverty reduction in the rural areas and help to slow-down the rural-urban migration. It will also ensure food security and contribute immensely to health and well being of the population.

Not withstanding its major contribution to the economy, agriculture in Ghana is largely dependent on rainfall. However, given the erratic and extremely unreliable nature of rainfall, probably due to climate variability, irrigation development is seen as an obvious strategy to increase agricultural production. There are direct linkages between improved control over water and cropping and related impacts which consistently underlie the Asian research findings that irrigation development alleviates poverty in rural areas of developing countries (Mellor and Desai 1985; Chambers *et al* 1989; Hossain 1989, Hussain 2005). Globally there is a strong positive relationship between higher density of irrigation and lower poverty rates, as Lipton *et al.* (2003) indicates. In Africa, only 3% of cropland is irrigated and the region has experienced very little reduction in poverty in the 1990s (World Bank, 2000). In contrast, those regions that have the greatest proportion of cultivated area irrigated (namely East Asia, Pacific, North Africa and Middle East) have experienced the greatest poverty reduction.

One irrigation development pathway involves the utilisation of small reservoirs. However, the performance of many of these systems is affected adversely by management problems and the economic benefit relative to the investment is characteristically low and only benefits a limited number of farmers. The total potential of irrigable land in Ghana is put at 500,000 hectares with the current area developed for irrigation estimated at 11,000 hectares which represents only 0.02% of its irrigable land. Irrigation of some of these arable lands could not materialise due to the projected capital involvement in channeling surface water over long distances to the irrigable lands. Availability of groundwater is therefore a major asset that can greatly influence agricultural production.

The use of hand-dug wells enables the utilisation of shallow groundwater for irrigated production of vegetables and cash crops during the dry season and, therefore, provides an alternative source of income for farmers and poor households. For instance, the large scale production of shallot and other vegetables using shallow groundwater in the Keta Strip has provided enormous income to the indigenous inhabitants (Kortatsi and Agyekum, 2000). In most cases, SGI has developed without any government or donor involvement. Since 1998, shallow groundwater irrigation using hand-dug shallow wells dug in alluvial beds have been spreading throughout the upper parts of the White Volta basin and are located mainly in inland valleys. Although SGI is increasingly being adopted by farmers within the White Volta Basin, its sustainability in the near future can not be guaranteed since little in known about the quantity and quality of shallow groundwater within the basin.

The potential use of shallow groundwater for small-scale irrigation as an alternative to surface and reservoir systems is an important issue for irrigation development in Ghana. Martin and Van de Giesen (2005) estimated that the groundwater utilisation is approximately 5% of the average groundwater recharge in most of the White Volta basin; the rest mainly evaporates or runs off through the river. The groundwater resource in the basin can therefore be seen as being under utilised.

It has been more fully realised that refined quantitative answers are needed concerning available groundwater resources and their management. Utilisation of groundwater continues to accelerate to meet the needs of irrigation, industrial, urban, and suburban expansion. As groundwater development intensifies, users become more interested in the response of aquifers to heavy pumping for example, and the hydrogeology as a whole. Competition for available sources has brought about awareness that one of the principal problems confronting hydrologists is resource management. The resource, therefore, needs to be assessed in quantity and quality and in the basin to aid sustainable development of the area in order to meet the development agenda for Ghana which is driven by Ghana's commitment to the MDGs.

1.2 Problem Statement

Food insecurity and poverty are major problems of the inhabitants of the White Volta Basin. The major activity in the basin is rainfed agriculture, which employs approximately 70% of the inhabitants, yet erratic and unreliable precipitation leads to low production. Supplemental irrigation is only available for an extremely low percentage of cropland, resulting in a low percentage of irrigated land in the dry season, which is approximately 1% of the total agricultural land within the basin (Unofficial report, GVP, 2007).

According to Laube *et al.*, (2008) seasonal migration of people from the north to the south of Ghana is decreasing as well which has led to an increase in the number of people in small-scale agriculture. Since agriculture is the main occupation of most of the inhabitants, more irrigable land and irrigation water is needed to improve agricultural production for food supply for the growing population.

Currently small-scale farmers try to reduce poverty and improve livelihoods through the expansion of shallow groundwater irrigation for the production of vegetables for the national market. As this is farmer-driven irrigation expansion, further investigation about the hydrogeology and the hydrochemistry of the shallow groundwater system is needed for this development.

1.3 Justification of the Study

There is no doubt that water is one of the most important inputs in agricultural production in Ghana apart from labour. More importantly almost all agricultural production depends on natural rainfall. Therefore, crop yields are invariably poor since the rains are very erratic. Groundwater development for irrigation should therefore be really looked at since it constitutes about 30.1% of the available freshwater on earth (United States Geological Survey, 2005)

The evaluation and management of groundwater resources for any use require an understanding of hydrogeological and hydrochemical properties of the aquifer, since these parameters control groundwater occurrence, its quantity and quality for any use. That is, it is important to have the aquifer characteristics such as geometry, hydraulic conductivity and transmissivity database readily available for developing local and regional water plans and also to assess and therefore predict future groundwater availability and suitability.

Additionally the hydrochemical study also reveals the quality of water that is suitable for drinking, agricultural and industrial purposes. There is therefore the need to investigate the availability in quantity and ~~quality of~~ shallow groundwater to ensure its development and sustainability for irrigation in the sub-basin.

1.4 Aim and Objectives of the Study

The main objective of the study is to investigate the groundwater potential for irrigation within the Atankwidi sub-basin of the White Volta Basin.

Specific Objectives

To achieve this main objective the following specific objectives should be met.

- To determine the aquifer geometry in the sub-basin
- To estimate the hydraulic conductivity and transmissivity of the aquifers
- To assess the groundwater quality.

1.5 Scope of the Study

The study seeks to investigate into the hydrogeological and hydrochemical framework of shallow groundwater system which is used mainly for irrigation in the Atankwidi sub-basin of the White Volta basin in the Upper East Region of Ghana. For this study, a shallow well is defined as a well dug into pervious layers above the first impervious layer or stratum. The shallow groundwater system being considered here ranges from the depth of 3 m up to 10 m.

2. LITERATURE REVIEW

2.1 Introduction

This chapter deals with the review of relevant literature in relation to the study. This includes the concept of groundwater occurrence and movement, groundwater use in the study area and for that matter Ghana and hydrogeological framework of Ghana. The hydrochemistry of drinking and agricultural (irrigation) water is also discussed in this chapter.

2.2 Hydrologic Cycle and Groundwater

According to Freeze and Cherry (1979), groundwater is defined as the subsurface water that occurs beneath the water table and flows through voids in soils and permeable geologic formations that are fully saturated. It does not exist in isolation but it is part of an integral link in the hydrological cycle as shown in Figure 2.1 and a valuable supporter of ecosystem.

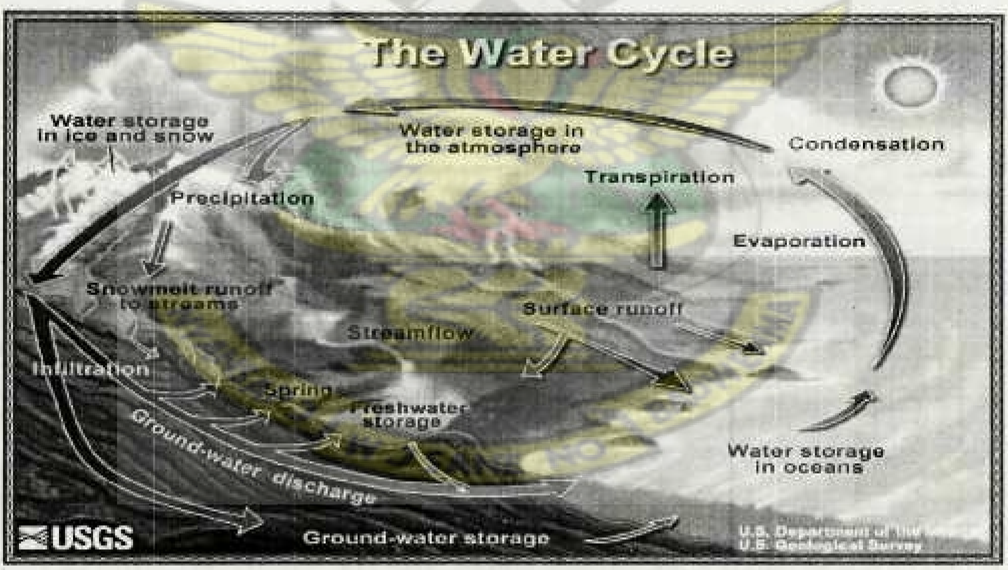


Figure 2.1: Hydrologic or Water cycle (http://ga.water.usgs.gov/edu/watercyclehi.html)

The hydrologic cycle is driven by the energy of the sun and takes water from stored water in oceans and transfers it through the atmosphere back to the oceans through different routes. A component of rains that fall on the land surface infiltrates into the soil with the remainder evaporating into the atmosphere or as runoff to rivers. Soil moisture can both be taken up by plants and transpired or flow quickly as interflow to a river channel. Some of the infiltrated water go down deeply, eventually accumulating above an impermeable bed, saturates available pores and forms underground reservoir known as groundwater. The underground water-bearing formation that is capable of yielding considerable amount of water is referred to as an aquifer.

2.3 Hydrogeological Framework of Ghana

The hydrogeological condition of an area is highly influenced by the characteristics and structure of basic geology and climate. In Ghana, the hydrogeological regions and their characteristics are very similar to the local geological conditions, because the climate zones of the country are mostly conformable to the geological regions (British Geological Survey, 1993).

Currently, a lot of hydrogeological studies have been conducted in the country in a bid to increase water supply particularly to the rural community. Ghana is divided into two major hydrogeological provinces. The main units are described as follows:

- The Basement Complex, composed of Precambrian crystalline igneous and metamorphic rocks and
- Palaeozoic sedimentary formation.

Minor provinces consist of;

i. Cenozoic, Mesozoic, and Palaeozoic sedimentary strata along narrow belts on the coast, and
ii. Quaternary alluvium along the major stream courses.

The Basement complex is further subdivided into sub-provinces on the basis of geology and groundwater conditions (Gill, 1969). Precambrian crystalline igneous and metamorphic rocks can be subdivided into Birimian, Granite, Dahomean, Togo, and Tarkwaian formation. These formations consist mainly of phyllite, schist, gneiss, migmatite, granite-gneiss and quartzites. The Basement Complex underlaid about 54% of the country. The Palaeozoic which is a consolidated sedimentary formation (locally referred to as the Voltaian formation) underlies the Volta Basin and consist mainly of sandstones, shale, arkose, mudstone, Sandy and pebbly beds and limestones. It underlies about 45% of Ghana.

The Cenozoic, Mesozoic, and Palaeozoic sedimentary strata (Coastal Provinces) underlie the remaining 1% of the country. They consist of unconsolidated alluvial sediments, beach sand, red continental deposit of mainly alternating limonitic sand, sandy clay gravel, marine shale, limestone and glauconic sandstone (Kortatsi, 2004).

The Basement Complex of Ghana is made up of the Birimian Volcanics and Sediments systems, which extend from the north through the mid-west to the south-western parts of the country. These rocks consist of a great thickness of isoclinals folded, metamorphosed sediments intercalated with metamorphosed tuff and lava. The latter are predominant in the upper part of the system, whereas the sediments are predominant in the lower part. The entire sequence is intruded by batholithic masses of granite and gneiss. The granite and gneiss are not inherently permeable, but secondary permeability and porosity have developed as result of jointing, shearing, fracturing and weathering.

Where precipitation is high and weathering processes penetrate deeply along fracture systems, the granite and gneiss commonly have been eroded to low-lying areas. On the other hand, where the precipitation is relatively low, the granite occurs in massive poorly jointed inselbergs that rise above the surrounding lowlands. In some areas, weathered granite or gneiss form permeable groundwater reservoirs.

2.4 Aquifer Characteristics

Aquifers generally have some characteristics or parameters that describe the quantity of groundwater that they can yield or produce and the rate of contaminant flow. These characteristics include the aquifer geometry, hydraulic conductivity, transmissivity, storativity and specific capacity. That is, each of these parameters does influence in one way or the other the quantity of water that an aquifer yields and the behaviour of contaminant flow.

Transmissivity and hydraulic conductivity describe the general ability of an aquifer to transmit water, that is, over the entire saturated thickness for transmissivity and over a unit thickness for hydraulic conductivity, and are among the most important hydrogeologic data needed for managing groundwater resources. Representative transmissivity and hydraulic conductivity data are required to ensure that the hydrologic assumptions and interpretations used in regional water plans are valid (Mace *et al*, 1997). Storativity describes the change in volume of water for a unit change in water level per unit area whiles specific capacity is the pumping rate per unit drawdown. Transmissivity, hydraulic conductivity, storativity and specific capacity data are needed in tasks such as:

- Quantitative assessment of groundwater,
- Numerical modeling of groundwater flow,
- Prediction of well performance,
- Evaluation of how site-specific test results compare with the variability of the regional aquifer, and
- Assessing the transport of solutes and contaminants.

It is important therefore ~~to have~~ a transmissivity, hydraulic conductivity, storativity and specific capacity database that are readily available for developing local and regional water plans and to predict future groundwater availability.

2.4.1 Methods of Estimating Aquifer Characteristics or Parameters

Accurate estimation of aquifer parameters such as transmissivity, hydraulic conductivity, storativity and specific capacity are as have already been indicated considered to be very crucial for successful groundwater development and management practices. Hydrogeologists have used many methods of estimating these aquifer parameters over the years, the most common of which is the pumping test in the field where a well is pumped and the effect of this pumping on the piezometric head in the vicinity is measured as drawdown. Other methods include the use of different empirical formulae.

2.4.1.1 Estimation of Hydraulic Conductivity based on Grain-size Analysis

Grain-size distribution analysis has been of interest to geologists since its introduction by Krumbein (1934). Such analysis is useful in distinguishing between different depositional environments. Since hydraulic conductivity is the measure of the ease with which fluid flows through porous material, certain relationships are expected to exist between hydraulic conductivity and statistical parameters that describe the grain-size distribution of depositional medium. Hydrogeologists have been concerned with determination of such relationships since the work by Hazen (1893).

Many different techniques have been proposed to determine its value, including field methods like pumping test of wells, laboratory methods and calculations from empirical formulae (Todd and Mays, 2005). However, accurate estimation of hydraulic conductivity in the field environment by the field methods is limited by the lack of precise knowledge of aquifer geometry and hydraulic boundaries (Uma *et al.* 1989). The cost of field operations and associated wells constructions can be prohibitive as well. Laboratory tests on the other hands, presents formidable problems in the sense of obtaining representative samples and, very often, long testing times. Alternatively, methods of estimating hydraulic conductivity from empirical formulae based on grain-size distribution characteristics have been developed and used to overcome these problems (Odong, 2007). Grain- size methods are comparably less expensive and do not depend on the geometry and hydraulic boundaries of the aquifer. Most importantly, since information about the textural properties of soils or rock is more easily obtained, a potential alternative for estimating hydraulic conductivity of soils is from grain-size distribution. Although in hydromechanics, it would be more useful to characterise the diameters of pores rather than those of the grains, the pore size distribution is very difficult to determine, so that approximation of hydraulic properties are mostly based on the easy-to-measure grain size distribution as a substitute (Cirpka, 2003).

2.4.1.2 Estimation of aquifer parameters using surficial geophysical methods

Geophysicists have realised that the integration of aquifer parameters calculated from the existed boreholes locations and surface resistivity parameters extracted from surface resistivity measurements can be highly effective, since a correlation between hydraulic and electrical aquifer properties can be possible, as both properties are related to the pore space structure and heterogeneity (De Lima *et al.*, 2005; Niwas *et al.*, 2006).

Resistivity techniques are well-established and widely used to solve a variety of geotechnical, geological and environmental subsurface detection problems (Ward, 1990). The primary purpose of the resistivity method is to measure the potential differences on the surface due to the current flow within the ground. Since the mechanisms which control the fluid flow and electric current and conduction are generally governed by the same physical parameters and lithological attributes, the hydraulic and electric conductivities are dependent on each other. Although there are other factors which govern the current flow and conduction into the soil (lithology, size, shape, mineralogy, packing and orientation of grains, shape and geometry of pores and pore channels, magnitudes of porosity, and permeability, compaction, consolidation and cementation and depth and water distribution) (Salem, 1999) are extremely variable. That is, the measured resistivity values are not absolute but relative, and therefore only relative conclusions about the area's hydraulic parameters can be made, and for this reason surface geophysical methods have been used for aquifer zone delineation and evaluation of the geophysical character of the aquifer zone in several locations in the world (Dhakate and Singh, 2005; Khalil, 2006)

2.5 Importance of Groundwater

Groundwater has been exploited by mankind since the beginning of time and it is estimated that around 700 billion m^3 are drawn out of the earth's aquifers each year. This makes groundwater by weight, the primary mineral raw material extracted from the earth, (Jean-Claude, 1995). Groundwater has many advantages over surface water:

- Quantitatively, the storage and inertia capacity of homogeneous aquifers, their very steady regime, allows them to act as buffers between very irregular rainfall and regular discharge through springs - therefore compensating for climatic variations and more or less ensuring water supply during periods of drought.
- Qualitatively, because of the presence of protective surficial geological formations, their depth, the filtering capacity of most of their reservoirs and the clogging of river banks, aquifer groundwater is generally better protected than surface water from massive pollution. The physico-chemical quality and the temperature of groundwater are relatively constant and in some cases it can be consumed without even bacteriological treatment.
- Economically, in ~~countries~~ having many aquifers, water is easily attainable, does not require long pipelines and thus involves lower pumping, treatment and energy costs.

2.5.1 Groundwater use in Ghana

Groundwater use in Ghana can be traced back to the 19^{th} century and during this period, communities relied on simple unlined hand dug wells at the initiative of the individuals or the communities. It has been recorded that the colonial administration under the supervision of the Rural Water Division, undertook a nation-wide hand dug well programme in the period of 1920 to 1945. Borehole drilling then began in the 1940s to provide water for larger communities. Since then, large numbers of both shallow and deep boreholes have been drilled by national and international non-governmental organisations.

Groundwater continues to be the most viable option for rural and small towns' water supply schemes and presently in Ghana, about 45% drinking water is from groundwater sources, and currently for dry season irrigation farming. Gyau-Boakye and Dapaah-Siakwan (1999) indicates that, groundwater is not only feasible but also the most economic source of potable drinking water due to the dispersed nature of the rural settlements.

2.6 Hydrogeological setting or framework of the White Volta Basin

The White Volta Basin is composed of about 45% crystalline rocks comprising the Birimian system and its associated Granitic Intrusives and isolated patches of Tarkwaian formations. The remaining 55% of the White Volta Basin is composed of Voltaian Systems consisting of the Upper Voltaian Sandstone, Obosum and Oti beds and Basal sandstone.

2.6.1 Crystalline Basement Complex Aquifers

Crystalline rocks are essentially impermeable and virtually have no primary porosity. Aquifer development is dependent on the formation of secondary porosity as a result of fissuring or weathering. Consequently most of the groundwater resources within the Northern and the North Eastern part of the White Volta Basin are obtained from the Crystalline Basement Complex, principally in the upper weathered rock or within faults and fractures in certain rock types. The weathering is brought about as a result of water circulating through joints, fractures and quart veins which were earlier developed in these rocks. According to Kortatsi (1997) there are two types of major aquifers in the White Volta basin. These are the weathered zone aquifers and the fissured zone aquifers. These aquifers are either phreatic semi-confined or confined depending on the clay and mica content of the upper weathered layer. The weathered zone aquifers develop in:

- A highly weathered zone where only quartz remains intact.
- A moderately weathered zone in which the less resistant minerals are partly decomposed.
- A thin zone of only slightly decomposed rock.
- The rock underlying zone of more or less fresh rock which is usually broken or fractured.

Well development in the second zone is usually successful but of poor yield due to low permeability resulting from the presence of altered products notably clay and mica. Wells developed into the third zone are relatively high yielding especially where quartz veins are present. Aquifers are highly variable in both configuration and depth. Groundwater also occurs in the alluvial deposits along stream and river channels within the valley and in buried river channels. These alluvial sediments usually consist of sandy loams and medium grained quartz sands which have abundant porosity and permeability. The alluvial cover is generally small in many areas and it varies in thickness from about 1m to approximately 6m, (Kortatsi, 1997).

2.6.2 The Voltaian Rocks

Many of the sedimentary rocks of the Voltaian Basin have undergone a slight degree of metamorphism and are well compacted and consolidated. Groundwater occurrence is therefore structurally and textually controlled. That is groundwater occurrence is closely associated with the existence of faults, joints, fractures bedding planes and weathered zones as well as the grain sizes of the beds. The Upper Voltaian consisting of sandstones, quartzitic and fieldspartic sandstones are fairly hard and well consolidated and therefore inherently impermeable. It is however characterised by well developed and extensive open joints, permeable bedding planes and faults particularly very close to the Birimian contact (Kortatsi, 1997). These fissure zones give rise to deeper groundwater circulation and thus the occurrence of relatively high yielding aquifers.

The occurrence of groundwater in the basal sandstone of the Lower Voltaian as in the case of other divisions of the Voltaian formation is primarily controlled by the development of secondary porosities in the form of fractures, faults, joints permeable bedding planes etc. This is due to the fact that the primary porosity has been destroyed due to compaction, consolidation and cementation. Groundwater also occurs in certain areas when there is an increase in deposited sand or a significant thickness of soil cover or weathered zone has developed. Generally, the unconsolidated sediments of the soil and the weathered zones have abundant porosity for groundwater storage and greater permeability for deep groundwater circulation.

2.6.3 Groundwater flow system

The discontinuous nature of permeable zones (weathered and fissured network) in the White Volta Basin makes regional groundwater movement largely non existent, local groundwater flow thus predominates. However, around the fringes of the Gambaga highlands stretching across to the fringes of Konkori highlands the Upper Sandstone have produced a network of permeable saturated weathered and fissured zones which could give rise to intermediate groundwater movement system (Kortatsi, 1997). Generally however the groundwater flow distribution coincides with the surface water flow distribution. That is, movement is generally from higher grounds (highlands) towards valleys and stream channels.

2.7 Shallow Groundwater Irrigation (SGI) in Atankwidi sub-basin

Tomato is the most important cultivated crop in the sub-basin under SGI. The main reason is that, the cultivation of tomato gives the highest guarantee for a stable income, because market conditions in the area are based on tomato. Furthermore, farmers do not like to experiment with other crops such as pepper since pepper is too labour intensive compared to yield (Van den Berg, 2008). The applications of shallow groundwater irrigation in the sub-basin are in many independent small areas along the river of approximately 1 to 20 hectares. An area where land is irrigated in general starts with a group of farmers who live close to that particular area and where, through experience enough water is found for dry season farming.

2.7.1 Shallow Hand dug Wells

The locations of the wells in the sub-basin are determined with trial-and-error method, so experience with water availability of previous years is important. Farmers also take into account the elevation of the area and moist of the soil at the start of the season. The number of wells is mainly determined by water availability, but also nearness to the crops is an important reason.

The digging of wells by farmers start from late September to late October with farmers with fields close to the river waiting till the river stops flowing in October. Farmers further away start digging earlier. According to Van den Berg (2008) wells are filled back with soil at the end of the dry season and reopened in the next season for three main reasons;

- animals could fall in,
- the rainy season erodes the area close to the well, which causes the well to be less stable the next dry season, and

- the mud heaps take a lot of space which can be used for cultivating crops in the rainy season.

The diameter of the wells varies from 60-90 cm with depth ranging from 3m to 15m. Most farmers have their own materials such as bucket, axe, hoe and bowl which they use to dig with few farmers having to borrow probably due to lack of funds. Van den Berg (2008) indicates that wells run dry as the season proceeds due to abstraction from wells for irrigation. Most of the farmers deepen their wells 1 to 3 times during the season for approximately 0.3-0.5 m per time.

2.8 Groundwater Quality

Groundwater quality can be defined as the physical, chemical and biological state of groundwater. Temperature, turbidity, colour, odour, and taste make up the list of physical parameters. Naturally, groundwater contains ions. These ions slowly dissolve from minerals in the soils, rocks, and sediments as the water travels along its flow path. Some small portion of the total dissolved solids may have originated from the precipitation water or river water that recharges the aquifer. The ions most commonly found in groundwater quality analysis include: Na^+, Ca^{2+}, Mg^{2+} HCO_3^-, Cl^-, SO_4^{2-}. Minor ions include NO_3^-, NO_2^-, F^- ; CO_3^- K^+, Mn^{2+}, Mn^{2+} and Fe^{2+}. The concentration of these ions gives groundwater their hydrochemical characteristic, and often reflects the geological origin and groundwater flow regime. For the purpose of this study, the attention was on the physico-chemical parameters of groundwater.

2.8.1 Factors Affecting Groundwater Quality

An understanding of the factors that affect groundwater quality can help in decisions making on well depth and the best water quality for a particular application. The major factors that directly or indirectly affect groundwater quality include:

- Climatic variations (rainfall, evaporation etc.),

- Permeability and chemical make up of the sediments through which groundwater moves,
- Depth of groundwater from surface.

2.9 Irrigation Water Quality

Besides affecting crop yield and soil physical conditions, irrigation water quality can affect fertility needs, irrigation system performance and how the water can be applied. Therefore, knowledge of irrigation water quality is critical to understanding what management changes are necessary for long-term productivity.

2.9.1 Assessment of Irrigation Water Quality

In irrigation water quality evaluation, emphasis is placed on the chemical and physical characteristics of the water and only rarely is any other factors considered important. The quality of irrigation water is assessed based on the following criteria:

- Salinity (total amount of dissolved salts in water),
- Sodium hazard (the amount of sodium in the water compared to calcium plus magnesium),
- Magnesium hazard (MH).

These criteria in relation to irrigation water quality and their acceptable limits are discussed below.

Salinity Hazard

Salinity hazard is a measure of the TDS expressed in the unit of electrical conductance and is the most influential water quality guideline on crop productivity. High concentration of salinity (electrical conductivity) in irrigation water affect crop yield through the inability of the plant to compete with ions in the soil solution for water (osmotic effect or physiological drought). The higher the electrical conductivity (EC_w), the less water is available to plants, even though the soil may appear wet. This is because plants can only transpire "pure" water, usable plant water in the soil solution therefore decreases dramatically as EC_w increases. Table 2.1 shows suggested criteria for irrigation water use based upon electrical conductivity.

Table 2.1: Criteria for Irrigation water use based on electrical conductivity (Bauder *et al*, 2007)

Classes of Water	Electrical Conductivity (dS/m)
Class 1: Excellent	≤0.25
Class 2: Good	0.25 - 0.75
Class 3: Permissible[1]	0.76 - 2.00
Class 4: Doubtful[2]	2.01 - 3.00
Class 5: Unsuitable[2]	≥3.00

[1] Leaching needed if used.
[2] Good drainage needed and sensitive plants will have difficulty obtaining stands.

Sodium Hazard

Sodium hazard is defined separately because of sodium's specific detrimental effects on soil physical properties. According to Karanth (1994), excessive Na^+ content of irrigation water renders it unsuitable for soils containing exchangeable Ca^{2+} and Mg^{2+} ions as the soil take up Na^+ in exchange for Ca^{2+} and Mg^{2+} causing deflocculation (dispersion) and impairment of the tilth and permeability of soils. The sodium hazard is typically expressed as the sodium adsorption ratio (SAR) which is defined as;

$$SAR = Na\,[0.5(Ca + Mg)]^{-0.5},$$ where chemical constituents are expressed in meq/l

This index quantifies the proportion of sodium (Na^{2+}) to calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions in a sample. General classifications of irrigation water based upon SAR values according to Bauder *et al*, (2007) are presented in Table 2.2

Table 2.2: Classification of irrigation water based on SAR values (Bauder *et al*, 2007)

SAR Values	Sodium hazard to water	Comments
1 – 9	Low	Use on sodium sensitive crops must be cautioned
10 – 17	Medium	Amendments (such as gypsum) and leaching needed
18 – 25	High	Generally unsuitable for continuous use.
≥ 26	Very High	Generally unsuitable for use.

Magnesium Hazard (MH)

Magnesium is believed to be injurious to plants. Nonetheless, the harmful effect is greatly reduced by the presence of calcium. The MH is defined as $100Mg\ (Ca + Mg)^{-1}$ with the chemical constituents expressed as meq/l. According to Szabolcs and Darab (1964), MH>50 in irrigation water is considered to be deleterious to most crops.

2.10 Domestic Water Quality

Water is said to have good chemical quality for domestic use if it is soft, low in total dissolved solids (TDS) and free from poisonous chemical constituents (Karanth, 1994). Evidence relating chronic human health effects to specific drinking water contaminants is very limited and in the absence of exact scientific information, scientists predict the likely adverse effects of chemicals in drinking water using laboratory animal studies and when available, human data from clinical reports and epidemiological studies.

Many organisations such as World Health Organisation (WHO), have established standards (guideline values) for many chemical constituents of drinking-water. A guideline value normally represents the concentration of a constituent that does not result in any significant risk to health over a lifetime of consumption (WHO, 2004). A number of provisional guideline values has been established at concentrations that are reasonably achievable through practical treatment approaches or in analytical laboratories; in these cases, the guideline value is above the concentration that would normally represent the calculated health-based value. Guideline values are also designated as provisional when there is a high degree of uncertainty in the toxicology and health data.

2.10.1 Physico-Chemical Parameters of Domestic Water

Physico-chemical parameters of water are the parameters that describe the physical and chemical states of water. These parameters can cause health problems beyond certain concentration levels. Some of these physico-chemical parameters have been discussed below.

Total Dissolved Solids (TDS)

TDS comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides and sulfates) and small amounts of organic matter that are dissolved in water. Concentrations of TDS in water vary considerably in different geological regions owing to differences in the solubilities of minerals. The palatability of water with a TDS level of less than 600 mg/l is generally considered to be good; drinking-water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000 mg/l (WHO, 2004). The presence of high levels of TDS may also be objectionable to consumers. No health-based guideline value for TDS has been proposed.

Turbidity

Turbidity in drinking-water is caused by particulate matter that may be present from source water as a consequence of inadequate filtration or from resuspension of sediments. It may also be due to the presence of inorganic particulate matter in some groundwaters or sloughing of biofilm within the distribution system. The appearance of water with a turbidity of less than 5 NTU is usually acceptable to consumers, although this may vary with local circumstances. No health-based guideline value for turbidity has been proposed; ideally, however, median turbidity should be below 0.1 NTU for effective disinfection, and changes in turbidity are an important process control parameter (WHO, 2004).

Temperature

Cool water is generally more palatable than warm water, and temperature will impact on the acceptability of a number of other inorganic constituents and chemical contaminants that may affect taste. High water temperature enhances the growth of microorganisms and may increase taste, odour, colour and corrosion problems.

Total Hardness

Hardness in water is caused by dissolved calcium and, to a lesser extent, magnesium. It is usually expressed as the equivalent quantity of calcium carbonate. Hardness caused by calcium and magnesium is usually indicated by precipitation of soap scum and the need for excess use of soap to achieve cleaning. Depending on pH and alkalinity, hardness above about 200 mg/l can result in scale deposition, particularly on heating. Todd (1980) classifies groundwater samples based on total hardness as shown in Table 2.3.

Table 2.3: Classification of groundwater samples based on total hardness (Todd, 1980)

Hardness (mg/l $CaCO_3$) range	**Water classification**
0 – 75	Soft
75 – 150	Moderately hard
150 – 300	Hard
>300	Very hard

pH

It is the measure of acidity or alkalinity of a solution. The pH scale runs from 0 to 14 (very acidic to very alkaline) with 7 as neutral condition. Dissolved chemical compounds and the biochemical processes in the water usually control the pH. In most unpolluted water, pH is primarily controlled by the balance between free CO_2, CO_3 and HCO_3 ions as well as natural compounds such as humic and fulvic acids. Although pH usually has no direct impact on consumers, it is one of the most important operational water quality parameters, the optimum pH required often being in the range 6.5–9.5.

Fluoride

Fluoride in water derives mainly from dissolution of natural minerals in the rocks and soils through which it passes. Macdonald *et al* (2005) indicates that, the most common fluorine-bearing minerals are fluorite, apatite and micas, and fluoride problems tend to occur where these elements are most abundant in the host rocks. Groundwaters from crystalline rocks, especially granites are particularly susceptible to fluoride build-up because they often contain abundant fluoride-bearing minerals. Fluoride is essential for healthy living and hence fluoride causes health concerns when concentrations in drinking-water are too low or high. It has been found to have a significant mitigating effect against dental caries and is widely accepted that some fluoride presence in drinking-water is important. Optimal concentrations are usually around 1 mg/l. The chronic ingestion of fluoride concentrations much grater than the WHO (2004) guideline value of 1.5 mg/l however is linked with development of dental fluorosis.

Chloride (Cl^-)

Chloride in drinking-water originates from natural sources, sewage and industrial effluents, urban runoff containing de-icing salt and saline intrusion. Excessive chloride concentrations increase rates of corrosion of metals in the distribution system, depending on the alkalinity of the water. This can lead to increased concentrations of metals in the supply. No health-based guideline value is proposed for chloride in drinking-water. However, chloride concentrations in excess of about 250 mg/l can give rise to detectable taste in water (WHO, 2004)

Nitrate (NO_3)

Nitrate (NO_3) is found naturally in the environment and is an important plant nutrient. It is present at varying concentrations in all plants and is a part of the nitrogen cycle. Nitrate can reach both surface water and groundwater as a consequence of agricultural activity (including excess application of inorganic nitrogenous fertilisers and manures), from wastewater disposal and from oxidation of nitrogenous waste products in human and animal excreta, including septic tanks. Some groundwaters may also have nitrate contamination as a consequence of leaching from natural vegetation. The WHO (2004) guideline values for both nitrate and nitrite are 50 mg/l and 3 mg/l respectively.

Sodium (Na)

Sodium concentration in potable water are typically less than 20 mg/l, they can greatly exceed this in some countries. It should be noted that some water softeners can add significantly to the sodium content of drinking-water. No firm conclusions can be drawn concerning the possible association between sodium in drinking-water and the occurrence of hypertension. Therefore, no health based guideline value is proposed. However, concentrations in excess of 200 mg/l may give rise to unacceptable taste (WHO, 2004).

Sulphate (SO_4)

Sulphates occur naturally in numerous minerals and are used commercially, principally in the chemical industry. The highest levels usually occur in groundwater and are from natural sources. In general, the average daily intake of sulphate from drinking-water, air and food is approximately 500 mg, food being the major source.

No health-based guideline is proposed for sulfate. However, because of the gastrointestinal effects resulting from ingestion of drinking-water containing high sulphate levels, it is recommended that health authorities be notified of sources of drinking-water that contain sulfate concentrations in excess of 500 mg/l (WHO, 2004).

Magnesium (Mg)

Magnesium ranks eighth among the elements in order of abundance and is a common constituent of natural water. Important contributor to the hardness of water, Mg salts break down when heated, forming scale in boilers. Concentrations greater than 125 mg/l also can have a cathartic and diuretic effect. The magnesium concentration may vary from 0 – 100 mg/l depending on the source of treatment of the water. Chemical softening, reverse osmosis, electrodialysis, or ion exchange reduces the magnesium and associated hardness to acceptable levels (Standard Methods, 1992).

Iron (Fe)

Iron is one of the most abundant metals in the Earth's crust. It is found in natural fresh waters at levels ranging from 0.5 - 50 mg/l. Iron is an essential element in human nutrition. Estimates of the minimum daily requirement for iron depend on age, sex, physiological status and iron bioavailability and range from about 10 - 50 mg/day (WHO, 2004). Iron stains laundry and plumbing fixtures at levels above 0.3 mg/l; there is usually no noticeable taste at iron concentrations below 0.3 mg/l, and concentrations of 1 – 3 mg/l can be acceptable for people drinking anaerobic well water.

Calcium (Ca)

The presence of calcium in water results from passage through or over deposits of limestone, dolomite, gypsum and gypsiferous shales. The calcium content may range from zero to several hundred milligrams per litre, depending on the source and treatment of the water.

Small concentrations of $CaCO_3$ combat corrosion of metal pipes by laying down a protective coating. Biologically, calcium prevents the absorption and transfer of toxic ions from the intestines to the blood. Calcium contributes to dialysis or ion exchange and is used to reduce associated hardness (Standard Methods, 1992).

Manganese (Mn)

Manganese is one of the most abundant metals in the Earth's crust, usually occurring with iron. Manganese greensand is used in some locations for potable water treatment and is an essential element for humans and other animals and occurs naturally in many food sources. Manganese is naturally occurring in many surface water and groundwater sources, particularly in anaerobic or low oxidation conditions, and this is the most important source for drinking-water. The guideline value for manganese is 0.4 mg/l (WHO, 2004)

3. DESCRIPTION OF STUDY AREA

3.1 Introduction

This chapter deals with the description of the Atankwidi sub-basin of the White Volta Basin. The location and size of sub-basin, geology, climate, land use and vegetation, soil type and groundwater use in relation to the study are also dealt with.

3.2 Location and Size

The Atankwidi sub-basin is located between latitudes 10°49'47 N and 10°55'35 N and longitudinal 0°55'27 W and 0°59'27 W, a tributary of the White Volta located in the Upper East Region of Ghana between Navrongo and Bolgatanga (Kassena Nankana District) with its upper reach in Burkina Faso as shown in Figure 3.1. The sub-basin is located in one of the areas with the highest groundwater use per km² in the Volta River basin (Martin 2006). The sub-basin covers an area of about 275 km^2 of the White Volta basin.

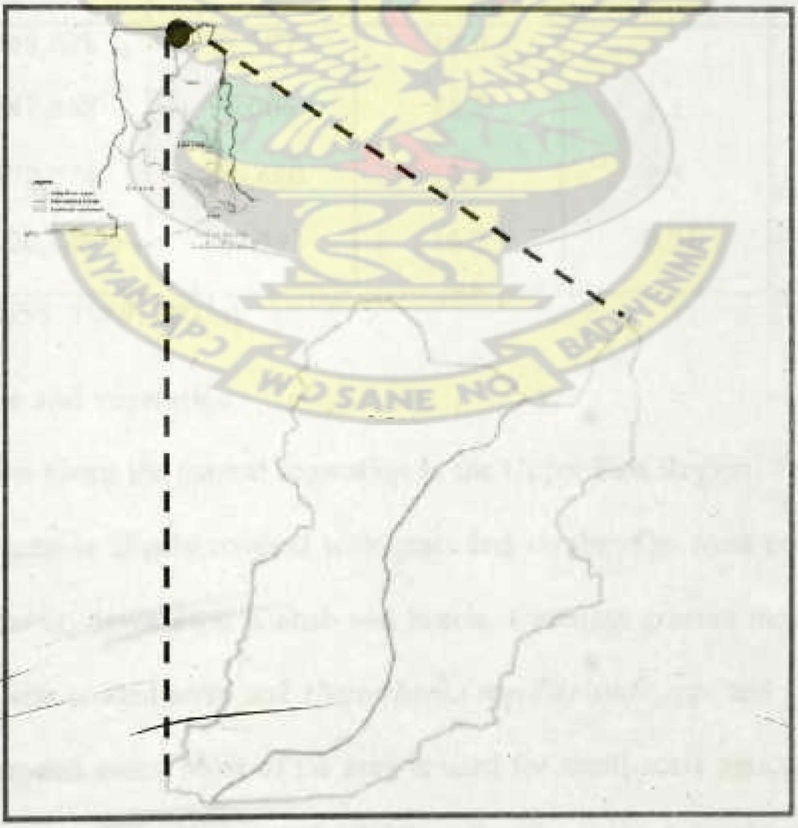


Figure 3.1: Map of the Atankwidi sub-basin

3.3 Population Size and Growth Rate

The population of the Kassena Nankana District within which the Atankwidi sub-basin falls is 149,491 (GSS, 2002a). Although population growth in the sub-basin has not kept pace with the overall development in Ghana, the local population certainly experienced a significant growth. The population of the UER almost doubled in the last forty years and increased by approximately 70 % in the Kassena Nankana District. The population density of the area (91 to 104 persons/km^2), is well above the national average level of 79 persons/km^2. Table 3.1 shows the population size and growth rate of the area from 1960 – 2000.

Table 3.1: Population size, Growth rate and Population density of Kassena Nankana District

Year	Upper East Region	Kassena Nankana District			
	Population	Population	As % of Region	Growth Rate (%)	Population Density (persons/km^2)
1960	468,638	93,397	19.9	–	37.2
1970	542,858	99,006	18.2	5.1	60.3
1984	772,774	149,680	19.4	2.5	91.2
2000	920,089	149,491	16.2	-0.01	91.0

Data Source: (GSS, 1989; 2002a)

3.4 Land use and vegetation

Open tree-savanna forms the natural vegetation in the Upper East Region. Trees show a large spacing and the area is largely covered with grass and shrubs. The most common economic trees are the sheanut, dawadawa, boabab and acacia. Common grasses include *Andropogen gayyanus* in the less eroded areas and *Hyperrhenia spp.*, *Aristida spp.* and *Heteropogen spp.* in the severely eroded areas. Most of the area is used for small-scale agriculture. During the rainy season, almost 70 % of the area is covered with small plots of rainfed agriculture (Martin, 2006). Other parts of the area are used for livestock grazing and drinking. In the dry season, the amount of agriculture is substantially lower, approximately 1 % of the area (Unofficial report, GVP, 2007). The other parts of agricultural land remain as bare soil until the next rainy season starts. Land not used for agriculture is either sparse vegetation on shallow soils in stony areas or land used for the grazing of livestock, which is covered by grass, shrubs and trees.

3.5 Climate

The study area falls within the Sudan-Savanna climate zone, which is characterised by high temperatures and a uni-modal rainfall distribution with a distinct rainy season lasting approximately from May to September. The mean annual rainfall in Navrongo is approximately 980mm.

The spatio-temporal distributions of precipitation and evaporation have a large impact on the water regime including the groundwater variability. In the rainy season daily rainfall may exceed 50 mm, this falls in less than one hour. Monthly rainfall only exceeds potential evaporation in the three wettest months, July, August and September. The total potential evaporation is 2050 mm, which is twice the annual rainfall. The average annual temperature is 29 °C. The mean daily minimum temperature is 25 °C, coinciding with the peak of the rainy season, and rises to a maximum of 34 °C in April.

Relative humidity is highest during the rainy season with 65 %. It drops quickly after the end of the rainy season in October, reaching a low of less than 10 % during the harmattan period in December and January (Martin, 2006). Monthly rainfall only exceeds potential evapotranspiration in the three wettest months July, August and September.

3.6 Relief and Drainage

The relief of the sub-basin is generally flat, gently undulating with slopes ranging from 1 to 5% except in a few uplands where slopes are about 10%. According to Adu (1969), the relief of the UER is related to the geology, where a range of Birimian greenstone hills rising up to 457m above sea level dominate north of Bawku and Zebilla along the border with Burkina Faso and in the southwest along the White Volta River (WVR). The granite areas are generally of low, gently rolling relief ranging from 122 m to 260 m above sea level. The relief under Voltain rocks has similar characteristics to granites, with few escarpments rising above 518 m near the border with Togo in the east. The mean elevation for the area is 197 m above sea level (Liebe, 2002).

3.7 Soil characteristics

The Soil Research Institute (SRI) distinguishes three soil types (Environmental Protection Agency / World Bank, 1999). Leptosols are predominant along the elevated northern and eastern border of the sub-basin. Fluvisols are found in the flat terrain to the sides of the main stream. The remaining area is covered by Lixisols. Lixisols consists of sandy loam to sandy clay loam with high clay contents in the upper part of the profile and have an increasingly coarse texture with depth, (Martin, 2006). Precipitation of iron oxides inside soil aggregates, sometimes to the extent of forming pisolithes, and bleaching of aggregate surfaces are often encountered as evidence of water logging and alternating oxidizing and reducing conditions in the upper part of the soil profile. In the elevated area around Zoko, the soils have a texture of loamy sand to sandy loam and are rather shallow so that moderately weathered granite is encountered at less than 2 m depth (Leptosols). In the low lying areas of little slope to the sides of the lower reach of the Atankwidi river, soil profiles down to hand auger depth consist of compacted clay loam and can be classified as Fluvisols (Martin, 2006).

3.8 Geological Setting

Three formations of the Birimian domain can be distinguished in the study area (Figure 3.2) from the geological map 1:125,000, sheets Navrongo (Van den Berg *et al.*, 1963) and Zuarungo (Murray and Mitchell, 1960). These are: Birimian metasediments; Granitoids (granodiorites, granite and gneiss) associated with the Birimian; Intrusive Bongo granite. Paleoproterozoic granitoids consisting of hornblende - biotite granodiorite, biotite granite and biotite gneiss make up the largest part of the study area and form the slightly undulating south-western part of the Atankwidi sub-basin. Birimian metasediments made up of phyllite, schist and quartzite are found in small patches among the granitoids.

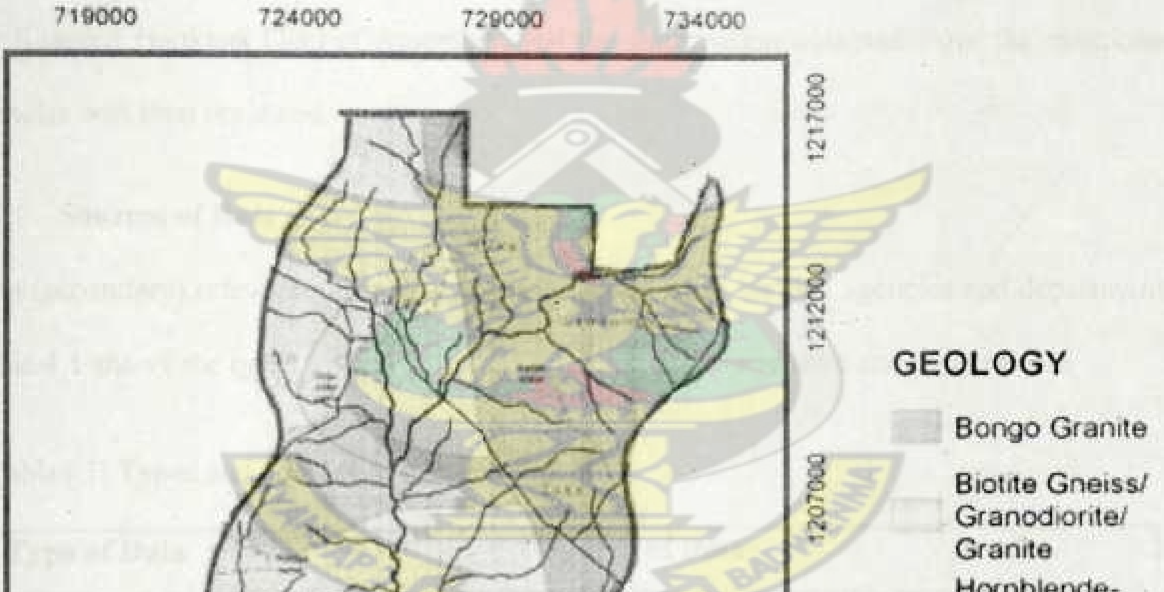


Figure 3.2: Geological and drainage map of the study area.

4. RESEARCH METHODOLOGY AND DATA COLLECTION

4.1 Introduction

The research methodology and data collection techniques adapted for the study are dealt with in this chapter. These include desk studies, sources of secondary data, soil and water sampling techniques, methods of laboratory and data analyses.

4.2 Desk Study

Relevant reports on the current status and extent of shallow groundwater irrigation in the sub-basin were collected from the Water Research Institute, Accra and the White Volta Basin Office in Bolgatanga. The background information of the study area was also obtained from the Kassena Nankana District Assembly. All the information obtained from the mentioned agencies was then reviewed.

4.3 Sources of Data

Data (secondary) relevant to the study were obtained from various agencies and departments. Table 4.1 shows the types of data collected from respective agencies and departments.

Table4.1: Types and sources of secondary data

Type of Data	Source of Data
Hydrogeological and Geophysical exploration data	Water Research Institute (WRI), Accra
Meteorological data	Ghana Meteorological Agency (GMA), Accra
Geological maps	Geological Survey Department, Accra
Topographical maps	Survey Department, Accra
Population and Housing Census, 2000	Ghana Statistical Service (GSS), Accra

4.4 Field Work

The field work for this study was conducted to first find out how the wells were dispersed in the sub-basin. As such, specific locations of wells were then taken with the help of GPS. The survey was also to ascertain the current status and extent of SGI and groundwater use generally in the area to aid data collection. Visits were therefore made to areas like Sirigu, Atankwire, Simburugu, Kaase and Akamo where farmers usually dig more shallow wells for dry season irrigation.

4.5 Determination of Aquifer geometry

Surface geophysical methods were used to delineate the aquifer system in the sub-basin. Geophysical exploration data of 390 locations in the area were obtained from the Groundwater section of the Water Research Institute of Ghana, Accra. The locations of the VES were planned so as to survey the whole sub-basin as shown in the map in Figure 4.1. The resistivity measurements from the data were processed and analysed to determine the aquifer configuration which included depths to water table and bedrock. The saturated/weathered thickness of aquifer in the area was then determined from the difference between the depth to the bedrock and the depth to water table.

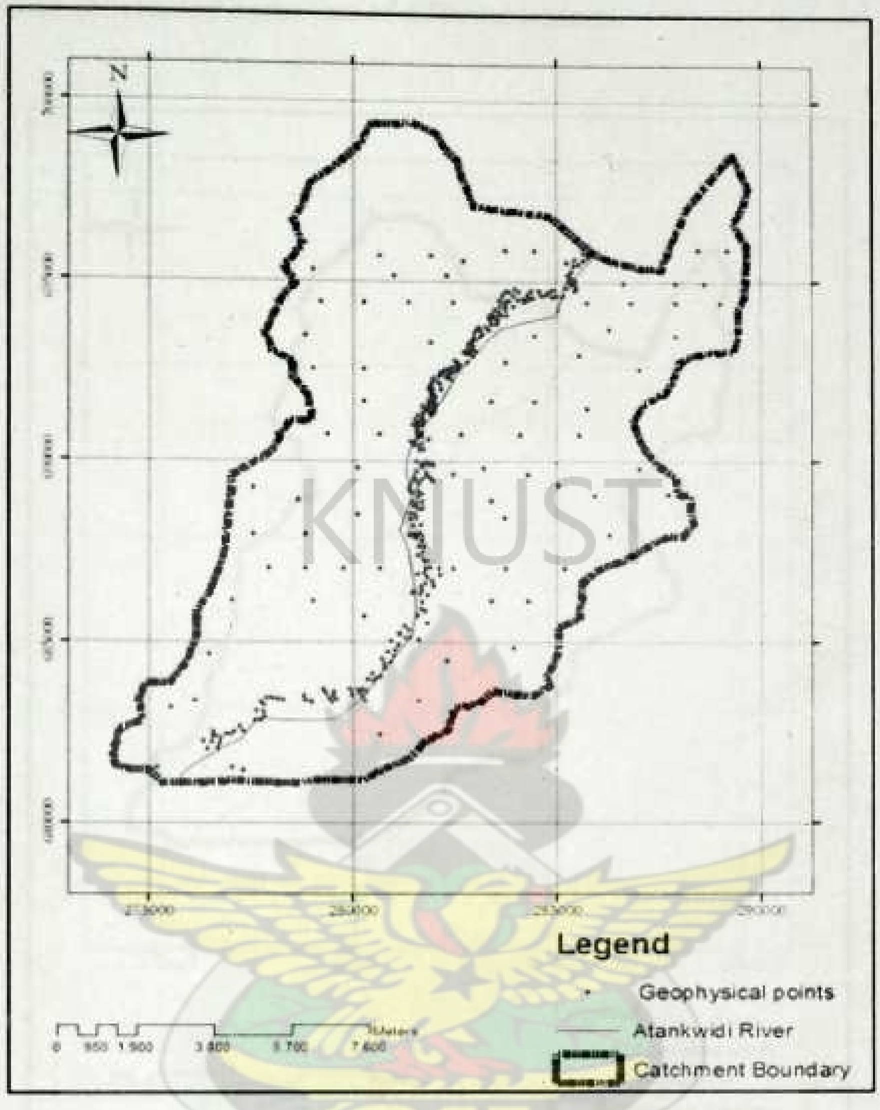


Figure 4.1: Map of VES locations in the study area

4.6 Sampling and Laboratory Analytical Techniques

Soil and groundwater samples were collected from various locations from the sub-basin. The techniques used in the sampling process and laboratory analysis are discussed below.

4.6.1 Soil sampling

Soil samples were collected from 20 dug outs with depths in the range of 1m – 4m in September when digging of wells had started. These disturbed soil samples were taken from wells at different locations of about 4km intervals as shown in the map in Figure 4.2. The coordinates of the respective locations where samples were collected were taken with the

GPS. The samples collected as such were of different texture.

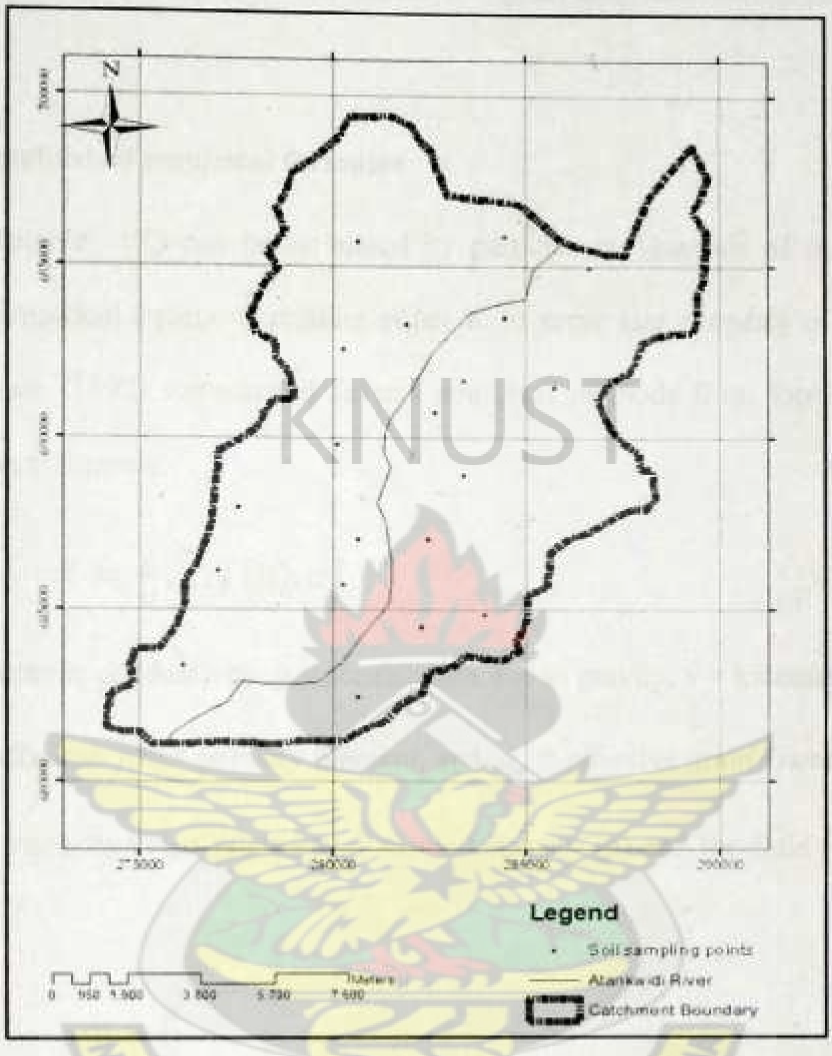


Figure 4.2: Map of soil sampling locations

Each of the samples which weighed about 1kg was kept in small polyethylene bags and labeled. They were then transported to the Geotechnical Engineering Laboratory of the Civil Engineering Department, KNUST where the samples were analysed.

The samples were tested in the laboratory for grain size distribution according to the standard procedures of British Standards Institution Methods of Test for Soils for Civil Engineering Purposes (BS1377). The samples were tested by the method of dry sieve analysis using a series of sorted BS sieves. Hydrometer tests were also performed on the very fine particles of the soil samples. To further analyse the distribution of the particles, the test results were then plotted on a semi-logarithmic graph to obtain the grain-size distribution curves for each sample.

4.6.1.1 Some established empirical formulae

Hydraulic conductivity (K) can be estimated by particle size analysis of the sediment of interest, using empirical equations relating either K to some size property of the sediment. Vukovic and Soro (1992) summarised several empirical methods from former studies and presented a general formula:

$$K = \frac{g}{v}.C.f(n).d_e^2 \tag{4.1}$$

Where K = hydraulic conductivity, g = acceleration due to gravity, v = kinematic viscosity, C = sorting coefficient, $f(n)$ = porosity function, and d_e = effective grain diameter.

The kinematic viscosity (v) is related to dynamic viscosity (μ) and the fluid (water) density (ρ) as follows:

$$v = \frac{\mu}{\rho} \tag{4.2}$$

The values of C, $f(n)$ and de are dependent on the different methods used in the grain-size analysis. According to Vukovic and Soro (1992), porosity (n) may be derived from the empirical relationship with the coefficient of grain uniformity (U) as follows:

$$n = 0.255(1 + 0.83^U) \tag{4.3}$$

where U is the coefficient of grain uniformity and is given by:

$$U = \frac{d_{60}}{d_{10}} \tag{4.4}$$

Here, d_{60} and d_{10} in the formula represent the grain diameter in (mm) for which, 60% and 10% of the sample respectively, are finer than.

Former studies have presented the following formulae which take the general form presented in equation (4.1) above but with varying ***C***, ***f(n)*** and ***de*** values and their domains of applicability.

Hazen: $K = \frac{g}{v} \times 6 \times 10^{-4}[1 + 10(n - 0.26)]d_{10}^2$ 4.5

Hazen formula was originally developed for determination of hydraulic conductivity of uniformly graded sand but is also useful for fine sand to gravel range, provided the sediment has a uniformity coefficient less than 5 and effective grain size between 0.1mm and 3mm.

Kozeny-Carman: $K = \frac{g}{v} \times 8.3 \times 10^{-3} \left[\frac{n^3}{(1-n)^2}\right] d_{10}^2$ 4.6

The Kozeny-Carman equation is one of the most widely accepted and used derivations of permeability as a function of the characteristics of the soil medium. This equation was originally proposed by Kozeny (1927) and was then modified by Carman (1937, 1956) to become the Kozeny-Carman equation .It is not appropriate for either soil with effective size above 3mm or for clayey soils (Carrier 2003).

Alyamani and Sen: $K = 1300[I_o + 0.025(d_{50} - d_{10})]^2$ 4.7

where, K = hydraulic conductivity (m/day), I_o = intercept (mm) of line formed by d_{50} and d_{10} with the grain-size axis, d_{10} = effective grain diameter (mm), and d_{50} = median grain diameter (mm).

It should be noted that the terms in the formula above bear the stated units for consistency. This formula therefore, is exceptionally different from those that take the general form of equation 4.1 above. It is however, one of the well known equations that also depend on grain-size analysis. The method considers both sediment grain sizes d_{10} and d_{50} as well as the sorting characteristics.

4.6.1.2 Determination of Hydraulic Conductivity (K)

The main purpose of the grain-size distribution curves was to determine the hydraulic conductivity of the soil samples. The Alyamani and Sen (1993) empirical formula for determining hydraulic conductivity was used. The main reason was that, the limitations of the other discussed empirical formulae did not permit its use with respect to the samples considered in this study. Also, as compared to the other empirical formulae, the Alyamani and Sen (1993) formula uses the combined effects of effective grain-size diameters, average grain-size diameters, sorting characteristics, initial slope and the intercept of grain-size distribution curves, whiles the others often use only the effective and the average grain-size diameters.

For the establishment of K, the percentiles corresponding to increments of 5% starting from 5% was computed from the grading analysis. The result is a sequence of grain-size readings as d_5, d_{10}, d_{15}......d_{90}, d_{95}. These readings were plotted against corresponding percentiles on an ordinary sheet as shown in Appendix 4. The inspection of these plots indicated that the initial portions invariably appeared as a straight line. A straight line was therefore drawn through these points as shown in Appendix 4 from which both the intercept of the line (I_o) and the corresponding grain-size values for which 50% (d_{50}) and 10% (d_{10}) are finer than were determined for each sample.

Limitations of Alyamani and Sen Formula

The formula like any other empirical formula has some limitations which are as follows:

- It is very sensitive to the shape of the grading curve.
- More accurate for well-graded soil samples.
- In general, estimating hydraulic conductivity in terms of grading characteristics can relatively lead to underestimation or overestimation unless the appropriate method is used (Odong, 2007).

4.6.1.3 Determination of Transmissivity

The transmissivity of the aquifer system in the area were determined from the estimated hydraulic conductivities and the saturated thicknesses as shown in the relation:

$$T = K \times b \tag{4.8}$$

where, T is the transmissivity (m^2/day), K is the hydraulic conductivity (m/day) and b is the saturated aquifer thickness (m). The saturated thicknesses of the aquifer system were obtained from the already determined aquifer geometry (difference between depth to bedrock and depth to water table).

4.6.2 Water sampling

Groundwater samples were collected from 40 wells in March 2009 for major and minor ions analyses. Sampling protocols according to Wood (1981), Claasen (1982), and Barcelona *et al* (1985) were followed. The map of groundwater sampling points is shown in Figure 4.3. Water samples according to standards were collected after pumping the well for about 5 minutes in order to purge the well of stagnant water. The purging was done to stabilized temperature, pH and electrical conductivity readings.

For metal analysis, samples were filtered through 0.45µm filters and preserved with 5ml 6 N HNO_3 in laboratory treated 100ml high density linear polyethylene bottles. However, samples for anion analyses were without preservation. The Universal Conductivity Meter Multiline P4 set that had an in-built temperature compensation probe was used to measure electrical conductivity and temperature simultaneously. For the determination of total alkalinity (as HCO_3^-), field titration with 1.6 N H_2SO_4 to pH ~4.5 using HACH Digital Multi Sampler Model 1690 was done.

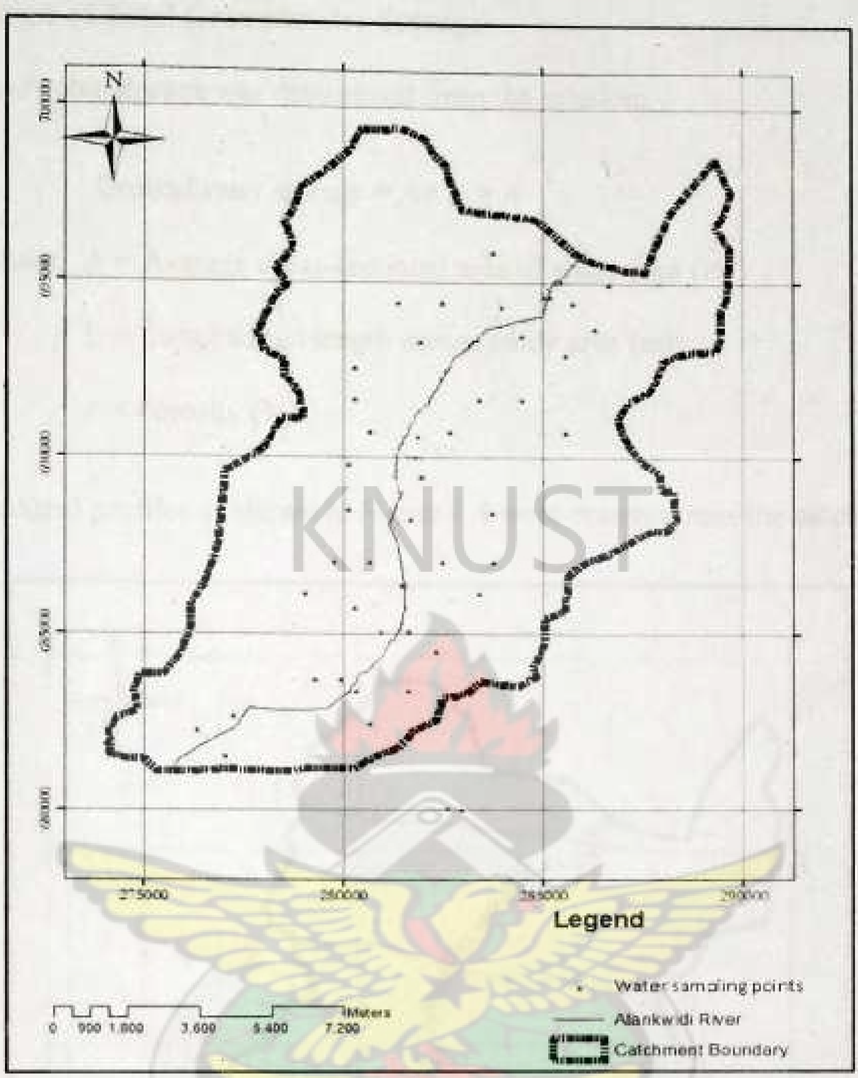


Figure 4.3: Map of Groundwater sampling locations

Chemical analyses for all major ions (Na^+, Ca^2, Mg^{2-}, HCO_3^-, Cl^-, SO_4^{2-}) as well as some minor ions (K^+, NO_3^-, F^-, PO_4^{2-}) were carried out with the Dionex DX-120 ion chromatograph at the Environmental Chemistry Laboratory at the Water Research Institute of Ghana. Manganese (Mn) and Iron (Fe) were also determined with mass spectrometer UNICAM 386 in the same laboratory. In accordance with international standards, results with ionic balance more than 5% were rejected.

4.7 Estimation of Total Groundwater Storage

The total groundwater storage was determined from the relation;

$$\text{Groundwater storage} = A \times L \times n \qquad 4.9$$

where, A = Average cross-sectional area of study area (m^2)

L = Longitudinal length across study area (m)

n = Porosity (%)

Five cross-sectional profiles as shown in Figure 4.4 were drawn across the catchment.

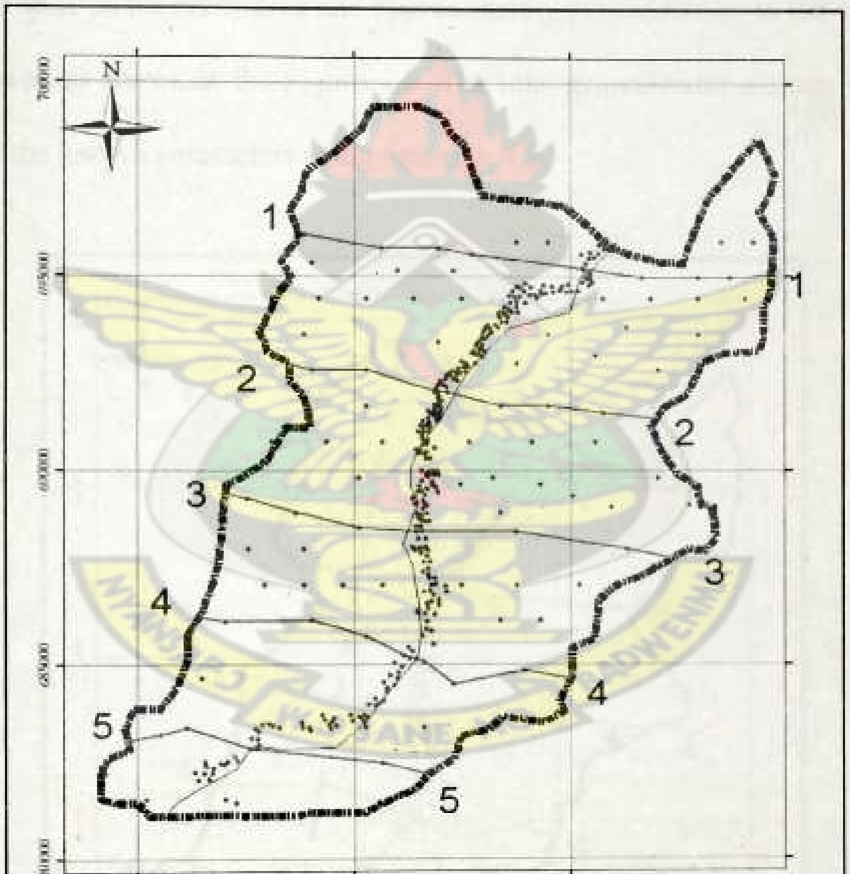


Figure 4.5: Map showing cross-sectional profiles

Using the Simpsons rule, the respective areas of the saturation zones of the five cross-sections were determined and hence the average area (A). The Simpsons rule is given by:

$$A = \frac{1}{3} \times \binom{width\ of}{interval} \times \left[\binom{first + last}{ordinate} + 4 \binom{sum\ of\ even}{ordinates} + 2 \binom{sum\ of\ remaining}{odd\ ordinates} \right] \qquad 4.10$$

The porosity was however determined from grain-size analysis using the Vukovic and Soro (1992) empirical formula for calculating porosity which has been stated above in equation 4.3

For the longitudinal length across the study area, the longitudinal length between the topmost and down most ends of the study area and approximately perpendicular to the cross-sectional profiles was taken as shown in the Figure 4.6. The total groundwater storage was thereafter computed with the known parameters using equation 4.9.

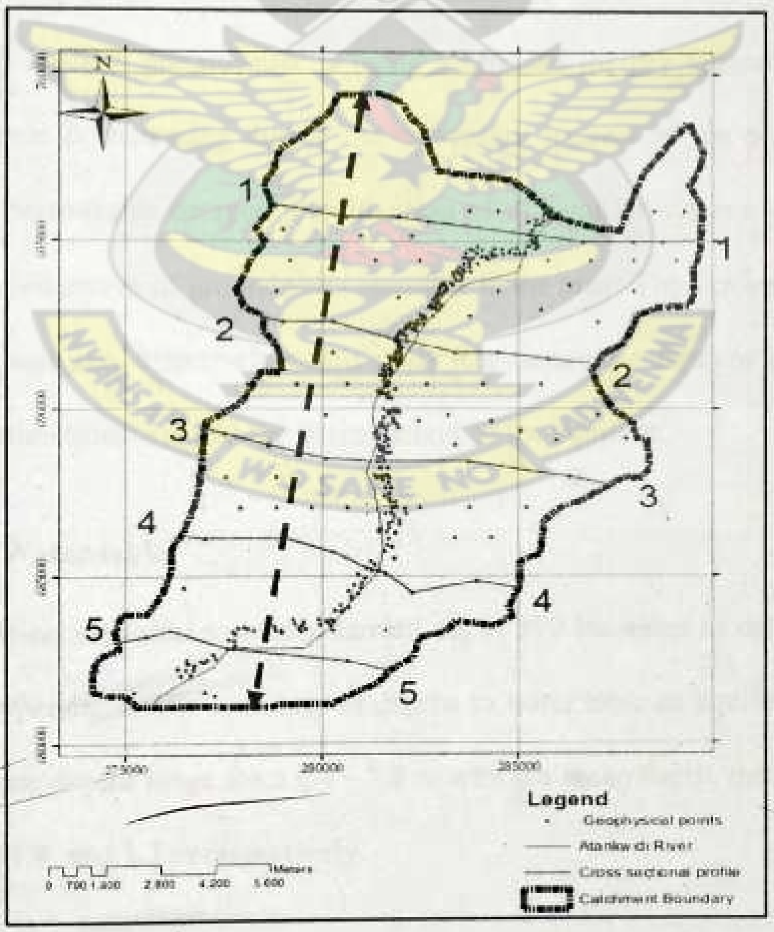


Figure 4.6: Longitudinal length across the study area

5. RESULTS AND DISCUSSIONS

5.1 Introduction

The results and discussions on the hydrogeological and the hydrochemical study have been presented in this chapter. The pertinent issues that have been discussed with regards to hydrogeology includes the following; depth to water table, depth to bedrock, saturated thickness of aquifers, hydraulic conductivity, transmissivity and volume of groundwater stored in the sub-basin. With regards to the hydrochemistry of groundwater samples, the physico-chemical parameters such as temperature, turbidity, total dissolved solids and ions such as Na^+, Ca^{2+}, K^+, Mg^{2+}, Fe^{2+}, HCO_3^-, SO_4^{2-}, Cl^-, PO_4^{2-}, NO_3^- and F^- have been discussed. The suitability of groundwater for agricultural (irrigation) use has also been established.

5.2 Analysis of Aquifer Characteristics or Parameters

The rate at which shallow groundwater is being abstracted for dry season irrigation in the Atankwidi sub-basin is increasing due to the increasing interest of the population in food production. This necessitates detailed identification of the aquifer system which is essential for sustainable development of groundwater resource in the area. The vertical electrical depth sounding method was used effectively in this study to estimate the depth to water table, depth to bedrock, saturation thickness and the lateral extent of the aquifers.

5.2.1 Depth to Water table

Results of the vertical electrical sounding carried out at 390 locations to determine the depth to water are in Appendix 1. The summary of depths to water table or aquifer top is shown in the Table 5.1. These depths range from 0.4 - 7.8 m with the mean depth, median and standard deviation are 1.7, 1.4, and 1.3 m respectively.

Table 5.1: Summary of depth to water table of Atankwidi sub-basin

Range of depths, m	Vertical Electrical depth Sounding points	Percentage
0 – 1	129	32.3
1 – 2	173	45.0
2 – 3	51	13.1
3 – 4	18	4.6
4 – 5	7	2.0
5 – 6	6	1.5
6 – 7	2	0.5
7 – 8	4	1.0
TOTAL	**390**	**100**

The area from the table above can be seen to generally have a shallow water table or depth to the aquifer top. That is, about 90 % of the values obtained fell within 0 – 3 m. This justifies the reason behind the depths of most hand dug wells in the area used for irrigation are of depth ranging between 3 – 5 m.

5.2.2 Depth to Bedrock

The Atankwidi sub-basin generally has depths to bedrock ranging from 2.0 - 38.3 m with a mean value of 8.4 m. The median and the standard deviation values are 7.3 m and 5.5 m respectively. The summary of the various depths to the bedrock in the study area is presented in the Table 5.2.

Table 5.2: Summary of depths to bedrock of aquifers the Atankwidi sub-basin

Range of depths, m	Vertical Electrical depth Sounding points	Percentage
0 – 5	99	25.4
5 – 10	193	49.5
10 – 15	62	16.0
15 – 20	21	5.4
20 – 25	7	1.8
25 – 30	3	0.8
30 – 35	3	0.8
35 – 40	1	0.3
TOTAL	**390**	**100**

Statistical inferences from Table 5.2 show that almost 90 % of the VES points that were investigated in the area had depths to bedrock between 2 – 15 m whilst about 10 % of the points exceeded up to 38.3 m.

5.2.3 Saturated thickness of Aquifers

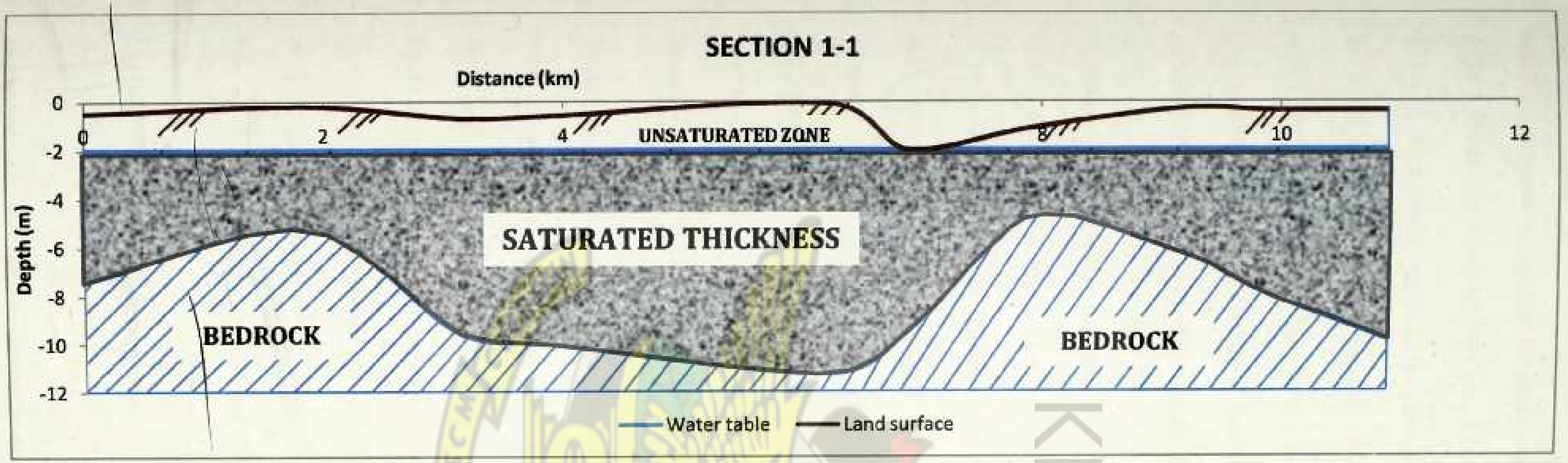
The saturated thickness of aquifers in the area ranges from 0.1 – 35 m with a mean, median and standard deviation of 6.3, 5.6 and 7.4 m respectively. The summary is given in the Table 5.3.

Table 5.3: Summary of saturated thickness of aquifer in Atankwidi sub-basin

Range of thickness, m	Vertical Electrical depth Sounding points	Percentage
0 – 5	192	49.2
5 – 10	135	34.6
10 – 15	41	10.5
15 – 20	12	3.1
20 – 25	4	1.0
25 – 30	3	0.8
30 – 35	3	0.8
TOTAL	**390**	**100**

It can be realised from the table that more than 80 % of the VES points showed a saturated thickness of 0.1 – 10 m with only 1 % showing thickness of between 30 – 35 m.

Diagrams to represent the saturated thicknesses of aquifers in the study area along the five cross-sectional profile lines in Figure 4.5 have been drawn. That of sections 1 – 1 and 2 – 2 are shown in Figure 5.1. The remaining sections (3 – 3, 4 – 4, and 5 – 5) are shown in Appendix 7.



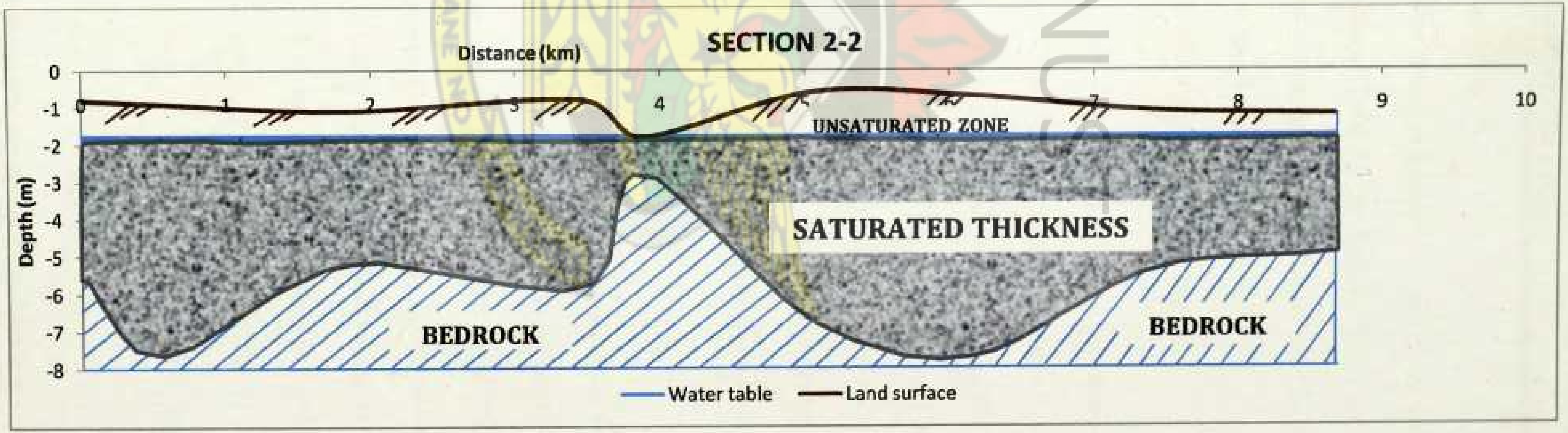


Figure 5.1: Saturated thicknesses of aquifers along cross-sectional profile lines

5.2.4 Hydraulic conductivity and Transmissivity

The ease with which water moves through pore spaces or fractures in aquifers are very crucial in the investigation of groundwater availability. Hydraulic conductivity and Transmissivity which both describe this characteristic are therefore considered to be some of the important characteristics of water-bearing formations (Alyamani and Sen, 1993). Their magnitude, pattern and variability therefore significantly affect groundwater flow patterns.

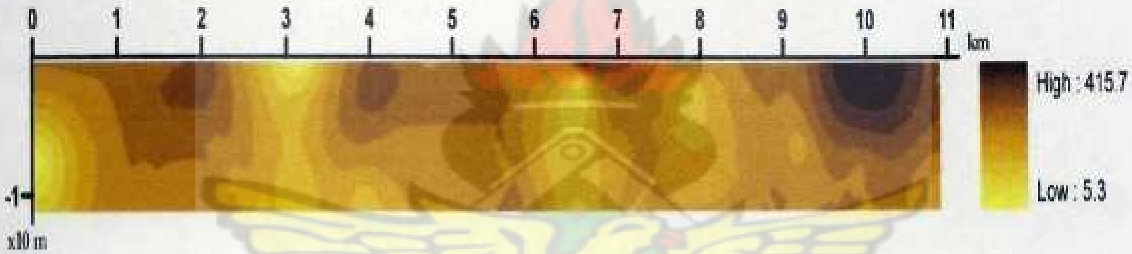
Hydraulic conductivities determined from grain size analysis using the Alyamani and Sen (1993) empirical formula ranges from 1.25×10^{-2} m/d to 1.52×10^{-2} m/d with a mean of 1.37×10^{-2} m/d. Details of results are shown in Appendix 5. These values suggest that the ease with which water moves through pore spaces or fractures is slow. The maximum was recorded at around the Kaase community in the study area where soil samples showed properties of silt, with the minimum being recorded at Bembisi-Sirigu area of the catchment where samples were typically clay. The results obtained are quite consistent with the hydraulic conductivities of both clay and silt.

Transmissivity values were computed from the product of the hydraulic conductivities and their respective saturated aquifer thickness. The transmissivity values in the sub-basin varied from 3.75×10^{-3} m^2/d to 5.32×10^{-1} m^2/d with a mean value of 9.86×10^{-2} m^2/d. These values again suggest low transmissivity of aquifers in the study area. Transmissivity values according to hydrogeologists are known to define aquifer conditions. Values expressed in m^2/s define confined aquifer conditions when they fall within the orders of 10^{-3} and 10^{-5}. With this as the basis, aquifer conditions in the sub-basin generally suggest that of unconfined aquifers.

5.2.5 Variation of groundwater with depth in the Atankwidi sub-basin

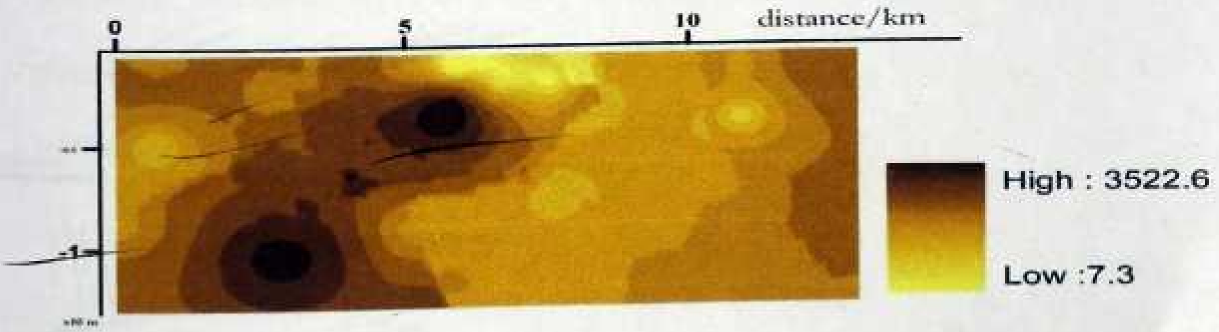
With the objective of mapping the detailed aquifer configuration and variations in saturation with depth with the aid of resistivity variation in the area, a two-dimensional (2D) electrical imaging of resistivity-depth sections were produced along five profile lines in the sub-basin to depict the variation of groundwater with depth. These profiles were arranged serially from north to south. The exact location and orientation of these profiles are shown in Figure 4.1 above. The resistivity-depth images of the various cross-sectional profiles are shown in Figure 5.2 and discussed below.

Section 1 - 1

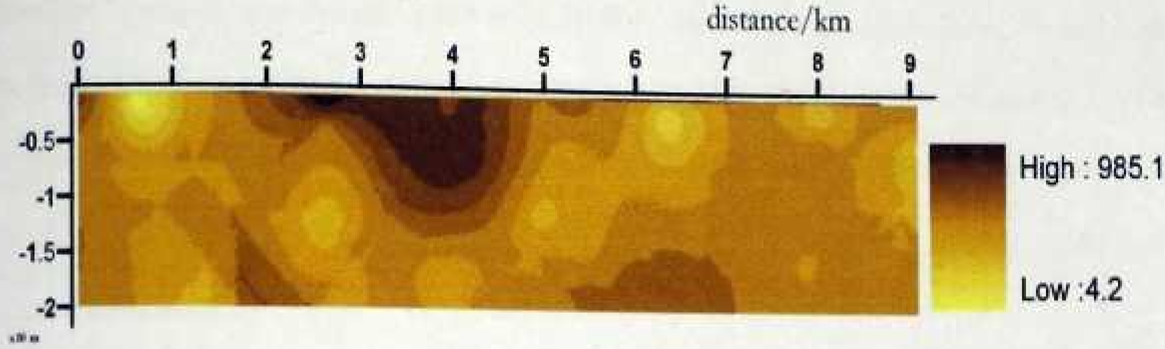


Section 2 – 2

Section 3 – 3



Section 4 – 4



Section 5 – 5

Figure 5.2: Resistivity-depth sections along the five cross-sectional profiles

As resistivity is the inverse of conductivity, low resistivity means high conductivity and hence high saturation and vice versa. The interpretations of the electrical images are all based on this assertion. Toward the south, as indicated by section 5 – 5, the saturated zone is at shallower depths. Thus the profiles oriented in different directions show the configuration of the aquifer zone and its elevation along the profile line. The aquifer zones are normally dipping southward, indicating local groundwater flow direction from north to south in the area. The direction of groundwater flow delineated from electrical images is consistent with the local hydrogeological setting.

5.2.6 Estimated Groundwater Storage

The total groundwater storage in the Atankwidi sub-basin has been computed from a known porosity which was determined from grain-size analysis using the Vukovic and Soro (1992) empirical formula, an average cross-sectional area of the study area using the Simpsons rule of determining areas of irregular surfaces and the longitudinal length across the study area as discussed below.

Estimated average cross-sectional area (A)

The cross-sectional area of sections 1 - 1 and 2 - 2 which are typical cross-sections of the study area from which areas were estimated using the Simpsons rule are shown in Figure 5.3. The other sections are shown Appendix 6.Table 5.4 shows the computed values of cross-sectional areas of the five cross-sections.

Table 5.4: Computed values of estimated cross-sectional areas

Cross-section	Section 1-1	Section 2-2	Section 3-3	Section 4-4	Section 5-5	Average area
Area, m^2	80,066.67	51,440.00	66,400.00	88,066.67	60,100.00	69,214.67

From the table, the average estimated cross-sectional area of the study area is **69,214.67 m^2.**

Estimated mean Porosity (n)

The result of estimated mean porosity in the study area is shown in Table 5.5.

Table 5.5: Estimated mean porosity of study area

No. of Aquifer (soil) samples	Mean, d_{10}	Mean, d_{60}	Mean, $U = d_{60} / d_{10}$	Mean, $n = 0.255(1+ 0.83^U)$
20	0.00388	0.07375	19.03226	0.262352

The estimated mean porosity of the study area from the Table above in percentage is **26.24 %** which is quite consistent with clayey soils.

Estimated total groundwater storage

With the estimated values of average cross-sectional area, mean porosity and the longitudinal length across the study area, the total groundwater storage was then computed with the values shown in Table 5.6

Table 5.6: Computational values of total groundwater storage

Mean cross-sectional area, m^2	Longitudinal length across study area, m	Mean porosity, %	Total groundwater storage, m^3
69,214.668	20,415	26.24	370,777,191.2

From the above table, the product of the mean cross-sectional area, the longitudinal length across study area and the mean porosity gives the total groundwater storage of the Atankwidi sub-basin as **370,777,191.2 m^3**. The White Volta Basin is reported to have groundwater storage of 3.9×10^{10} m^3 (Kortatsi, 1997) suggesting that, the groundwater storage of Atankwidi sub-basin (that falls within Ghana) represents about 0.95 % of that of the White Volta Basin as a whole.

5.3 Hydrochemical Analysis and Evaluation of Groundwater Quality

Water quality analysis is one of the most important issues in groundwater studies. It reveals the suitability of the water for domestic, agricultural and industrial purposes and also helps to understand the possible change in quality probably due to rock-water interaction or anthropogenic effects. In classifying and assessing groundwater quality, the importance and the role chemical parameters play cannot be over emphasised.

5.3.1 Physico-chemical Analysis of Water samples

The results of physico-chemical analysis of groundwater samples from the Atankwidi sub-basin are summarised in Table 5.7.

Table5.7: Summary of physico-chemical water quality parameters in the Atankwidi sub-basin

Parameter	Minimum	Maximum	Mean	Median	STD
1	2	3	4	5	6
Temp	26.40	34.00	29.94	29.90	1.92
pH	6.73	7.93	7.24	7.21	0.33
EC	100.00	484.00	236.25	217.5	99.88
TDS	55.00	266.20	129.94	119.63	54.93
TSS	1.00	294.00	55.19	31.50	69.79
Turb	1.75	316	69.23	36.25	81.53
Br_2	0.00	1.98	0.47	0.34	0.47
Ca	5.60	40.9	15.27	13.2	8.36
Cl	3.00	44.00	15.54	12.90	9.28
NO_2	0.001	0.12	0.02	0.02	0.03
NO_3	0.001	10.10	1.06	0.43	1.89
PO_4	0.01	14.30	3.52	2.95	2.42
SO_4	4.00	84.00	23.42	20.00	16.95
Na	7.80	70.90	24.79	20.15	16.16
K	1.4	25.30	9.76	10.65	5.12
K	1.4	25.30	9.76	10.65	5.12

1	2	3	4	5	6
K	1.4	25.30	9.76	10.65	5.12
F	0.03	0.65	0.33	0.35	0.18
HCO_3	12.20	258.64	117.97	117.12	62.98
CaH	14.00	102.00	37.56	33.10	20.51
MgH	3.9	77.8	26.99	25.85	14.65
Mg	0.90	18.90	6.57	6.25	3.36
Mn	0.005	0.65	0.12	0.04	0.18
Fe	0.02	13.1	2.25	0.99	3.00
Zn	0.005	0.06	0.02	0.01	0.01

All concentrations are measured in mg/l, pH in pH unit, Turbidity in NTU, electrical conductivity in μS/cm and temperature in °C.

Generally, the chemical constituents of the groundwater samples are low as shown in Figure 5.4, with HCO_3^- as the predominant anion which is known to be very consistent with the chemistry of most natural waters in granitic formations (Freeze and Cherry, 1979). NO_3^- and F^- occur in minor concentrations compared with the other anions. The decreasing order of cations in the groundwater samples is in order of $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > Fe^{2+}$ and that of anions is $HCO_3^- > SO_4^{2-} > Cl^- > PO_4^{2-} > NO_3^- > F^-$.

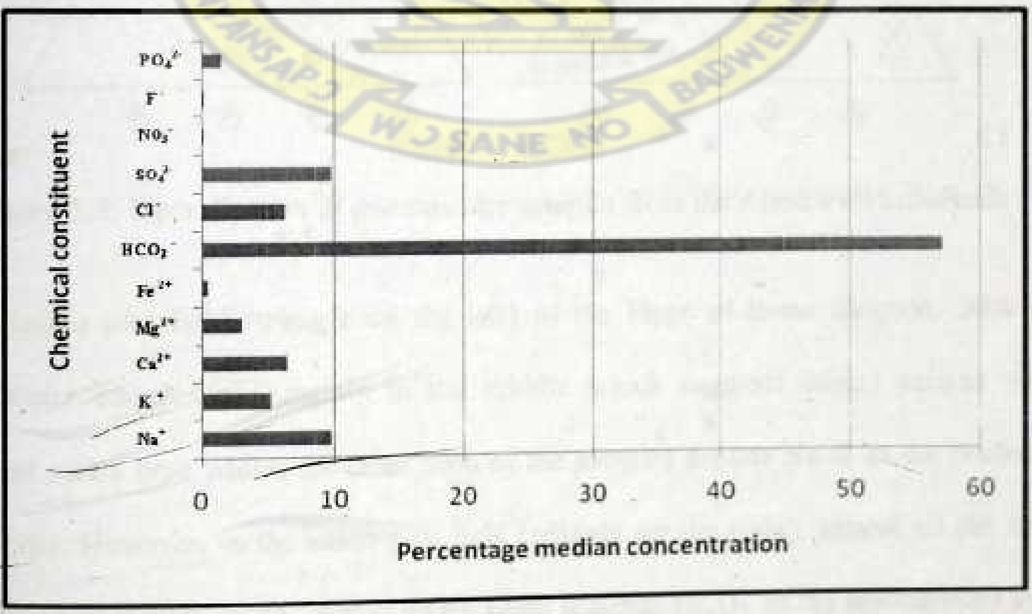


Figure 5.4: Median concentration of chemical constituents in the Atankwidi sub-basin

5.3.2 Hydrochemical facies of groundwater samples

Hydrochemical facies are distinct zones that possess cation and anion concentration categories (Sadashivaiah *et al.*, 2008). The chemical analysis results of the groundwater samples in the Atankwidi sub-basin has been presented by plotting them on a Piper tri-linear diagram (Piper 1944) in Figure 5.5 which reveals the analogies, dissimilarities and different types of waters in the sub-basin.

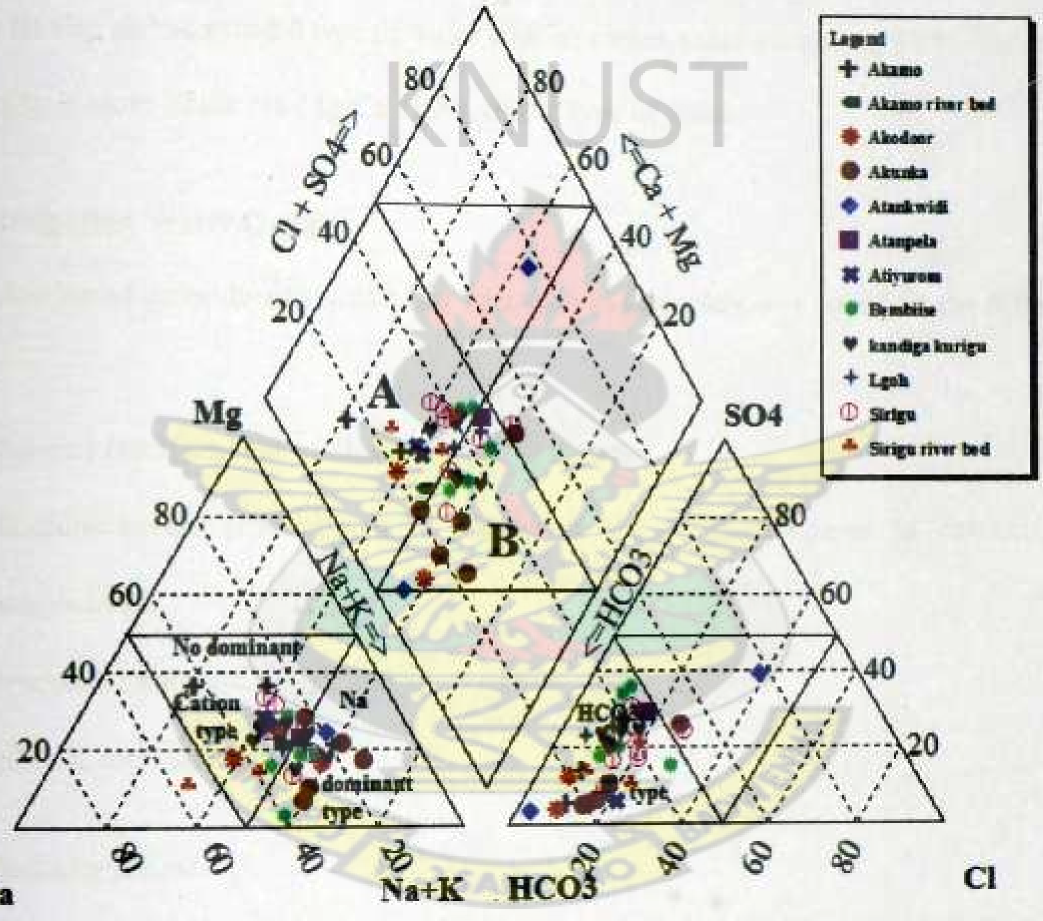


Figure 5.5: Piper diagram of groundwater samples from the Atankwidi Sub-Basin

In the cation plot field (triangle on the left) of the Piper tri-linear diagram, 50% of the groundwater samples plot mainly in the middle which suggests mixed cations with no dominant cation type whiles the other 50% of the samples depicts Na-K as the predominant cation type. However, in the anion plot field (triangle on the right), almost all the samples plotted are towards the HCO_3^- corner which again suggests HCO_3^- as the predominant anion.

The groundwater samples plotted in the $Ca\text{-}Mg\text{-}HCO_3$ dominant of the diamond field (section A) suggests active recharge, short residence time and temporary hardness (Kortatsi *et al.*, 2008). This type of waters usually has chemical properties which are dominated by alkaline earths and weak acids (Karanth, 1994), and apparently not associated with a particular geological formation (Kortatsi *et al.*, 2008) but may have emanated from either dolomite ($CaMg(CO_3)_2$) or calcite ($CaCO_3$) in rock matrix. Some (35 %) of the groundwater samples (section B) also showed mixed type of water with no cation-anion exceeding 50 %. This water specifically is more of the $Na\text{-}Mg\text{-}Ca\text{-}HCO_3$ mixed type of water.

5.4 Irrigation Water Quality

The evaluation of groundwater quality for irrigation in this study was based on the following factors:

- Salinity (total amount of dissolved salts in water),
- Sodium hazard (the amount of sodium in the water compared to calcium plus magnesium),
- Magnesium hazard (MH), and
- pH and total alkalinity.

5.4.1 Salinity Hazard

The most influential water quality guideline on crop productivity is the water salinity hazard as measured by electrical conductance (Bauder *et al.*, 2007). High concentration of salinity (electrical conductivity) in irrigation water affect crop yield through the inability of the plant to compete with ions in the soil solution for water (osmotic effect or physiological drought). The severity of the osmotic effect may vary with the plants growth stage and in some cases may go unnoticed because of a uniform yield decline over the whole crop (George, 1979). Table 5.8 shows the classification of groundwater samples for irrigation water use based upon electrical conductivity.

Table 5.8: Classification of groundwater samples in Atankwidi sub-basin for Irrigation water use based on electrical conductivity (Bauder *et al*, 2007)

Number of samples	Percentage	Electrical Conductivity (µS/cm)	Classes of Water
26	65	≤250	Class 1: Excellent
14	35	250 – 750	Class 2: Good
0	0	750 – 2000	Class 3: Permissible
0	0	2000 – 3000	Class 4: Doubtful
0	0	≥3000	Class 5: Unsuitable

5.4.2 Sodium Hazard

According to Karanth (1994), excessive Na^+ content of irrigation water renders it unsuitable for soils containing exchangeable Ca^{2+} and Mg^{2+} ions as the soil take up Na^+ in exchange for Ca^{2+} and Mg^{2+} causing deflocculation (dispersion) and impairment of the tilth and permeability of soils. The sodium hazard is typically expressed as the sodium adsorption ratio (SAR). The general classifications of groundwater samples in the study area for irrigation based on SAR values according to Bauder *et al*, (2007) generally showed low SAR.

5.4.3 Classification of Irrigation Water Quality

When the salinity and sodium absorption ratio (SAR) of water are known, the classification of irrigation waters can be determined by graphically plotting these values on the Wilcox diagram (Wilcox and Durum, 1967). The diagram expresses the relationship between sodium (SAR) and salinity (EC) hazards, in other words, it expresses the integrated effect of both sodium and salinity hazards of irrigation waters. That for the Atankwidi sub-basin was therefore plotted as shown in Figure 5.6.

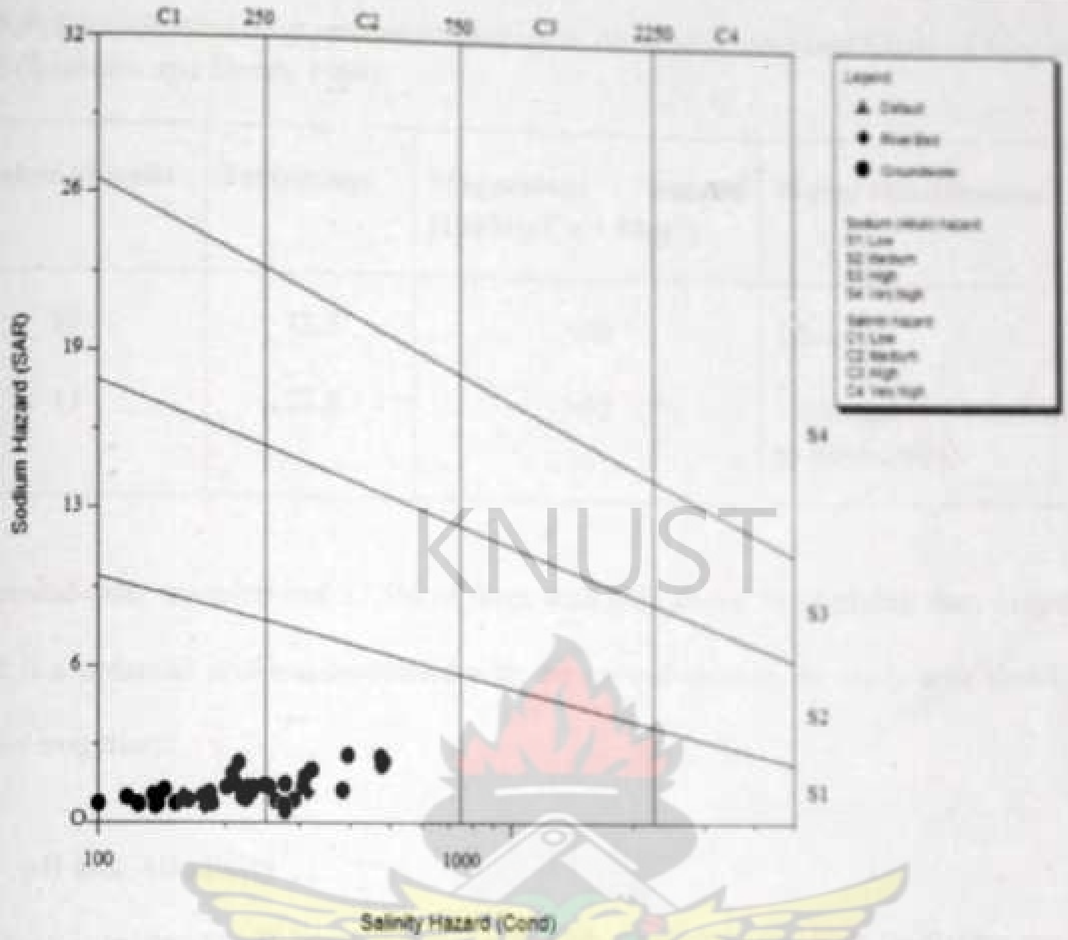


Figure 5.6: Classification of irrigation waters in the Atankwidi sub-basin (Wilcox and Durum, 1967)

The Wilcox diagram above for the Atankwidi sub-basin again confirms generally low sodium (SAR) hazard and low to medium salinity hazard associated with groundwater samples. This makes groundwater samples in the sub-basin generally good for irrigation as far as sodium and salinity hazards are concern.

5.4.4 Magnesium Hazard

Magnesium is believed to be injurious to plants, but the harmful effect is greatly reduced by the presence of calcium. The magnesium hazard (MH) is defined as $100Mg\ (Ca + Mg)^{-1}$ with the chemical constituents expressed as meq/l. The classification of groundwater samples according to Szabolcs and Darab (1964) based on magnesium hazard is shown in Table 5.9

Table5.9: Classification of groundwater samples in Atankwidi sub-basin based on Magnesium hazard (Szabolcs and Darab, 1964).

Number of wells	Percentage	Magnesium hazard [$100Mg(Ca + Mg)^{-1}$]	Water classification
29	72.5	<50	Desirable
11	27.5	>50	Undesirable (deleterious to most crops)

The groundwater sampled had 27.5% of them with MH above 50 implying that, magnesium hazard is a potential problem associated with the groundwater in the study area should it be used for irrigation.

5.4.5 pH and Alkalinity

Alkalinity is related to pH, because water with high alkalinity has a high "buffering capacity" or capacity for neutralising added acids. The major chemicals responsible for alkalinity in water are the dissolved carbonates and bicarbonates from the geologic materials of the aquifer from which the water is drawn. The dissolved carbonates and bicarbonates increase the media pH over time by neutralising H^+ ions in the media solution. Although there are no established optimum or toxic levels for alkalinity, typical recommendations range from 37.5 – 130 mg/l $CaCO_3$ (Will and Faust, 1999). The concentration of alkalinity varied from 10 – 216 mg/l with the mean, median and standard deviation of 96.7, 96 and 51.62 mg/l respectively. 22.5% of the total groundwater samples had their concentrations above this desirable range probably due to the relatively high concentrations of bicarbonate (HCO_3^-) in the samples. Nonetheless, 5 % of the groundwater samples had low alkalinity concentrations. Low alkalinity of irrigation water provides no buffering capacity against pH changes which leads to the decline of media solution pH when acid-residue fertilisers are used (Will and Faust, 1999).

5.4.6 Assessment of Irrigation water quality based on all criteria used

The irrigation water quality was assessed based on all the criteria used (SAR, salinity hazard, magnesium hazard and alkalinity) to know the percentage of groundwater samples that fell within the recommended ranges.

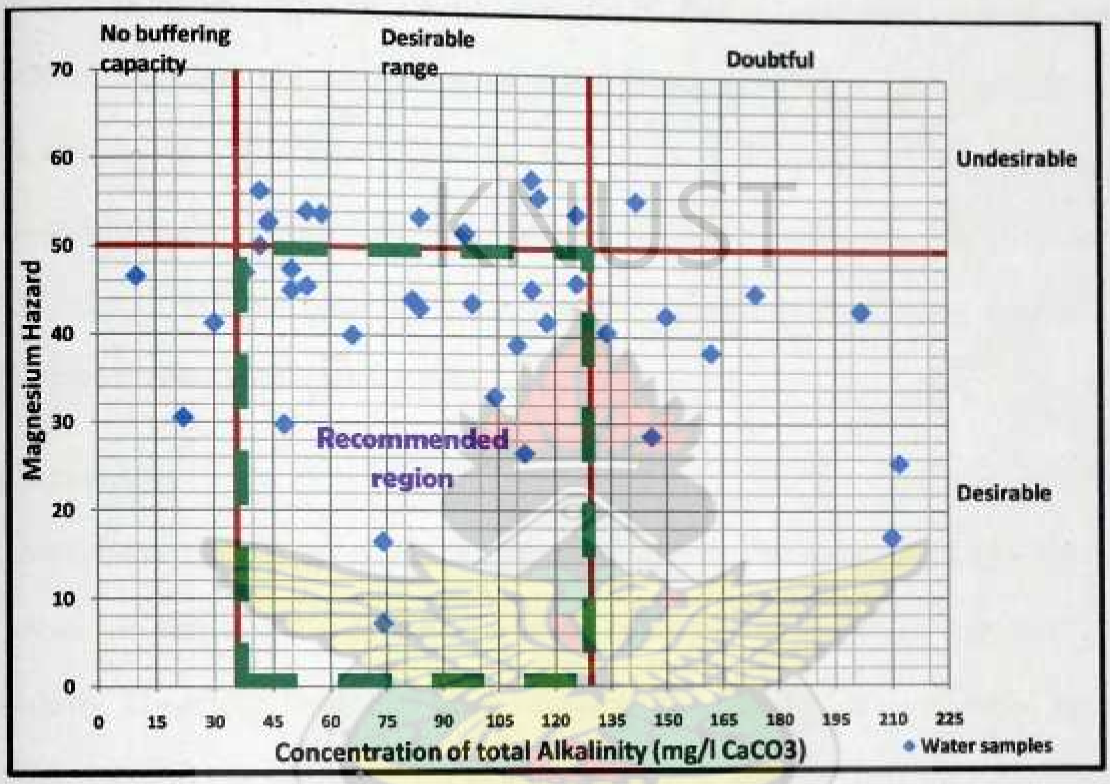


Figure 5.7: Assessment of irrigation water quality based on MH and alkalinity

Figure 5.7 shows the assessment of groundwater samples based on both magnesium hazard and total alkalinity. Since all the groundwater samples fell within the recommended ranges of both sodium (SAR) and salinity hazards at the same time, the only limitations will be from magnesium hazard and alkalinity. Therefore the percentages of samples that fall within the desirable ranges of both magnesium hazard and alkalinity at the same time are considered to be the percentage of samples with absolutely no limitation. With this assumption, the percentage of samples that fall within the recommended region of the Figure above is 52.5 % with 25 % and 22.5 % of the samples with magnesium hazard and alkalinity problems respectively.

5.5 Domestic Water Quality

The assessment of groundwater samples in the Atankwidi sub-basin for domestic use in this study was based on the criteria that, water is said to have good chemical quality if it is soft, low in total dissolved solids (TDS) and also free from poisonous and harmful chemical constituents (Karanth, 1994). The physico-chemical parameters considered in the assessment included temperature, pH, total dissolved solids (TDS), turbidity, total suspended solids (TSS), electrical conductance, total hardness, total alkalinity, nitrate (NO_3^-), fluoride (F^-), iron (Fe^{2+}), sulphate (SO_4^{2+}), chlorine (Cl^-), magnesium (Mg^{2+}), manganese (Mn^{2+}), calcium (Ca^{2+}), sodium (Na^+) and potassium (K^+). The WHO guidelines for drinking water quality (2004) were adopted for analysis in this study.

5.5.1 Turbidity

The groundwater samples in the area had high turbidity values ranging from 1.75 - 316 NTU. The mean, median and the standard deviation values are 69.23, 36.25 and 81.53 NTU respectively. These high levels may be as a result of high dissolved and suspended solids in the water samples. The maximum values were recorded in samples taken from river beds in the area which is quite usual with surface waters. Only 12.5 % of the total samples fell within the WHO (2004) recommended limit for drinking water of 5 NTU, which suggests that groundwater in the study area is aesthetically unpleasant for drinking with regards to turbidity. The variations in turbidity with respect to locations are shown in the Figure 5.8.

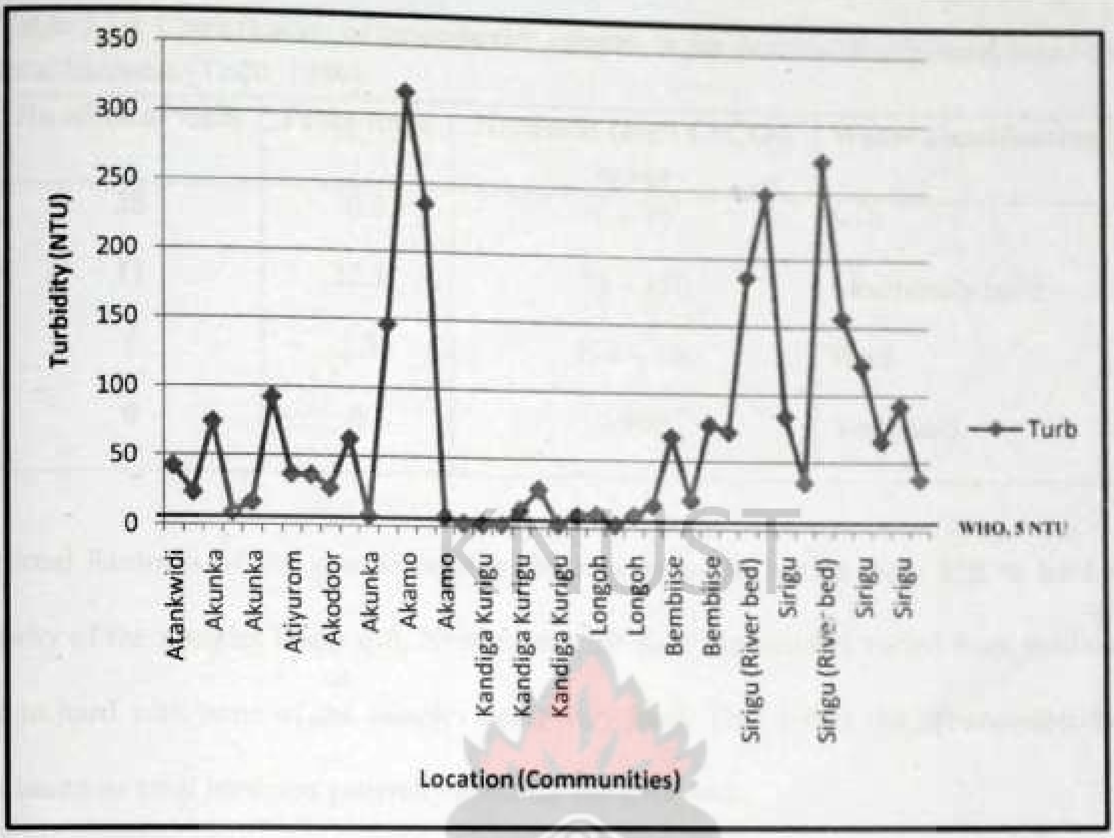


Figure 5.8: Variations in Turbidity with respective locations in the Atankwidi sub-basin

5.5.2 Total Dissolved Solids (TDS)

TDS of groundwater samples in the study area varied from 55 - 266.2 mg/l with mean, median and standard deviation values of 129.94, 119.63 and 54.93 mg/l respectively. These concentrations are significantly lower than the WHO (2004) recommended limit for drinking water quality of 1000 mg/l. With respect to TDS, the groundwater quality in the area can therefore be considered to be of good quality for drinking.

5.5.3 Total hardness

The classification of groundwater samples in the sub-basin based on total hardness was done according to Todd (1980) as shown in Table 5.10.

Table 5.10: Classification of groundwater samples in the Atankwidi sub-basin based on total hardness (Todd, 1980).

Number of wells	Percentage	Hardness (mg/l $CaCO_3$) range	Water classification
28	70.0	0 – 75	Soft
11	27.5	75 – 150	Moderately hard
1	2.5	150 – 300	Hard
0	0	>300	Very hard

The total hardness of the groundwater in the area generally varied from soft to hard with majority of the samples being soft. Nonetheless, 30 % of the samples varied from moderately hard to hard with none of the samples being very hard. This makes the groundwater in the area based on total hardness generally good for domestic use.

5.5.4 Iron and Manganese

Iron (Fe) and manganese (Mn) are naturally present throughout the environment and are generally perceived as safe, as often as taste will deter users from drinking water rich in these elements (Schaefer *et. al.*, 2009). Although no health-based guideline value has been established for Fe, the WHO (2004) drinking water quality guidelines recommend a concentration of 0.3 mg/l below which taste will often be affected. The concentration in the area varied from 0.02 – 13.1 mg/l with mean, median and standard deviation of 2.25, 0.99 and 3.00 mg/l respectively. 75 % of the total samples were above the recommended limit with Sirigu having the maximum concentration. Iron levels in the groundwater of the Atankwidi sub-basin are therefore relatively high probably due to natural sources in the earth crust such as geochemical processes within the aquifers. Figure 5.9 shows the variations in iron concentration in groundwater at different locations.

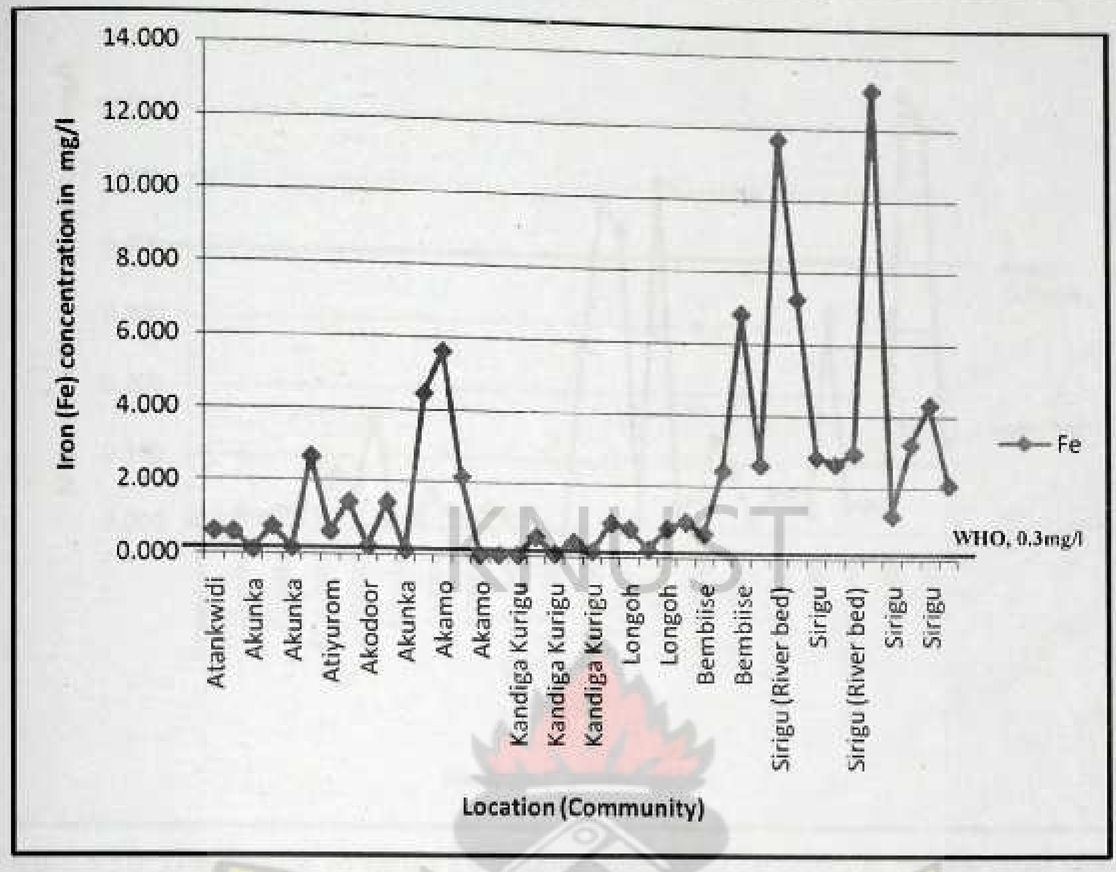


Figure 5.9: Distribution of varied Iron concentration in groundwater samples in the area

Manganese concentrations ranged from 0.005 – 0.65 mg/l with mean, median and standard deviation of 0.12, 0.04 and 0.18 mg/l respectively. Out of the total samples, 12.5 % were above the WHO guideline value for drinking water quality of 0.4 mg/l. Although manganese is an essential element for humans, high concentrations may have adverse neurological effects (Santos-Burgoa *et al*, 2001). Distribution of varied manganese concentration levels in groundwater samples of the Atankwidi sub-basin is shown in Figure 5.10.

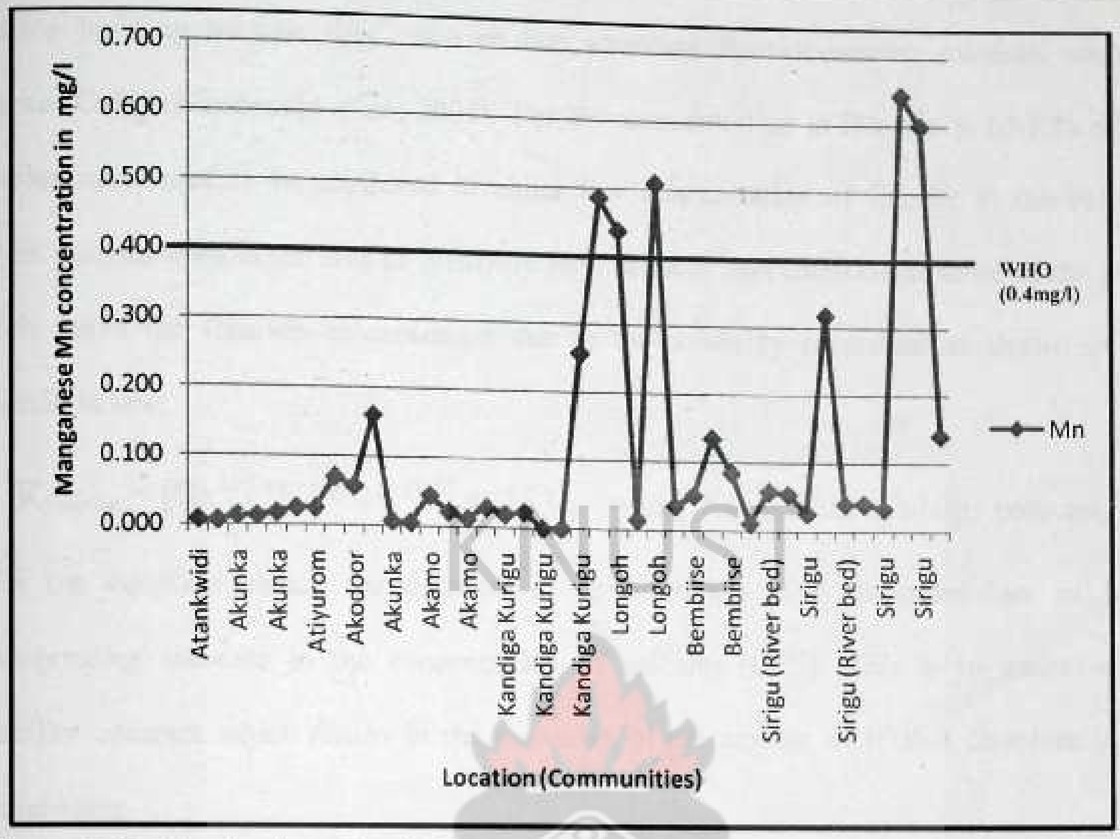


Figure 5.10: Distribution of varied Manganese concentration levels in groundwater samples

5.5.5 Fluoride

Fluoride (F^-) concentration in the range of 0.5 – 1.5 mg/l is physiologically beneficial since it promotes dental health and prevents dental caries (WHO, 2004). Below the specified range, dental decay occurs whilst above the beneficial range and depending on the actual concentration, dental fluorosis may occur (Dissanayake, 1991). Fluoride concentration of groundwater samples in the area varied from 0.03 – 0.65 mg/l with mean, median and standard deviation of 0.33, 0.35 and 0.18 mg/l respectively. None of the groundwater samples fell above the WHO guideline value of 1.5 mg/l with 32.5 % of the total samples falling within the beneficial range. 67.5 % of the samples fell below the beneficial range which suggests dental decay as the main potential physiological problem associated with groundwater in the area. Groundwaters from crystalline rocks, especially granites which happen to be one of the main underlying rocks in the study area are particularly susceptible to fluoride build-up because they often contain abundant fluoride-bearing minerals such as fluorite (CaF_2) (Macdonald *et al.*, 2005). The low concentration in fluoride in 67.5 % of the samples can therefore be attributed to either low concentration of fluorite in the rock of certain communities in the area or relatively high calcium concentration in some of the wells which limits the fluoride concentration due to the solubility constraint as shown in the equation below;

$K_{fluorite} = [Ca^{2+}] [F^-] = 10^{-10.57}$ at 25°C, where $K_{fluorite}$ is the solubility constant.

From the equation above, the decrease in concentration of F^- is taken care of by a corresponding increase in the concentration of calcium (Ca^{2+}). This is to maintain the solubility constant which results in the limitation of the amount of F^- that dissolves in the groundwater.

5.5.6 Other Trace elements

Other trace elements such as Copper (Cu), Lead (Pb), Nickel (Ni), Cadmium (Cd) and Zinc (Zn) in the groundwater samples were also analysed and the concentrations in all the samples were far below the WHO (2004) guideline values for drinking water quality for the respective elements.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This research recognises the need for the availability of hydrogeological and hydrochemical data for the estimation of groundwater potential for a specific use and its sustainable management. Specifically, this research focused on the investigation of groundwater availability and quality for irrigation in the Atankwidi sub-basin which has established a database to facilitate its management. It is anticipated that the findings of this research will help decision-makers prioritise their investments in relation to irrigation development to ensure food security in Ghana. The following key conclusions have been drawn from the results of the study:

- Hydraulic conductivity values of the aquifer in the study area did not show a wide range which confirms the homogeneity of the geological formations.
- The mean transmissivity value was found to be 9.86×10^{-2} m^2/d and hence defined the unconfined nature of the aquifer.
- The aquifer geometry in the Atankwidi sub-basin as delineated using geophysical (electromagnetic and vertical electrical depth sounding, VES) exploration techniques is shallow and lies above the first impervious layer or stratum and hence susceptible to pollution.
- Two main water types (Ca-Mg-HCO_3 and Na-Mg-Ca-HCO_3) have been delineated using the Piper diagram. Further more, the relative abundance of cations in the groundwater is in the order of $Na^+ > Ca^{2+} > K^+ > Mg^{2+} > Fe^{2+}$. HCO_3^- was however the predominant anion which also had a decreasing order of $HCO_3^- > SO_4^{2-} > Cl^- > PO_4^{2-} > NO_3^- > F^-$.
- The suitability of groundwater for irrigation evaluated based on sodium (SAR), salinity and magnesium hazards, pH and alkalinity showed low SAR and low to

medium salinity hazard and is therefore good for irrigation but with some potential magnesium hazard and alkalinity problems which partially limits its use for irrigation by developing sodic soil conditions with continuous use.

- Groundwater in the sub-basin had high turbidity with 87.5 % of samples above the recommended limit, making it aesthetically unpleasant for domestic use whiles 75 % of samples had Fe concentrations above the recommended limit also questioning the taste for domestic use. The F^- concentration of 67.5 % of the groundwater samples fell below the beneficial range which suggests dental decay as the main potential physiological problem associated with groundwater in the area for drinking purpose.

6.2 Recommendations

Based on the results and conclusions of the study, the following recommendations have been made:

- In order to ensure sustainability, there should be a long-term monitoring plan of groundwater levels to determine if the levels show a particular trend over a period of time.
- Groundwater quality in the sub-basin should be monitored regularly to ensure early detection and intervention of any pollution or contamination that may occur due to the susceptibility of the regional aquifer system to pollution (weedicides, pesticides etc.).
- Due to the magnesium hazard problems that were recorded in some of the areas, soil conditions should also be monitored with time to ascertain any problem of sodicity and if necessary leach the soil.
- Further research should be conducted to estimate the safe yield in order to know the volume of water that can be abstracted and readily available for irrigation and its sustainability.

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APPENDICES

Appendix 1: Geophysical (VES) exploration data

LOCATION	LAT. (N)	LONG. (W)	DEPTH TO BEDROCK	WATER TABLE	THICKNESS
1	2	3	4	5	6
Anateen	10.8382	0.97826	3.1	2.1	1
Anateen	10.83944	0.97774	10.3	0.5	9.8
Anateen	10.83957	0.97945	6.5	1.4	5.1
Anateen	10.84124	0.97916	6.6	5.2	1.4
Kandiga	10.83981	0.98137	5.2	1	4.2
Anateen	10.83802	0.98049	8.8	5.3	3.5
Anateen	10.8417	0.97607	25.9	2.1	14.5
Anateen	10.84061	0.97734	14.8	1.9	10.8
Akoka	10.841127	0.97872	5.7	0.8	4.9
Akoka	10.84227	0.97922	4.2	1.4	2.8
Akoka	10.84164	0.97514	14.8	0.7	14.1
Akoka	10.8423	0.97434	6.4	0.9	5.5
Akoka	10.84241	0.97244	3.7	2.5	1.3
Akoka	10.84353	0.97314	6.1	0.6	5.5
Kandiga	10.84521	0.96963	24.5	1.4	23.1
Kandiga	10.84518	0.96835	5.8	2	3.8
Kandiga	10.84599	0.96779	5	0.6	4.4
Kandiga	10.84746	0.96801	32.1	0.6	30.2
Kandiga	10.848442	0.9886	6.2	1.6	3.6
Kandiga	10.84758	0.96931	7.2	0.5	6.7
Kandiga	10.8492	0.96785	11	2	9.1
Atiyoori	10.85048	0.96478	8.6	1.6	7.3
Atiyoori	10.85093	0.96588	23.9	3.4	17
Atiyoori	10.85083	0.96711	5.8	0.8	5
Atiyoori	10.84994	0.96854	3.5	1.1	2.4
Kaase/Dazong	10.85022	0.96341	26.2	1.6	21.8
Kaase/Dazong	10.85127	0.95867	3.5	2.4	1.1
Kaase/Dazong	10.85019	0.95851	19.4	1.1	15.9
Kaase/Dazong	10.85019	0.9572	5.1	0.7	4.4
Kaase/Dazong	10.84946	0.95696	11.1	1	10.1
Kaase	10.85306	0.95446	19	3.8	15.2
Kaase	10.85194	0.95396	32.4	1	18.2
Kaase	10.85088	0.95304	10.4	1.9	8.5
Kaase	10.84992	0.95248	11.4	3.1	8.3
Kaase	10.85053	0.9515	15.4	4.3	11.1
Kaase	10.85141	0.9522	7.8	6.3	1.5
Akamo/Dazong	10.85313	0.94836	6.4	2.1	4.3

1	2	3	4	5	6
Akamo/Dazong	10.85162	0.94795	6.1	0.6	5
Akamo/Dazong	10.85225	0.94606	9	3	6
Akamo/Dazong	10.85141	0.94552	6.5	1.9	4.6
Akamo/Dazong	10.85251	0.9447	9.2	1.7	7.5
Akamo/Dazong	10.85314	0.94554	21.4	1.1	16.6
Akamo/Dazong	10.85267	0.94653		1.7	
Akamo/Dazong	10.85231	0.95193	3.2	1.1	2.1
Akamo	10.8569	0.94325	4.7	3.4	1.3
Akamo	10.85634	0.94131	7.5	3.9	3.6
Akamo	10.85532	0.94311	12	1	9.5
Akamo	10.85546	0.94444	9	1.8	7.2
Akamo	10.855757	0.94234	4.4	2.1	2.3
Akamo	10.85835	0.94068	12.6	1.3	11.2
Akamo/Kologo	10.86077	0.94124	7.8	0.7	7.1
Akamo/Kologo	10.8594	0.94065	3	1.3	1.8
Akamo/Kologo	10.86003	0.93909	7.2	1.2	6.1
Akamo/Kologo	10.86154	0.93845	4.5	2.2	2.3
Akamo/Kologo	10.86235	0.93989	19.6	0.6	17.3
Kandiga/Kologo	10.865114	0.93908	6.9	1.2	5.7
Kandiga/Kologo	10.86298	0.93807	3.2	1.8	1.4
Kandiga/Kologo	10.86427	0.93742	12.2	7.7	4.5
Kandiga/Kologo	10.86601	0.93595	11.4	7.3	4.1
Akamo/Kologo	10.86688	0.93708	11.4	2.1	9.3
Akamo/Kologo	10.86609	0.93456	6.9	5.6	1.3
Akamo/Kologo	10.86552	0.93288	13	0.9	12.1
Akamo/Kologo	10.86711	0.93728	7.4	3.5	3.9
Akamo/Kologo	10.86793	0.93519	11	0.6	10.4
Akamo/Kologo	10.86951	0.93076	11	0.6	10.4
Akamo/Kologo	10.8689	0.93612	23.1	2	21.1
Akamo/Kologo	10.8715	0.93309	8.8	3.2	5.7
Akamo/Kologo	10.87257	0.93124	13.8	0.7	13.1
Zorkko/Gamborigo	10.87304	0.93237	6.2	2.6	3.6
Zorkko/Gamborigo	10.87491	0.93217	2.6	1.7	0.9
Zorkko/Gamborigo	10.87699	0.93425	8	2.3	5.8
Zorkko/Gamborigo	10.87669	0.93257	7.1	3.8	3.3
Zorkko/Gamborigo	10.87654	0.93072	6.7	2.5	4.2
Zorkko/Gamborigo	10.87873	0.92971	10.2	0.7	7.9
Zorkko/Gamborigo	10.87997	0.92981	12.5	0.8	7.7
Zorkko/Gamborigo	10.88099	0.93078	7.9	3.1	4.8
Zorkko/Gamborigo	10.87953	0.93126	8.4	1.4	7.1
Zorkko/Gamborigo	10.87889	0.93225	8	6	6

1	2	3	4	5	6
Zorkko/Gamborigo	10.87786	0.93202	8.6	0.8	5.4
Zorkko/Gamborigo	10.87763	0.93396	8.9	0.9	5.7
Zorkko/Gamborigo	10.88193	0.93161	17.5	2.1	14.2
Zorkko/Gamborigo	10.88161	0.92818	7.1	2.1	5
Zorkko/Gamborigo	10.88313	0.92825	5.6	4.1	1.5
Zorkko/Gamborigo	10.8834	0.93034	6.8	5.4	1.4
Zorkko/Gamborigo	10.8849	0.93072	6.4	0.8	5.6
Zorkko/Gamborigo	10.88493	0.93171	2.3	1.4	0.8
Zorkko/Gamborigo	10.88335	0.93137	5.3	1.5	0.8
Zorkko/Gamborigo	10.88168	0.933	4.2	5	0.3
Zorkko/Gamborigo	10.88868	0.93296	5.2	0.9	3.3
Zorkko/Gamborigo	10.89011	0.9321	10.7	1	4.2
Zorkko/Gamborigo	10.88862	0.93149	11.4	4	6.7
Zorkko/Gamborigo	10.88712	0.93207	3.7	5	6.4
Zorkko/Gamborigo	10.88566	0.93195	4.4	1.3	2.3
Zorkko/Gamborigo	10.88641	0.93315	4.1	1.1	3.3
Zorkko/Gamborigo	10.892	0.93515	18.1	1.9	2.2
Kurigi/Gaborigo	10.8919	0.93376	6.3	1	13.3
Kurigi/Gaborigo	10.89173	0.93299	6.3	3.3	3
Kurigi/Gaborigo	10.89141	0.93208	5.2	1.3	5
Kurigi/Gaborigo	10.89223	0.93251	6.6	1.5	3.7
Kurigi/Gaborigo	10.89402	0.9324	4.8	2	4.6
Kurigi/Gaborigo	10.89586	0.93346	3.1	0.6	4.2
Kurigi/Gaborigo	10.894	0.93399	6	0.7	2.4
Kurigi/Gaborigo	10.89081	0.93365	8.1	1.9	4.1
Kurigi/Gaborigo	10.89146	0.93474	38.3	1.4	6.7
Kurigi/Gaborigo	10.89697	0.93347	7.1	1	35
Kurigi/Gaborigo	10.89807	0.93262	8.2	2.2	4.9
Kurigi/Gaborigo	10.89826	0.93179	4.6	0.8	7.4
Kurigi/Gaborigo	10.89992	0.9322	11.9	1.7	2.9
Kurigi/Gaborigo	10.89959	0.93324	3.1	1.4	10.5
Kurigi/Gaborigo	10.899991	0.93427	8.4	0.9	2.2
Kurigi/Gaborigo	10.89878	0.934	5.9	1	7.4
Kurigi/Gaborigo	10.89849	0.9333	9.2	1.7	4.2
Kurigi/Gaborigo	10.89563	0.93456	3.1	2.3	8.9
Kurig/Gamborigo	10.89699	0.93449	4.2	2	1
Kandiga Longo	10.90222	0.93465	5.6	1.3	2.9
Kandiga Longo	10.90112	0.93316	27.5	1	4.6
Kandiga Longo	10.90222	0.93274	9.2	1.9	22.6
Lonhogo/Gamborigo	10.90176	0.93215	9.6	1.3	7.9
Lonhogo/Gamborigo	10.90408	0.90141	4.6	1.5	8.1

1	2	3	4	5	6
Lonhogo/Gamborigo	10.90428	0.93276	2.9	1.5	3.1
Lonhogo/Gamborigo	10.90289	0.93308	12.6	0.8	2.1
Lonhogo/Gamborigo	10.90413	0.93463	10.3	3.4	9.2
Lonhogo/Gamborigo	10.90325	0.93509	4.8	1.3	9
Bembisi/Kanga	10.905235	0.93332	17	1	3.9
Bembisi/Kanga	10.90553	0.9321	5.5	1.4	11.9
Bembisi/Kanga	10.90502	0.92993	6.7	1	4.4
Bembisi/Kanga	10.90613	0.93034	30.2	1.9	4.7
Bembisi/Kanga	10.90734	0.93100	6.4	1.3	26
Bembisi/Kanga	10.90647	0.931	13.3	1.4	5
Bembisi/Kanga	10.90524	0.93402	4.2	1.9	11.4
Bembisi/Kanga	10.90628	0.93391	8.5	3	1.1
Bembisi/Kanga	10.90901	0.93165	16.7	2.2	6.3
Bembisi/Kanga	10.90908	0.93058	23	0.9	5.6
Bembisi/Kanga	10.90892	0.92961	8	2.1	12.9
Bembisi/Kanga	10.90979	0.93016	14.7	2.2	5.8
Bembisi/Kanga	10.90994	0.93098	7	0.6	14
Bembisi/Kanga	10.90972	0.93191	6.9	2	5
Bembisi/Kanga	10.90892	0.93245	2.1	0.7	6.2
Bembisi/Kanga	10.90845	0.93202	4.1	1.2	1
Bembisi/Kanga	10.90756	0.93336	6.3	1.4	27
Bembisi/Kanga	10.90988	0.93326	7.4	1.3	5
Bembisi/Kanga	10.91273	0.93247	14.3	5.3	2.1
Bembisi/Kanga	10.91288	0.93158	10.4	2.9	11.4
Bembisi/Kanga	10.91531	0.93064	7.6	1.5	7.8
Bembisi/Kanga	10.9144	0.9322	6.7	1.6	6
Bembisi/Kanga	10.91416	0.93347	14.1	1.7	5
Bembisi/Kanga	10.91365	0.93273	12.3	1.5	9.5
Bambisi/Kanga	10.91474	0.93417	5.2	1.4	11
Bambisi/Kanga	10.91463	0.93357	5.8	1.1	4.2
Bambisi/Kanga	10.91591	0.93312	2.6	1.5	4.3
Bambisi/Kanga	10.91624	0.93214	4.1	0.6	2
Bambisi/Kanga	10.91721	0.93200	4.8	1.6	2.5
Bambisi/Kanga	10.91857	0.93311	6.2	1.7	3.1
Bambisi/Kanga	10.91760	0.93345	5.1	0.9	5.3
Bambisi/Kanga	10.91660	0.93299	7.5	0.8	4.3
Bambisi/Kanga	10.91647	0.39400	5.3	0.7	4.4
Bambisi/Kanga	10.91490	0.93458	5.2	1	4.3
Bambisi/Kanga	10.91392	0.93409	6.3	1.1	4.1
Bambisi/Kanga	10.91923	0.93281	6.0	1.0	5.3
Bambisi/Kanga	10.91912	0.93172	9.9	0.6	5.4

1	2	3	4	5	6
Bambisi/Kanga	10.92016	0.93155	12.6	1.1	8.8
Bambisi/Kanga	10.92128	0.93171	14.8	7.8	4.8
Bambisi/Kanga	10.92226	0.93187	14.6	0.8	14
Bambisi/Kanga	10.92045	0.93224	16.3	1.7	12.9
Bambisi/Kanga	10.91993	0.93302	6.3	1.6	13.6
Bambisi/Kanga	10.91924	0.93402	5.5	1.5	4.8
Bambisi/Kanga	10.92157	0.93304	2.2	1.0	4.5
Bambisi/Kanga	10.92041	0.93366	7.8	0.6	1.5
Bambisi/Kanga	10.92395	0.93199	11.9	1.2	6.6
Bambisi/Kanga	10.92349	0.93162	5.0	1.9	10
Bambisi/Kanga	10.92290	0.93091	7.9	1.3	3.7
Bambisi/Kanga	10.92240	0.93024	20.8	0.9	7
Bambisi/Kanga	10.92203	0.92951	7.3	0.7	16.8
Bambisi/Kanga	10.92159	0.93008	4.4	0.8	6.5
Bambisi/Kanga	10.92271	0.92929	6.8	0.9	7.2
Bambisi/Kanga	10.92353	0.92964	13.9	2.2	4.1
Bambisi/Kanga	10.92339	0.93064	8.3	1.8	3.6
Sirigu/Bikundooni	10.92495	0.93027	5.1	1.1	7.2
Sirigu/Bikundooni	10.92512	0.92950	5.1	1.0	4.1
Sirigu/Bikundooni	10.92482	0.92938	4.4	1.5	3.6
Sirigu/Bikundooni	10.92427	0.92915	13.3	0.8	3.6
Sirigu/Bikundooni	10.92356	0.92953	6.3	1.3	11.9
Sirigu/Bikundooni	10.92578	0.92963	9.4	1.3	5
Sirigu/Bikundooni	10.92630	0.92908	8.3	1.0	8.4
Sirigu/Bikundooni	10.92712	0.92992	8.3	1.7	6.6
Sirigu/Bikundooni	10.92622	0.63038	3.8	1.5	6.8
Sirigu/Bikundooni	10.92434	0.93056	6.1	0.5	3.3
Sirigu/Bikundooni	10.25250	0.93060	6.0	0.7	5.4
Sirigu/Gunwokgor	10.92994	0.92990	4.2	1.1	4.9
Sirigu/Gunwokgor	10.93002	0.92870	2.1	3.1	1.1
Sirigu/Gunwokgor	10.92725	0.92976	4.6	0.5	1.6
Sirigu/Gunwokgor	10.92812	0.9279	2.7	1.1	3.5
Sirigu/Gunwokgor	10.92946	0.92815	9.3	0.6	2.1
Sirigu/Gunwokgor	10.93140	0.92833	9.4	1.1	8.2
Sirigu/Gunwokgor	10.93097	0.92955	4.0	1.3	8.1
Sirigu/Gunwokgor	10.92822	0.92995	5.7	1.2	2.8
Sirigu/Gunwokgor	10.92812	0.93064	2.3	0.9	4.8
Sirigu/Gunwokgor	10.92897	0.93034	8.1	2.3	5.8
Sirigu/Gunwokgor	10.93313	0.92687	8.1	1.9	6.2
Sirigu/Gunwokgor	10.93199	0.92597	10.3	1.9	8.4
Sirigu/Gunwokgor	10.93078	0.92578	2.7	0.7	2

1	2	3	4	5	6
Sirigu/Gunwokgor	10.93139	0.92672	4.4	1.0	3.4
Sirigu/Gunwokgor	10.93261	0.92504	7.6	1.4	6.2
Sirigu/Gunwokgor	10.93301	0.92408	9.7	2.2	7.5
Sirigu/Gunwokgor	10.93383	0.92567	6.8	1.3	5.5
Sirigu/Gunwokgor	10.93292	0.92600	4.1	1.1	3
Sirigu/Gunwokgor	10.93214	0.92749	4.3	1.2	3.1
Sirigu/Gunwokgor	10.93273	0.92739	8.4	0.5	7.9
Sirigu/Gunwokgor	10.93227	0.92802	8.8	2	6.8
Sirigu/Gunwokgor	10.93539	0.92493	9.8	1.7	8.1
Sirigu/Gunwokgor	10.93499	0.92402	11.6	1.5	9.3
Sirigu/Gunwokgor	10.93433	0.92361	7.0	1.0	6
Sirigu/Gunwokgor	10.93404	0.92441	9.6	2.3	7.3
Sirigu/Gunwokgor	10.93501	0.92199	16.7	1.2	15.5
Sirigu/Gunwokgor	10.9605	0.92285	10.0	2.0	8
Pokmulingo Sirigo/Zokor	10.93742	0.92281	14.2	1.0	13.2
Pokmulingo Sirigo/Zokor	10.93714	0.92131	7.0	1.3	5.7
Pokmulingo Sirigo/Zokor	10.93647	0.92045	6.8	1.8	5
Pokmulingo Sirigo/Zokor	10.93759	0.9199	8.6	1.5	7.1
Pokmulingo Sirigo/Zokor	10.93826	0.92049	7.9	0.7	7.2
Pokmulingo Sirigo/Zokor	10.93912	0.920551	9.2	0.7	6
Pokmulingo Sirigo/Zokor	10.93994	0.92146	6.2	1.4	4.8
Pokmulingo Sirigo/Zokor	10.93917	0.92190		1.7	
Pokmulingo Sirigo/Zokor	10.93797	0.92242	11.6	0.9	10.7
Pokmulingo Sirigo/Zokor	10.93832	0.92127	7.5	0.7	6.8
Pokmulingo Sirigo/Zokor	10.93704	0.92196	8.4	3.0	5.4
Pokmulingo Sirigo/Zokor	10.94128	0.92055	7.6	0.7	6.9
Pokmulingo Sirigo/Zokor	10.94053	0.92083	13.0	2.8	10.2
Pokmulingo Sirigo/Zokor	10.94238	0.92024	6.8	1.2	5.6
Pokmulingo Sirigo/Zokor	10.94329	0.91986	9.2	0.9	8.4
Pokmulingo Sirigo/Zokor	10.94392	0.91941	7.4	0.6	6.5
Pokmulingo Sirigo/Zokor	10.94304	0.91894	5.6	1.0	4.6
Pokmulingo Sirigo/Zokor	10.94391	0.91784	2.1	1.2	0.9
Pokmulingo Sirigo/Zokor	10.94326	0.91717	6.6	0.9	5.7
Pokmulingo Sirigo/Zokor	10.94208	0.91858	7.7	1.8	5.9
Pokmulingo Sirigo/Zokor	10.94145	0.91914	8.3	0.8	7.5
Pokmulingo Sirigo/Zokor	10.94059	0.91997	5.5	1.4	4.1
Pokmulingo Sirigo/Kadare	10.94659	0.91714	7.2	0.6	5.6
Pokmulingo Sirigo/Kadare	10.94579	0.91689	4.0	1.7	2.3
Pokmulingo Sirigo/Kadare	10.94472	0.91642	3.4	2.4	1

1	2	3	4	5	6
Pokmulingo Sirigo/Kadare	10.94464	0.91529	3.1	2.1	1
Pokmulingo Sirigo/Kadare	10.94573	0.91500	2.7	1.0	1.7
Pokmulingo Sirigo/Kadare	10.94706	0.91486	7.5	2.9	4.6
Pokmulingo Sirigo/Kadare	10.94637	0.91575	7.8	1.1	6.7
Pokmulingo Sirigo/Kadare	10.94709	0.91632	20.0	2.0	12.3
Kadare/Yua	10.94755	0.91491	5.3	1.0	4.3
Yoawa	10.94679	0.91434	4.2	1.1	3.1
Kadare/Yua	10.94677	0.91309	4.2	1.5	2.7
Kadare/Yua	10.94826	0.91324	5.4	1.4	4
Kadare/Yua	10.94911	0.91147	8.1	0.9	7.2
Kadare/Yua	10.95060	0.91263	10.4	2.1	8.3
Kadare/Yua	10.94945	0.91334	3.8	0.9	2.9
Kadare/Yua	10.95043	0.91363	5.8	2.1	3.7
Kadare/Yua	10.94919	0.91455	3.6	1.1	2.5
Kadare/Yua	10.94824	0.91580	8.8	0.6	8.2
Kadare/Yua	10.95190	0.91156	5.7	1.6	4
Kadare/Yua	10.95085	0.91057	11.8	7.8	4
Kadare/Yua	10.95102	0.90940	16.1	2.1	14
Kadare/Yua	10.95029	0.90893	10.0	3.0	7
Kadare/Yua	10.95112	0.90804	5.4	1.5	3.9
Kadare/Yua	10.95140	0.90705	2.9	1.0	1.9
Kadare/Yua	10.95270	0.91248	5.5	2.8	2.7
Kadare/Yua	10.52880	0.91333	8.3	1.1	7.2
Kadare/Yua	10.95201	0.90825	7.2	1.1	6.1
Kadare/Yua	10.95311	0.90763	3.8	1.0	2.8
Kadare/Yua	10.95283	0.91024	5.3	2.8	2.5
Kadare/Yua	10.95360	0.91135	4.9	0.5	4.4
Kadare/Yua	10.95191	0.91411	6.0	1.6	4.4
Kadare/Yua	10.95066	0.91486	8.8	1.0	7.8
Kadare/Yua	10.95304	0.90580	16.6	3.8	12.8
Kadare/Yua	10.95172	0.90538	8.8	1.4	8.4
Kadare/Yua	10.95213	0.90415	8.9	0.6	3.3
Kadare/Yua	10.95291	0.90363	7.2	1.3	5.9
Kadare/Yua	10.95166	0.90284	8.1	1.0	7.1
Kadare/Yua	10.95173	0.90169	20.6	0.9	19.7
Kadare/Yua	10.95175	0.90016	15.1	1.0	10.8
Kadare/Yua	10.95378	0.89940	13.9	3	10.9

1	2	3	4	5	6
Kadare/Yua	10.95331	0.90239	5.5	1.4	4.1
Kadare/Yua	10.95469	0.89842	10.2	6.8	3.4
Kadare/Yua	10.95383	0.89731	8.5	1.5	7
Kadare/Yua	10.95316	0.89784	19.1	1.6	13.6
Kadare/Yua	10.95468	0.89763	5.0	1.0	4
Kadare/Yua	10.95589	0.89771	4.7	1.2	3.5
Kadare/Yua	10.95689	0.89888	9.5	0.6	8.9
Kadare/Yua	10.95808	0.89859	5.2	0.8	4.4
Kadare/Yua	10.95693	0.89922	11.2	1.9	9.3
Kadare/Yua	10.55558	0.89891	18.8	2.0	16.8
Kadare/Yua	1095945	0.89792	6.7	2.7	4
Kadare/Yua	10.95982	0.8968	10.3	1.2	9.1
Kadare/Yua	10.96073	0.89582	8.5	1.2	7.3
Kadare/Yua	10.96155	0.89467	6.4	2.5	3.9
Kadare/Yua	10.96332	0.89486	10.5	1.5	9
Kadare/Yua	10.9624	0.89579	10.5	1.5	9
Kadare/Yua	10.96093	0.89768	8.8	0.6	8.2
Kadare/Yua	10.96034	0.89944	6.2	1.4	4.8
Kadare/Yua	10.96284	0.89255	6.2	1.4	4.8
Kadare/Yua	10.96185	0.89329	12.1	1.2	10.9
Kadare/Yua	10.96394	0.89418	16.1	1.0	12.7
Anateem	0.98219	10.81665	3.6	0.7	2.9
Anateem	0.98666	10.81667	3.2	1.3	1.9
Anateem	0.99112	10.81665	2.2	0.8	1.4
Atababa	1.00624	10.81666	2.6	1.6	1
Anateem	0.98519	10.82899	3.3	2.2	1.1
Kandiga Junction	1.00008	10.83941	3.9	2.2	1.7
Anateem	0.97253	10.83255	2.6	1.7	0.9
Anateem	0.98344	10.80946	3.1	1.9	1.2
Atiyuroum	0.9831	10.85002	2.1	0.9	1.2
Kologo	0.9329	10.85003	2.3	0.7	1.6
Kologo	0.94496	10.8501	8.6	1.4	4.4
Kologo	0.941667	10.841667	4.8	0.6	4.2
Akomkongo	0.99167	10.83333	8.2	1.1	5.9
Azeadima	0.975	10.83333	3.8	2.7	1.1
Azeadima-Agandaa	0.96667	10.88333	5.6	2.2	2.3
Kandiga-Azuredoone	0.95833	10.88333	16.8	1.5	14.2
Kurigu	0.95	10.88333	5	1.4	2.7
Kurigu Akamo	0.94167	10.88333	2.1	0.8	1.3
Akamo	0.94504	10.87132	17.1	2.4	11.4
Kaase Awuaboka	0.975	10.875	2	1.3	0.7

1	2	3	4	5	6
Kaase Akamo	0.95667	10.87512	12.5	1.2	8.9
Akawanma Atiyuroum	0.98	10.86167	4.3	2.7	1.6
Atiyure	0.92667	10.86021	20	1	17.9
Gamboringo	0.91167	10.86333	3.2	1.1	1.1
Gamboringo	0.90002	1088333	4	0.8	3.2
Agusi Gamboringo	0.91333	10.88332	7.1	0.4	3.5
Agusi Guoaso	0.92501	10.88333	8.3	1.4	6.2
Agusi	0.91667	10.87504	9	1.2	6.2
Agusi	0.90833	10.87505	8.6	4.4	1.4
Zorkkor	0.87667	10.90188	7.7	1.4	4
Zorkkor Tiabisi	0.89318	10.90149	7.5	1.2	6.3
Gamboringo	0.91344	10.89574	3.8	1.1	2.7
Kanga Gamboringo	0.91667	10.90012	12.3	1.3	11
Zorkkor Gamboringo	0.89002	10.89167	13	1.3	11.7
Zorkkor Tarongo	0.88332	10.90833	12.3	1	11.3
Zorkkor Kanga	0.88333	10.91667	8.8	2.2	6.6
Zorkkor Goawu	0.89667	10.91667	10.1	1.6	4.5
Zorkkor Kanga	0.91833	10.90833	9.8	1	8.8
Zorkkor Kodorogo	0.91001	10.91667	7.8	0.7	7.1
Zorkkor Kanga Abu	0.92333	10.91667	3.9	3.8	0.1
Zorkkor Kanga	0.92512	10.90667	20	3.5	16.5
Bembisi Longho	0.94167	10.91667	3.7	2.2	1.5
Bembisi Longho	0.95333	10.91667	8.2	2.4	5.7
Bembisi	0.96502	10.91667	7.8	1.7	6.1
Zorkkor	0.90833	10.90667	9.6	1.7	7.9
Kandiga	0.97011	10.89167	3.8	1.5	2.3
Kandiga Longho	0.96012	10.90001	2.7	1.6	1.6
Kandiga Longho	0.96002	10.90021		1.5	1.5
Kandiga Kurigu	0.95833	10.89167	2.3	1.5	0.8
Kandiga Kurigu	0.94667	10.89667	8	1.9	6.1
Kandiga Kurigu	0.94667	10.90833	3.2	1	2.2
Kandiga Longho	0.97022	10.90333	10.5	2	8.5
Nayorogo Sambulungu	0.865	10.95	10.4	3.7	6.7
Nayorogo Sambulungu	0.875	10.95	7.1	0.6	6.5
Abokobisi Sambulungu	0.885	10.95	2.6	0.9	1.7
Abokobisi	0.895	10.95	8.3	0.9	7.4
Yongo	0.965	10.95	4.7	3.4	1.3
Sirigu	0.955	10.95	3	0.7	2.3
Sirigu Dazongo	0.945	10.95	2.1	0.6	1.5
Sirigu Gunwoko	0.935	10.95	10.2	1.7	8.5
Sirigu	0.925	10.95	13.8	3	7.7

1	2	3	4	5	6
Kandiga Bembisi	0.945	10.925	2.9	0.8	2.1
Kandiga Bembisi	0.945	10.93333	5.1	1	4.1
Sirigu Bico	0.93	10.92667	5.9	1	4.9
Mirigu Nyong	0.95667	10.93333	7.5	2.9	4.6
Mirigu Nyong	0.95833	10.94167	9.5	0.9	8.6
Sirigu Gunwonko	0.93	10.94	4.4	1.4	3
Zorkko Kordorogo	0.91667	10.925	6.6	0.6	6
Zorkko Kordorogo	0.91333	10.935	2.3	0.8	1.5
Zorkko Kadare	0.90667	10.94167	9.3	1	8.3
Kadare	0.89667	10.93667	2.7	1.3	1.4
Zorkkor Goo	0.90667	10.925	7.6	1.7	5.9
Bongo Balungu	0.88333	10.93333	8.5	1.9	6.6
Bongo Balungu	0.875	10.94167	13.3	1.2	12.1
Sambulungu	0.89	10.94333	4.1	1.1	3
Kadare	0.895	10.92333		2.1	2.1
Sambulungu	0.86833	10.955	8	1.6	0.4
Sambulungu	0.875	10.955	6.3	1.7	4.6
Abokobisi	0.88667	10.955	2.7	0.9	1.8
Sambulungu Sikabisi	0.86333	10.96333	7.4	0.9	6.5
Sikabisi	0.87	10.96333	5.8	4.1	1.7
Sikabisi	0.87833	10.96333	5.6	1.2	4.4
Kadare Sambulungu	0.88333	10.965	4	1.4	2.6
Abokobisi	0.88833	10.96167	11.2	1.5	9.7
Sirigu	0.91333	10.96333	9.3	0.8	8.5
Yua	0.90667	10.96333	7.6	0.9	6.7
Sirigu	0.92667	10.95667	11.3	4.2	7.1
Sirigu	0.93833	10.95667	13.6	1.5	12.1
Sirigu	0.94167	10.96167	7.8	0.8	7
Sirigu Dazong	0.95667	10.95833	3.2	1.5	1.7
Sirigu Natugma	0.95833	10.965	5.2	1.8	3.4
Sirigu Basaigo Abola	0.93	10.96167	9.5	0.8	8.1

Appendix 2: Results of Grading analysis and hydrometer tests

CIVIL ENGINEERING DEPARTMENT
GEOTECHNICAL ENGINEERING LABORATORY
GRADING ANALYSIS

PROJECT:
SAMPLE NO: 1
DATE:
DESCRIPTION:

GRADING TEST — Total Dry Weight = 50.0

Sieve size BS designatio	Sieve size Metric (mm)	Weight retained (g)	Percentage retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			100.00
1 in	26.50		0.0	100.00
¾ in	19.00		0.0	100.00
½ in	13.20		0.0	100.00
⅜ in	9.50		0.0	100.00
1/4	6.70	0.00	0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.18	0.00	0.0	100.00

Total Dry Weight = 50.0

Sieve size BS designatio	Sieve size Metric (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
No. 7	2.36	0.52	1.04	98.96
No. 14	1.18	4.50	9.00	89.96
No. 25	0.600	9.65	19.30	70.66
No. 36	0.425	3.90	7.80	62.86
No. 52	0.300	2.05	4.10	58.76
NO. 72	0.212	1.05	2.10	56.66
No. 100	0.150	0.82	1.64	55.02
No. 200	0.075	1.81	3.62	51.40

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	26.00	1.0160	16.00	16.500	135.425	0.867	0.067	1.275	13.675	44.44
1.00	7:51	26.00	1.0150	15.00	15.500	139.375	0.867	0.048	1.275	12.675	41.19
2.00	7:52	26.00	1.0140	14.00	14.500	143.325	0.367	0.034	1.275	11.675	37.94
4.00	7:54	26.00	1.0129	12.90	13.400	147.670	0.867	0.025	1.275	10.575	34.37
8.00	7:58	26.00	1.0125	12.50	13.000	149.250	0.867	0.018	1.275	10.175	33.07
15.00	8:05	26.00	1.0120	12.00	12.500	151.225	0.867	0.013	1.275	9.675	31.44
30.00	8:20	26.00	1.0110	11.00	11.500	155.175	0.867	0.009	1.275	8.675	28.19
60.00	8:50	26.00	1.0105	10.50	11.000	157.150	0.867	0.007	1.275	8.175	26.57
120.00	9:50	25.00	1.0100	10.00	10.500	159.125	0.888	0.005	1.035	7.435	24.16
240.00	11:50	25.00	1.0095	9.50	10.000	161.100	0.888	0.003	1.035	6.935	22.54
1440.00	7:50	25.00	1.0090	9.00	9.500	163.075	0.888	0.001	1.035	6.435	20.91

CIVIL ENGINEERING DEPARTMENT

GEOTECHNICAL ENGINEERING LABORATORY

GRADING ANALYSIS

PROJECT:

SAMPLE NO: 2

DATE:

DESCRIPTION:

GRADING TEST Total Dry Weight = 50.0

Sieve size		Weight retained	Percentage retained	passing
BS designatio	Metric (mm)	(g)	(%)	(%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			
1 in	26.50			
¾ in	19.00			100.00
½ in	13.20	0.00	0.0	100.00
⅜ in	9.50	0.00	0.0	100.00
1/4	6.70	0.00	0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.18	0.00	0.0	100.00

Total Dry Weight = 50.0

Sieve size		Weight retained	Percentage retained	Percentage passing
BS designatio	Metric (mm)	(g)	(%)	(%)
No. 7	2.36	0.00	0.00	100.00
No. 14	1.18	0.05	0.10	99.90
No. 25	0.600	0.09	0.18	99.72
No. 36	0.425	0.26	0.52	99.20
No. 52	0.300	1.15	2.30	96.90
NO. 72	0.212	2.76	5.52	91.38
No. 100	0.150	4.15	8.30	83.08
No. 200	0.075	9.87	19.74	63.34

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	26.00	1.0190	19.00	19.500	123.575	0.867	0.064	1.275	16.675	54.19
1.00	7:51	26.00	1.0165	16.50	17.000	133.450	0.867	0.047	1.275	14.175	46.07
2.00	7:52	26.00	1.0140	14.00	14.500	143.325	0.867	0.034	1.275	11.675	37.94
4.00	7:54	26.00	1.0126	12.60	13.100	148.855	0.867	0.025	1.275	10.275	33.39
8.00	7:58	26.00	1.0120	12.00	12.500	151.225	0.867	0.018	1.275	9.675	31.44
15.00	8:05	26.00	1.0114	11.40	11.900	153.595	0.867	0.013	1.275	9.075	29.49
30.00	8:20	26.00	1.0105	10.50	11.000	157.150	0.867	0.009	1.275	8.175	26.57
60.00	8:50	26.00	1.0100	10.00	10.500	159.125	0.867	0.007	1.275	7.675	24.94
120.00	9:50	25.00	1.0097	9.70	10.200	160.310	0.888	0.005	1.035	7.135	23.19
240.00	11:50	25.00	1.0090	9.00	9.500	163.075	0.888	0.003	1.035	6.435	20.91
1440.00	7:50	25.00	1.0087	8.70	9.200	164.260	0.888	0.001	1.035	6.135	19.94

CIVIL ENGINEERING DEPARTMENT

GEOTECHNICAL ENGINEERING LABORATORY

GRADING ANALYSIS

PROJECT:

SAMPLE NO: 3

DATE:

DESCRIPTION:

GRADING TEST Total Dry Weight (g) 50.0

Sieve size		Weight	Percentage	
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			
1 in	26.50			
¾ in	19.00			
½ in	13.20			
⅜ in	9.50			100.00
¼	6.70		0.0	100.00
3/16	4.75		0.0	100.00
1/8	3.18		0.0	100.00

Total Dry Weight (g) 50.0

Sieve size		Weight	Percentage	Percentage
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.36	0.16	0.32	99.68
No. 14	1.18	2.11	4.22	95.46
No. 25	0.600	12.52	25.04	70.42
No. 36	0.425	12.66	25.32	45.10
No. 52	0.300	10.27	20.54	24.56
NO. 72	0.212	3.62	7.24	17.32
No. 100	0.150	1.17	2.34	14.98
No. 200	0.075	1.01	2.02	12.96

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	26.00	1.0075	7.50	8.000	169.000	0.867	0.075	1.275	5.175	16.82
1.00	7:51	26.00	1.0072	7.20	7.700	170.185	0.867	0.053	1.275	4.875	15.84
2.00	7:52	26.00	1.0070	7.00	7.500	170.975	0.867	0.038	1.275	4.675	15.19
4.00	7:54	26.00	1.0068	6.80	7.300	171.765	0.867	0.027	1.275	4.475	14.54
8.00	7:58	26.00	1.0067	6.70	7.200	172.160	0.867	0.019	1.275	4.375	14.22
15.00	8:05	25.50	1.0066	6.60	7.100	172.555	0.877	0.014	1.153	4.153	13.50
30.00	8:20	25.50	1.0065	6.50	7.000	172.950	0.877	0.010	1.153	4.053	13.17
60.00	8:50	25.50	1.0065	6.50	7.000	172.950	0.877	0.007	1.153	4.053	13.17
120.00	9:50	25.00	1.0065	6.50	7.000	172.950	0.888	0.005	1.035	3.935	12.79
240.00	11:50	25.00	1.0064	6.40	6.900	173.345	0.888	0.004	1.035	3.835	12.46
1440.00	7:50	25.00	1.0063	6.30	6.800	173.740	0.888	0.001	1.035	3.735	12.14

CIVIL ENGINEERING DEPARTMENT
GEOTECHNICAL ENGINEERING LABORATORY
GRADING ANALYSIS

PROJECT:

SAMPLE NO: 4

DATE:

DESCRIPTION:

GRADING TEST Total Dry Weight = 50.0

Sieve size BS designation	Metric (mm)	Weight retained (g)	Percentage retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			100.00
1 in	26.50		0.0	100.00
¾ in	19.00		0.0	100.00
½ in	13.20		0.0	100.00
⅜ in	9.50		0.0	100.00
¼	6.70		0.0	100.00
3/16	4.75		0.0	100.00
1/8	3.18		0.0	100.00

Total Dry Weight = 50.0

Sieve size BS designation	Metric (mm)	Weight retained (g)	Percentage retained (%)	Percentage passing (%)
No. 7	2.36	0.10	0.20	99.80
No. 14	1.18	0.53	1.06	98.74
No. 25	0.600	3.23	6.46	92.28
No. 36	0.425	4.11	8.22	84.06
No. 52	0.300	5.49	10.98	73.08
NO. 72	0.212	3.85	7.70	65.38
No. 100	0.150	2.27	4.54	60.84
No. 200	0.075	3.00	6.00	54.84

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings Rh'	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	25.50	1.0180	18.00	18.500	127.525	0.877	0.065	1.153	15.553	50.55
1.00	7:51	25.50	1.0170	17.00	17.500	131.475	0.877	0.047	1.153	14.553	47.30
2.00	7:52	25.50	1.0158	15.80	16.300	136.215	0.877	0.034	1.153	13.353	43.40
4.00	7:54	25.50	1.0150	15.00	15.500	139.375	0.877	0.024	1.153	12.553	40.80
8.00	7:58	25.50	1.0135	13.50	14.000	145.300	0.877	0.017	1.153	11.053	35.92
15.00	8:05	25.50	1.0130	13.00	13.500	147.275	0.877	0.013	1.153	10.553	34.30
30.00	8:20	25.50	1.0115	11.50	12.000	153.200	0.877	0.009	1.153	9.053	29.42
60.00	8:50	25.50	1.0110	11.00	11.500	155.175	0.877	0.007	1.153	8.553	27.80
120.00	9:50	25.00	1.0102	10.20	10.700	158.335	0.888	0.005	1.035	7.635	24.81
240.00	11:50	25.00	1.0090	9.00	9.500	163.075	0.888	0.003	1.035	6.435	20.91
1440.00	7:50	25.00	1.0085	8.50	9.000	165.050	0.888	0.001	1.035	5.935	19.29

CIVIL ENGINEERING DEPARTMENT

GEOTECHNICAL ENGINEERING LABORATORY

GRADING ANALYSIS

DATE:

DESCRIPTION:

PROJECT:

SAMPLE NO: 5

GRADING TEST Total Dry Weight = 50.0

Sieve size		Weight	Percentage	
BS designatio	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			100.00
1 in	26.50		0.0	100.00
¾ in	19.00		0.0	100.00
½ in	13.20		0.0	100.00
⅜ in	9.50		0.0	100.00
¼	6.70	0.00	0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.18	0.00	0.0	100.00

Total Dry Weight = 50.0

Sieve size		Weight	Percentage	Percentage
BS designatio	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.36	0.54	1.08	98.92
No. 14	1.18	2.71	5.42	93.50
No. 25	0.600	6.89	13.78	79.72
No. 36	0.425	4.43	8.86	70.86
No. 52	0.300	3.94	7.88	62.98
NO. 72	0.212	2.18	4.36	58.62
No. 100	0.150	1.18	2.36	56.26
No. 200	0.075	2.42	4.84	51.42

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	25.50	1.0170	17.00	17.500	131.475	0.877	0.066	1.153	14.553	47.30
1.00	7:51	25.50	1.0155	15.50	16.000	137.400	0.877	0.048	1.153	13.053	42.42
2.00	7:52	25.50	1.0141	14.10	14.600	142.930	0.877	0.035	1.153	11.653	37.87
4.00	7:54	25.50	1.0130	13.00	13.500	147.275	0.877	0.025	1.153	10.553	34.30
8.00	7:58	25.50	1.0125	12.50	13.000	149.250	0.877	0.018	1.153	10.053	32.67
15.00	8:05	25.50	1.0120	12.00	12.500	151.225	0.877	0.013	1.153	9.553	31.05
30.00	8:20	25.50	1.0114	11.40	11.900	153.595	0.877	0.009	1.153	8.953	29.10
60.00	8:50	25.50	1.0107	10.70	11.200	156.360	0.877	0.007	1.153	8.253	26.82
120.00	9:50	25.00	1.0102	10.20	10.700	158.335	0.888	0.005	1.035	7.635	24.81
240.00	11:50	25.00	1.0097	9.70	10.200	160.310	0.888	0.003	1.035	7.135	23.19
1440.00	7:50	25.00	1.0090	9.00	9.500	163.075	0.888	0.001	1.035	6.435	20.91

CIVIL ENGINEERING DEPARTMENT

GEOTECHNICAL ENGINEERING LABORATORY

GRADING ANALYSIS

PROJECT:

SAMPLE NO: 6

DATE:

DESCRIPTION:

GRADING TEST Total Dry Weight = 50.0

Sieve size		Weight retained	Percentage retained	passing
BS designatio	Metric (mm)	(g)	(%)	(%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			
1 in	26.50			
¾ in	19.00			100.00
½ in	13.20	0.00	0.0	100.00
⅜ in	9.50	0.00	0.0	100.00
1/4	6.70	0.00	0.0	100.00
3/16	4.75	0.00	0.0	100.00
1/8	3.18	0.00	0.0	100.00

Total Dry Weight = 50.0

Sieve size		Weight retained	Percentage retained	Percentage passing
BS designatio	Metric (mm)	(g)	(%)	(%)
No. 7	2.36	0.46	0.92	99.08
No. 14	1.18	0.85	1.68	97.40
No. 25	0.600	1.53	3.03	94.36
No. 36	0.425	1.05	2.08	92.28
No. 52	0.300	1.79	3.55	88.74
NO. 72	0.212	2.46	4.87	83.86
No. 100	0.150	2.95	5.85	78.02
No. 200	0.075	6.09	12.07	65.95

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	25.50	1.0215	21.50	22.000	113.700	0.877	0.062	1.153	19.053	61.35
1.00	7:51	25.50	1.0210	21.00	21.500	115.675	0.877	0.044	1.153	18.553	59.74
2.00	7:52	25.50	1.0195	19.50	20.000	121.600	0.877	0.032	1.153	17.053	54.91
4.00	7:54	25.50	1.0160	16.00	16.500	135.425	0.877	0.024	1.153	13.553	43.64
8.00	7:58	25.50	1.0157	15.70	16.200	136.610	0.877	0.017	1.153	13.253	42.68
15.00	8:05	25.50	1.0145	14.50	15.000	141.350	0.877	0.013	1.153	12.053	38.81
30.00	8:20	25.50	1.0136	13.60	14.100	144.905	0.877	0.009	1.153	11.153	35.91
60.00	8:50	25.50	1.0130	13.00	13.500	147.275	0.877	0.006	1.153	10.553	33.98
120.00	9:50	25.00	1.0125	12.50	13.000	149.250	0.888	0.005	1.035	9.935	31.99
240.00	11:50	25.00	1.0120	12.00	12.500	151.225	0.888	0.003	1.035	9.435	30.38
1440.00	7:50	25.00	1.0114	11.40	11.900	153.595	0.888	0.001	1.035	8.835	28.45

CIVIL ENGINEERING DEPARTMENT

GEOTECHNICAL ENGINEERING LABORATORY

GRADING ANALYSIS

PROJECT:

SAMPLE NO: 7

DATE:

DESCRIPTION:

GRADING TEST Total Dry Weight (g) 50.0

Sieve size		Weight	Percentage	
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			
1 in	26.50			
¾ in	19.00			
½ in	13.20			
⅜ in	9.50			100.00
1/4	6.70		0.0	100.00
3/16	4.75		0.0	100.00
1/8	3.18		0.0	100.00

Total Dry Weight (g) 50.0

Sieve size		Weight	Percentage	Percentage
BS designation	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.36	0.02	0.04	99.96
No. 14	1.18	0.07	0.14	99.82
No. 25	0.600	0.24	0.48	99.34
No. 36	0.425	0.16	0.32	99.02
No. 52	0.300	0.32	0.64	98.38
NO. 72	0.212	0.65	1.30	97.08
No. 100	0.150	1.11	2.22	94.86
No. 200	0.075	3.54	7.08	87.78

Hydrometer readings

Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	25.50	1.0265	26.50	27.000	93.950	0.877	0.056	1.153	24.053	78.17
1.00	7:51	25.50	1.0240	24.00	24.500	103.825	0.877	0.042	1.153	21.553	70.05
2.00	7:52	25.50	1.0220	22.00	22.500	111.725	0.877	0.031	1.153	19.553	63.55
4.00	7:54	25.50	1.0200	20.00	20.500	119.625	0.877	0.022	1.153	17.553	57.05
8.00	7:58	25.50	1.0160	16.00	16.500	135.425	0.877	0.017	1.153	13.553	44.05
15.00	8:05	25.50	1.0154	15.40	15.900	137.795	0.877	0.012	1.153	12.953	42.10
30.00	8:20	25.50	1.0138	13.80	14.300	144.115	0.877	0.009	1.153	11.353	36.90
60.00	8:50	25.50	1.0128	12.80	13.300	148.065	0.877	0.006	1.153	10.353	33.65
120.00	9:50	25.00	1.0115	11.50	12.000	153.200	0.888	0.005	1.035	8.935	29.04
240.00	11:50	25.00	1.0110	11.00	11.500	155.175	0.888	0.003	1.035	8.435	27.41
1440.00	7:50	25.00	1.0100	10.00	10.500	159.125	0.888	0.001	1.035	7.435	24.16

CIVIL ENGINEERING DEPARTMENT

GEOTECHNICAL ENGINEERING LABORATORY

GRADING ANALYSIS

PROJECT:

SAMPLE NO: 8

DATE:

DESCRIPTION:

GRADING TEST Total Dry Weight = 50.0

Sieve size		Weight	Percentage	.
BS designatio	Metric (mm)	retained (g)	retained (%)	passing (%)
3 in	75.00			
2 ½ in	63.00			
2 in	53.00			
1 ½ in	37.10			100.00
1 in	26.50		0.0	100.00
¾ in	19.00		0.0	100.00
½ in	13.20		0.0	100.00
⅜ in	9.50		0.0	100.00
¼	6.70		0.0	100.00
3/16	4.75		0.0	100.00
1/8	3.18		0.0	100.00

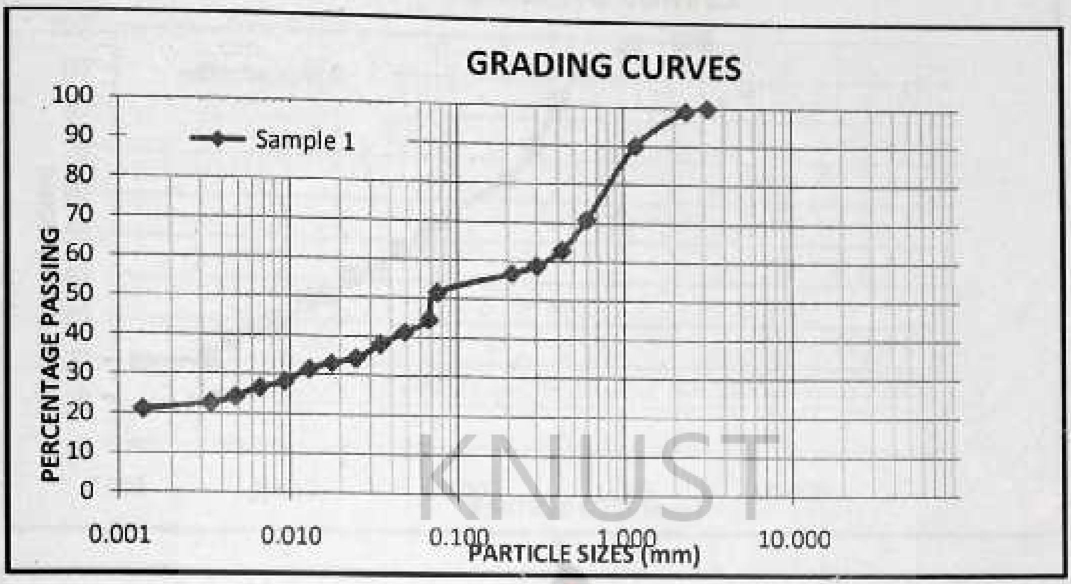
Total Dry Weight = 50.0

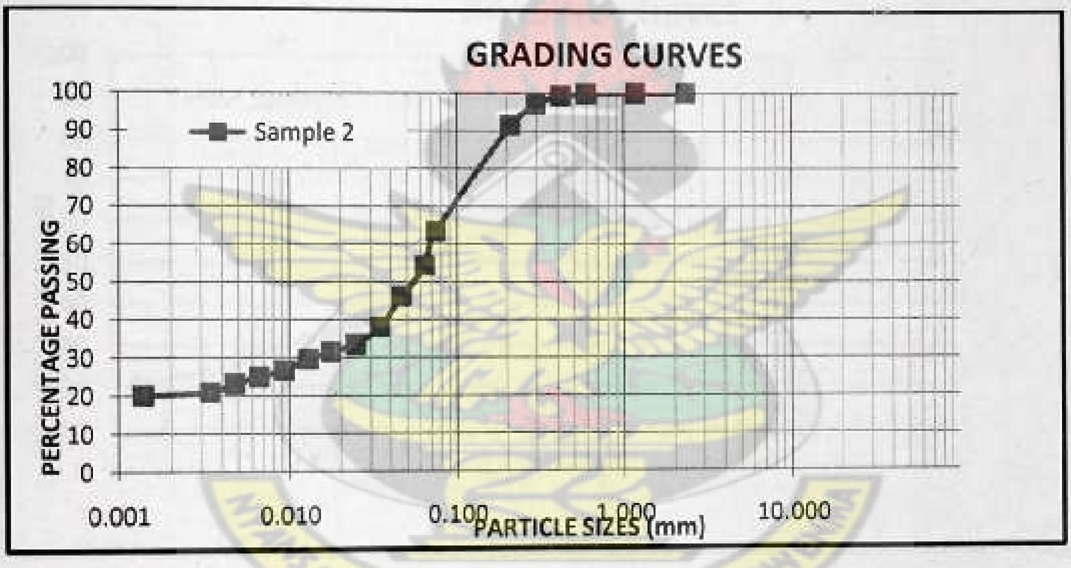
Sieve size		Weight	Percentage	Percentage
BS designatio	Metric (mm)	retained (g)	retained (%)	passing (%)
No. 7	2.36	0.00	0.00	100.00
No. 14	1.18	0.06	0.12	99.88
No. 25	0.600	0.06	0.12	99.76
No. 36	0.425	0.14	0.28	99.48
No. 52	0.300	0.96	1.92	97.56
NO. 72	0.212	3.00	6.00	91.56
No. 100	0.150	3.40	6.80	84.76
No. 200	0.075	6.25	12.50	72.26

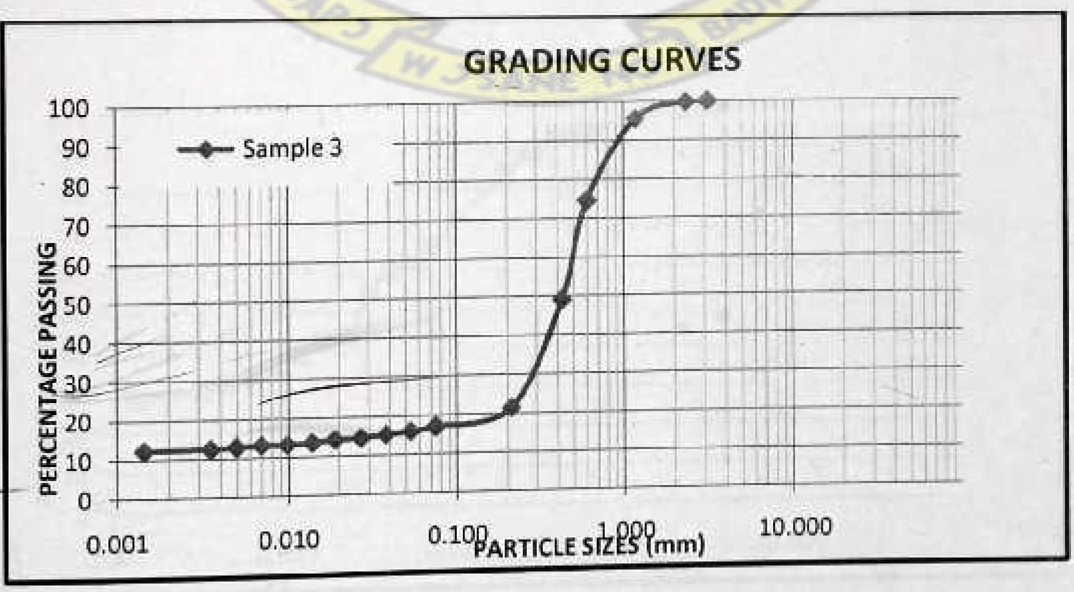
Hydrometer readings

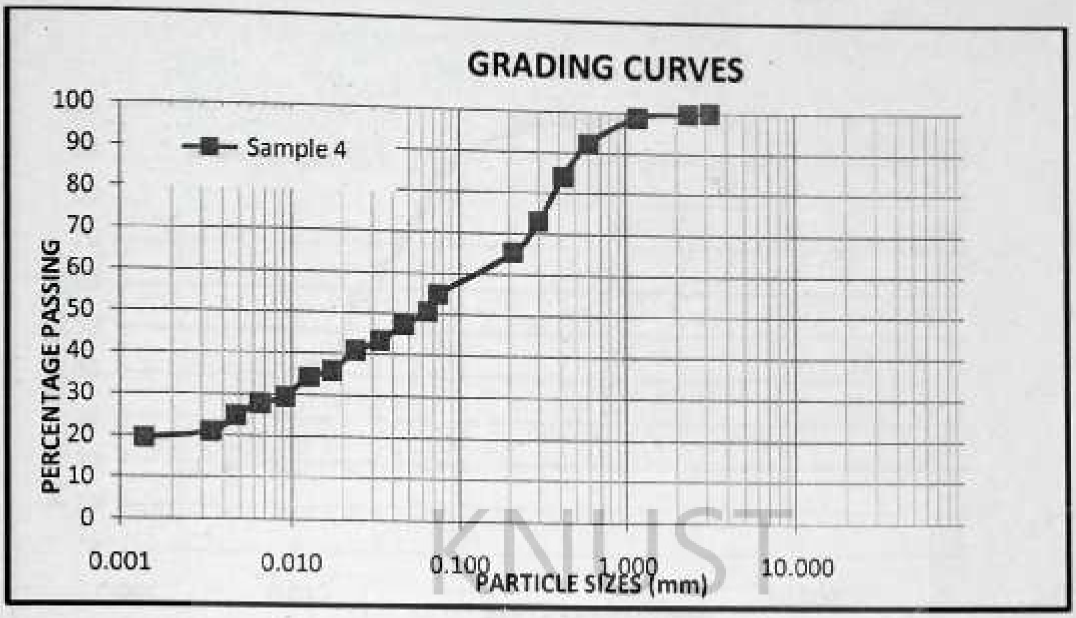
Elapsed tme,(min)	Time (mins)	Temp (° c)	Direct hydrometer readings	Reading Rh'	Rh=Rh' + Cm	Hr (mm)	Viscosity	D (mm)	Temp Corr,Mt	Rd= Rh'-Ro'+Mt	K (%)
0.50	7:50	25.50	1.0220	22.00	22.500	111.725	0.877	0.061	1.153	19.553	63.55
1.00	7:51	25.50	1.0195	19.50	20.000	121.600	0.877	0.045	1.153	17.053	55.42
2.00	7:52	25.50	1.0163	16.30	16.800	134.240	0.877	0.034	1.153	13.853	45.02
4.00	7:54	25.50	1.0140	14.00	14.500	143.325	0.877	0.025	1.153	11.553	37.55
8.00	7:58	25.50	1.0110	11.00	11.500	155.175	0.877	0.018	1.153	8.553	27.80
15.00	8:05	25.50	1.0100	10.00	10.500	159.125	0.877	0.013	1.153	7.553	24.55
30.00	8:20	25.50	1.0085	8.50	9.000	165.050	0.877	0.010	1.153	6.053	19.67
60.00	8:50	25.50	1.0080	8.00	8.500	167.025	0.877	0.007	1.153	5.553	18.05
120.00	9:50	25.50	1.0075	7.50	8.000	169.000	0.877	0.005	1.153	5.053	16.42
240.00	11:50	25.50	1.0070	7.00	7.500	170.975	0.877	0.003	1.153	4.553	14.80
1440.00	7:50	25.50	1.0065	6.50	7.000	172.950	0.877	0.001	1.153	4.053	13.17

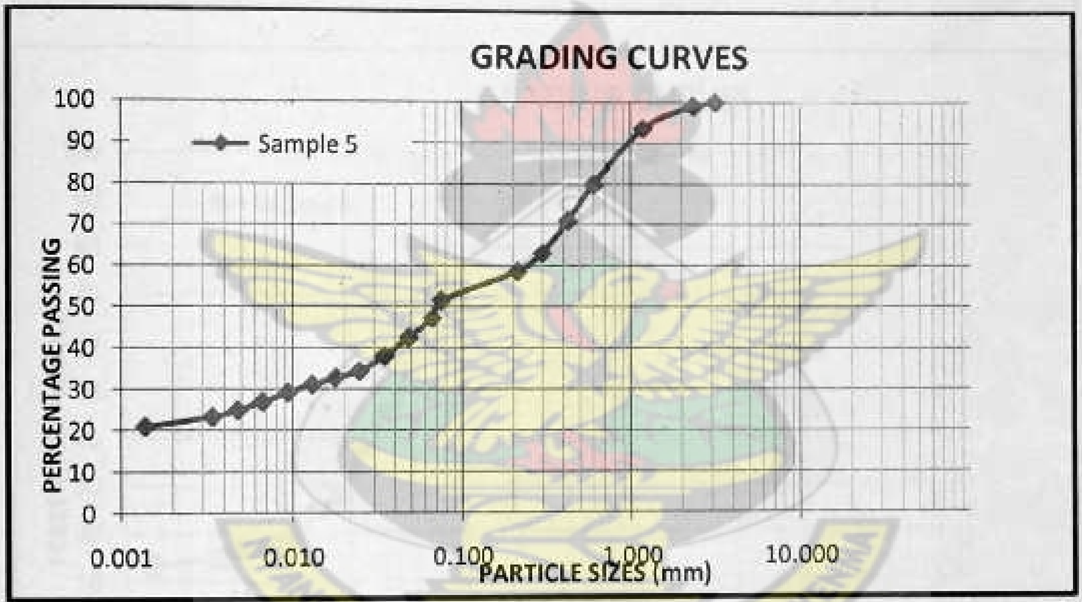
Appendix 3: Grading curves on semi- logarithmic sheet of soil samples

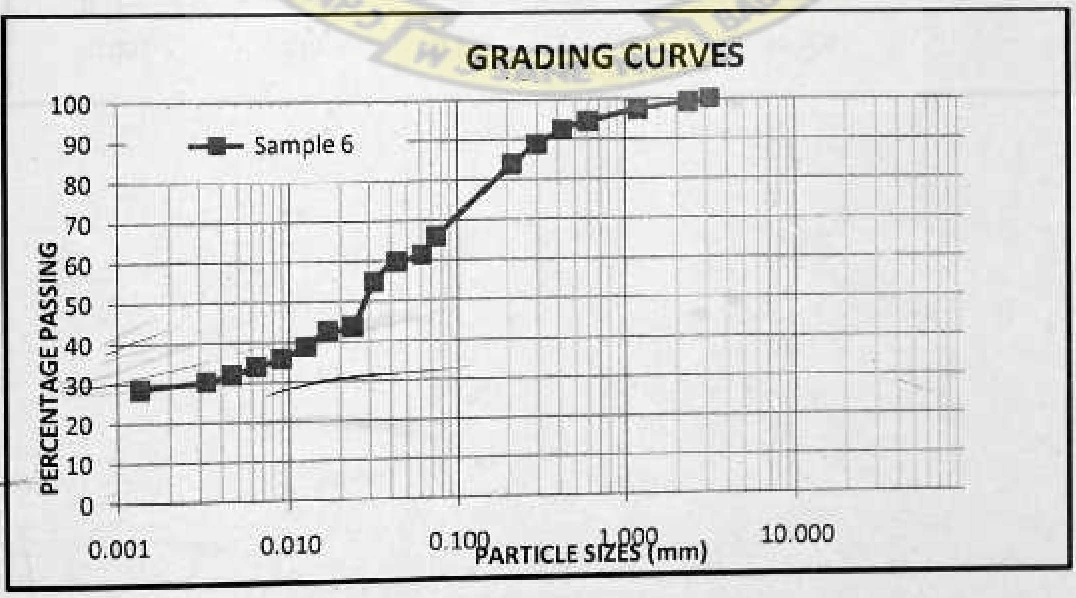


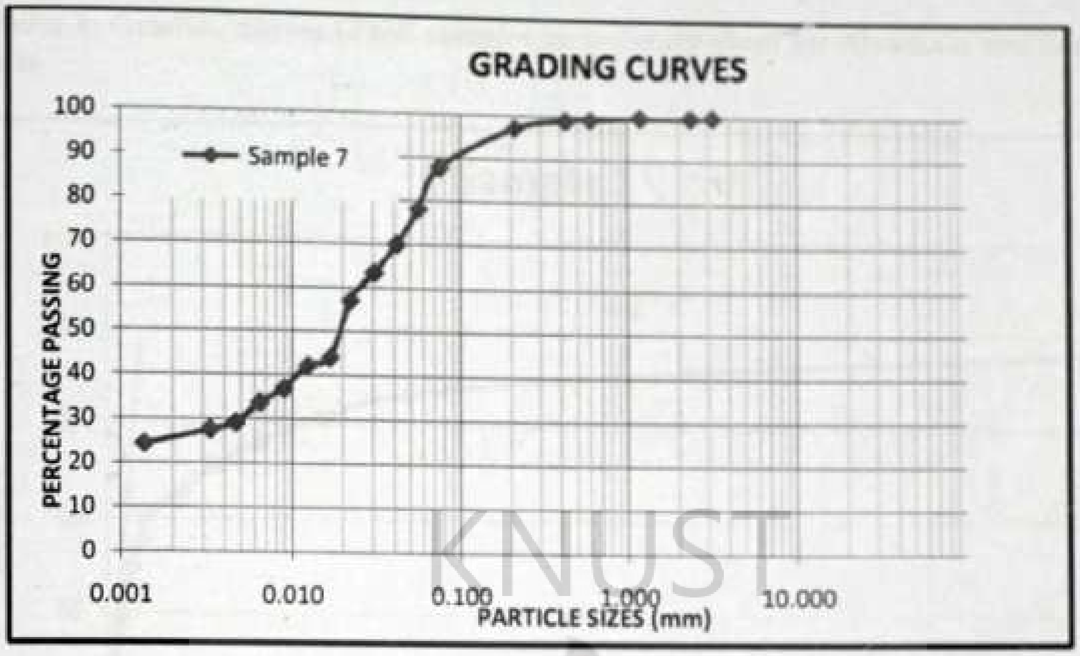


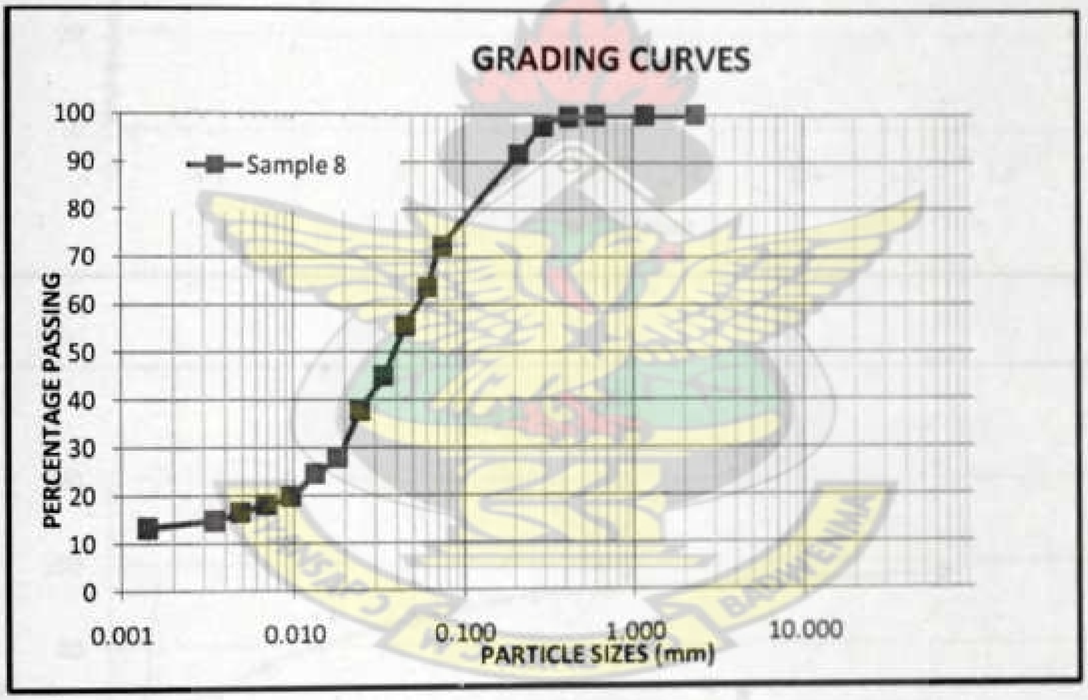



GRADING CURVES
Sample 4
PERCENTAGE PASSING
0
10
20
30
40
50
60
70
80
90
100
0.001
0.010
0.100
1.000
10.000
PARTICLE SIZES (mm)

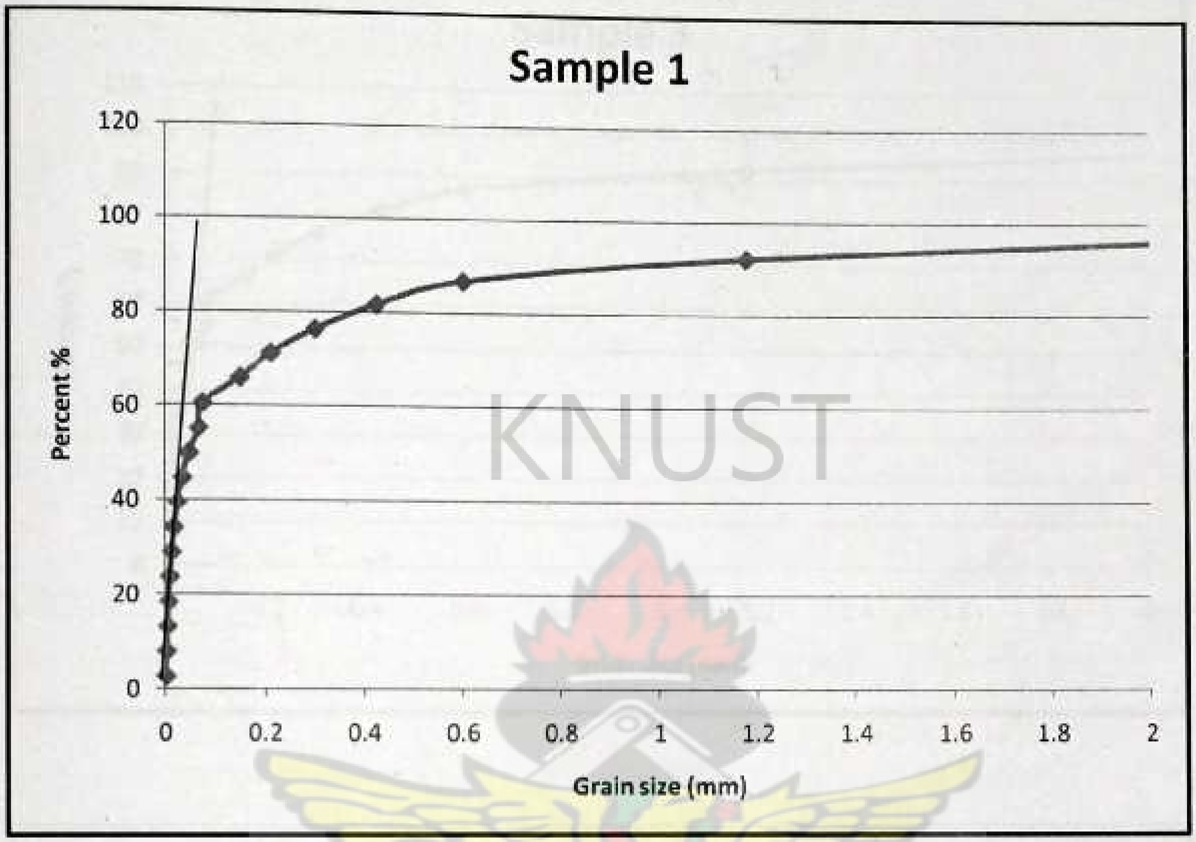

GRADING CURVES
Sample 5
PERCENTAGE PASSING
0
10
20
30
40
50
60
70
80
90
100
0.001
0.010
0.100
1.000
10.000
PARTICLE SIZES (mm)

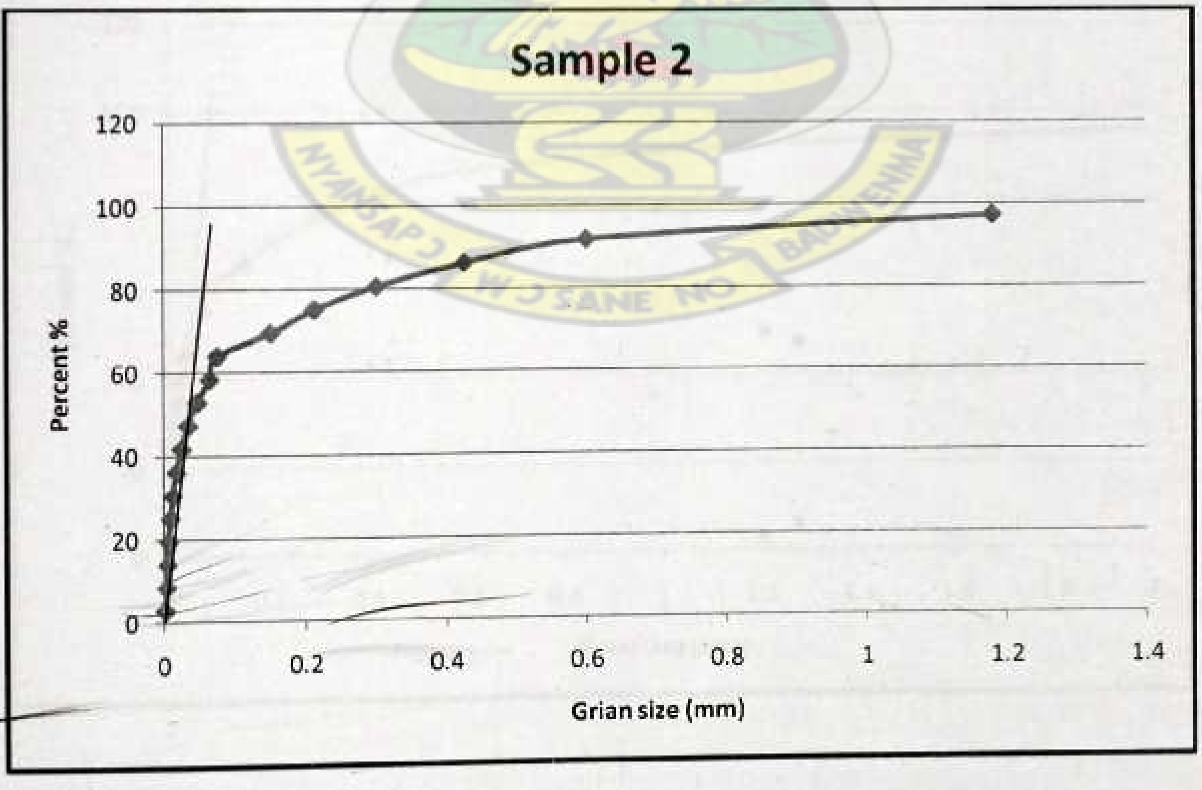

GRADING CURVES
Sample 6
PERCENTAGE PASSING
0
10
20
30
40
50
60
70
80
90
100
0.001
0.010
0.100
1.000
10.000
PARTICLE SIZES (mm)

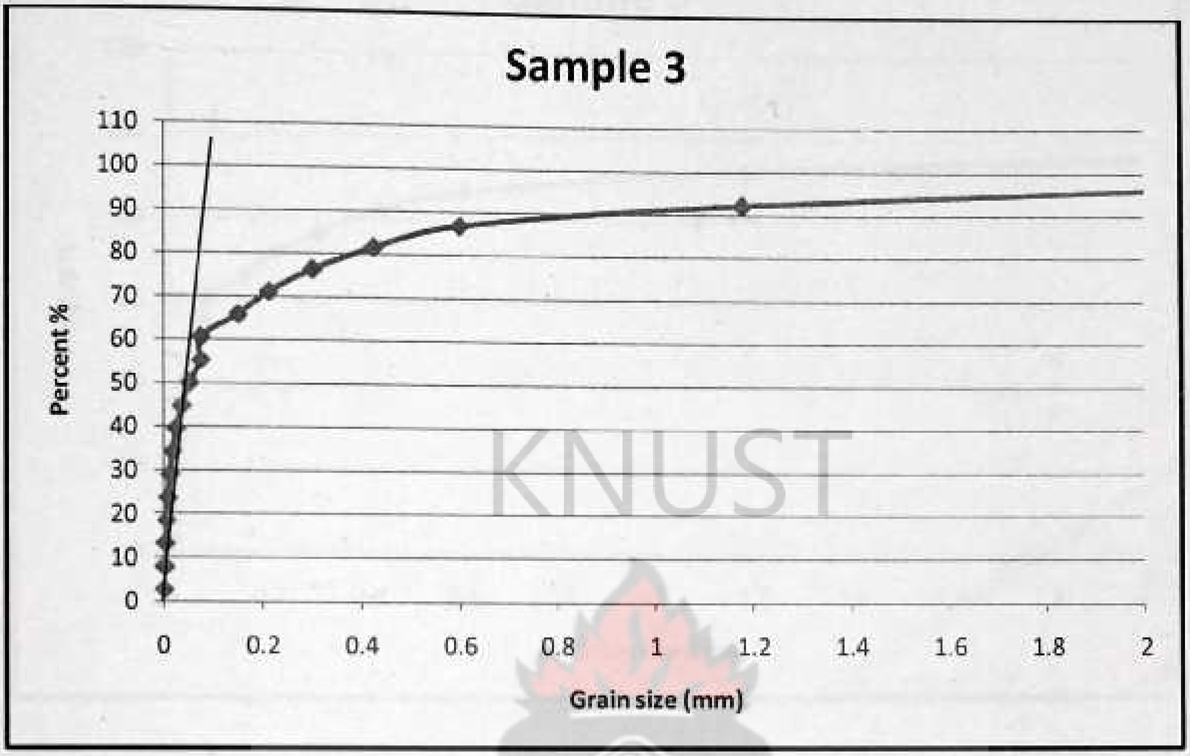

GRADING CURVES
Sample 7
PERCENTAGE PASSING
100
90
80
70
60
50
40
30
20
10
0
0.001
0.010
0.100
1.000
10.000
PARTICLE SIZES (mm)

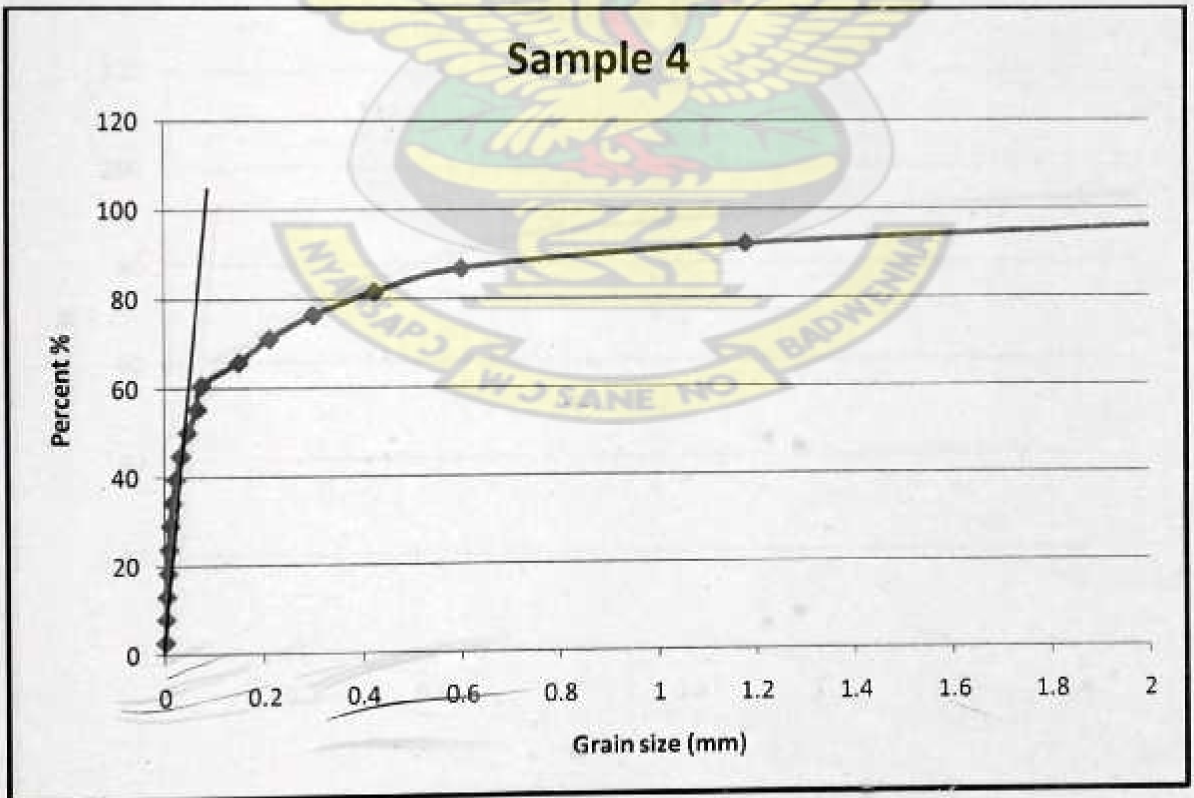

GRADING CURVES
Sample 8
PERCENTAGE PASSING
100
90
80
70
60
50
40
30
20
10
0
0.001
0.010
0.100
1.000
10.000
PARTICLE SIZES (mm)

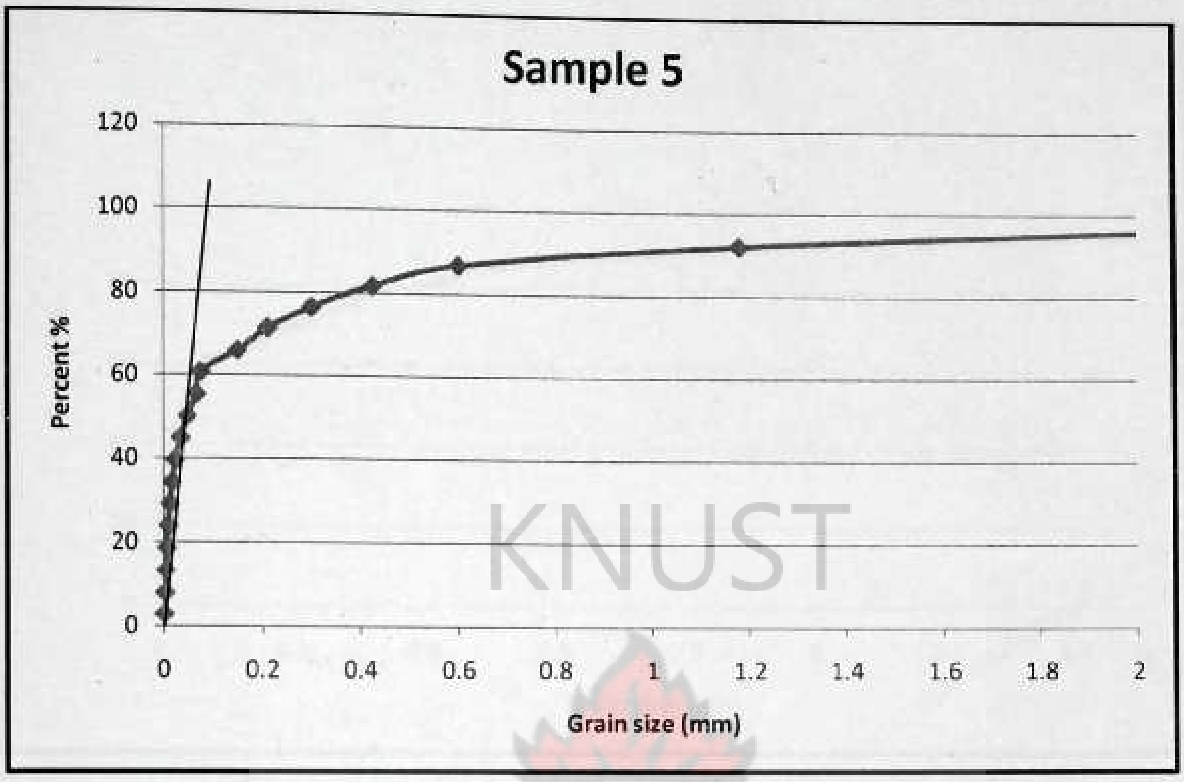
Appendix 4: Grading curves of soil samples on ordinary sheet for Alyamani and Sen formula.

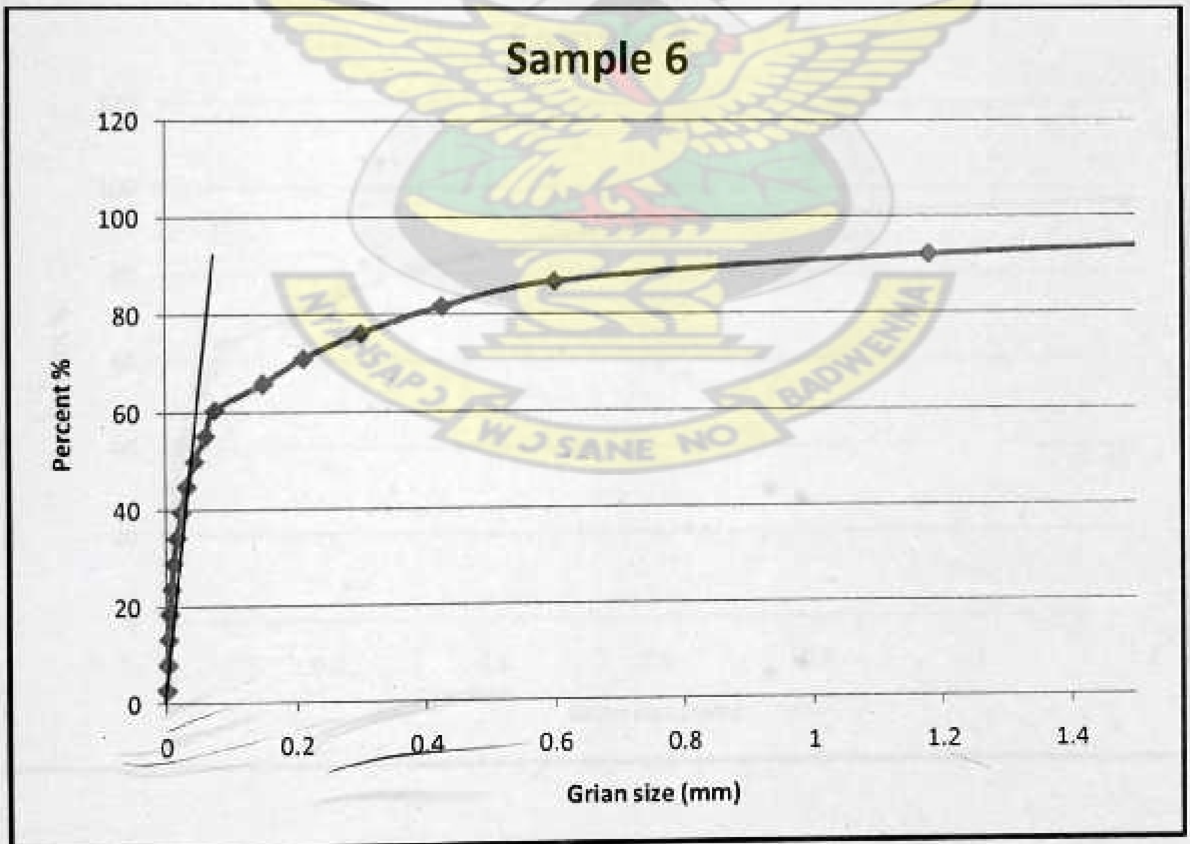


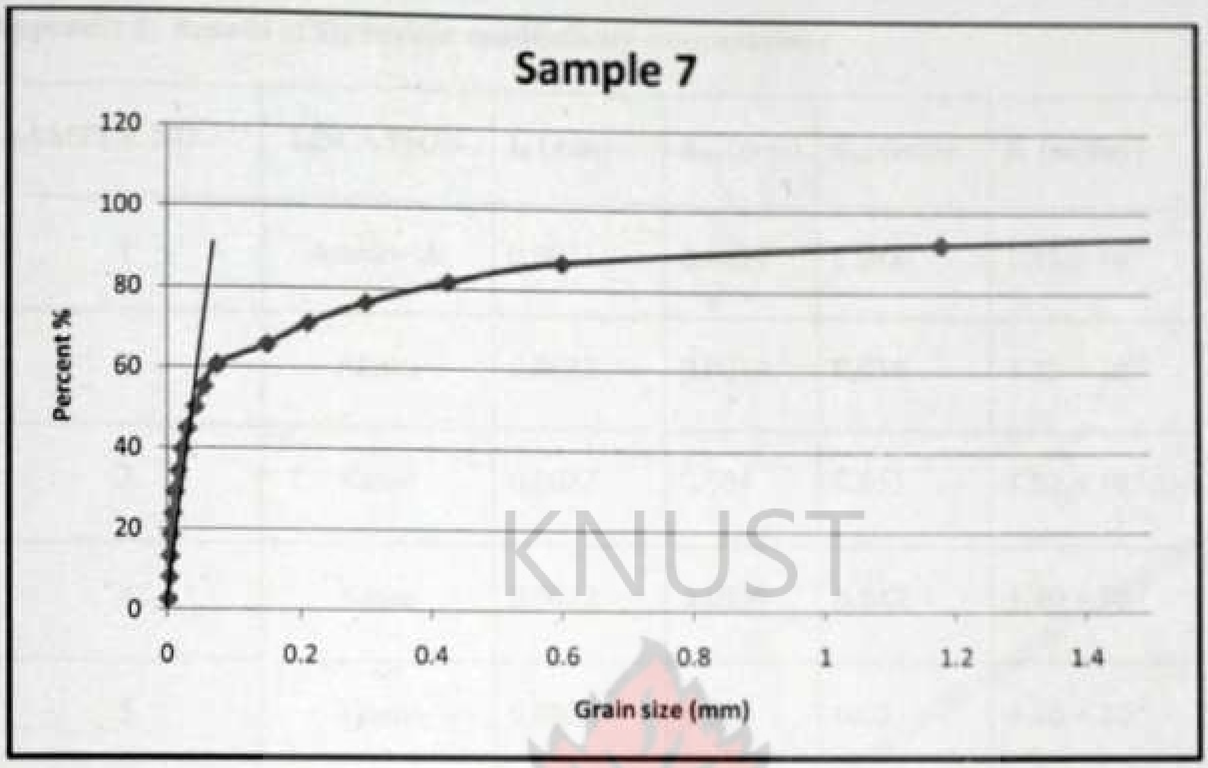


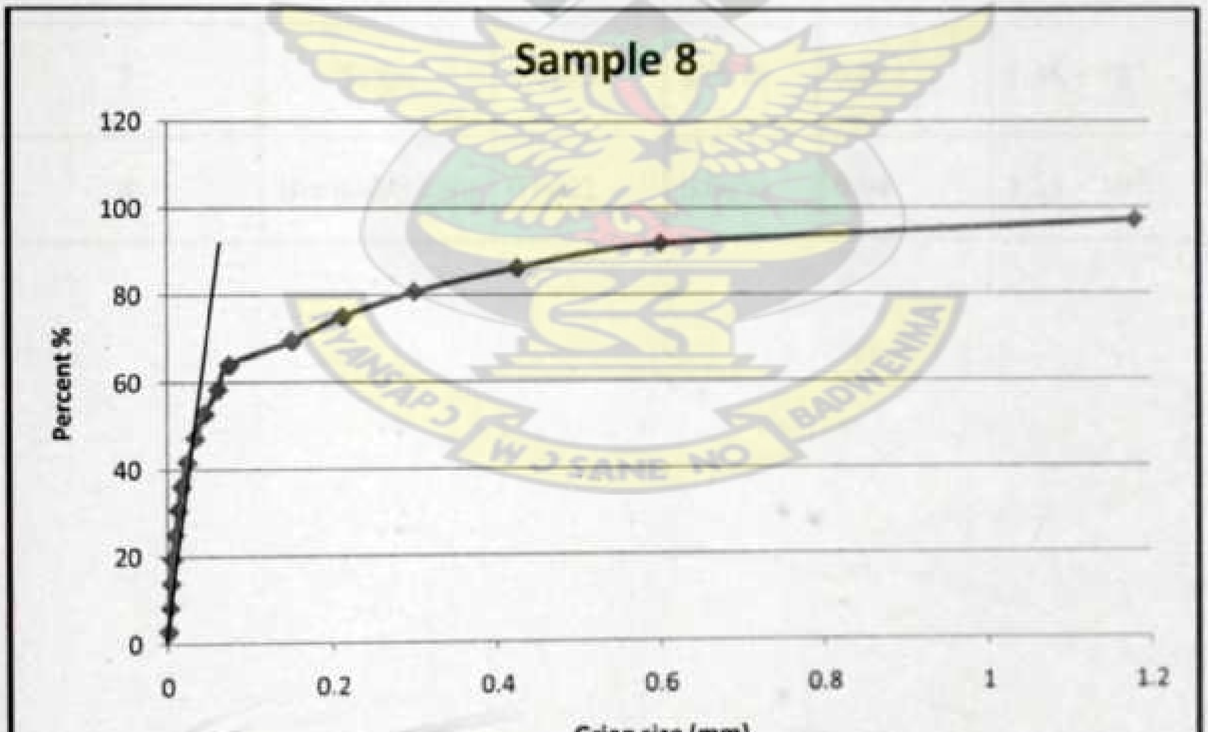

Sample 3
110
100
90
80
70
60
50
40
30
20
10
0
Percent %
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Grain size (mm)


Sample 4
120
100
80
60
40
20
0
Percent %
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Grain size (mm)


Sample 5
120
100
80
60
40
20
0
Percent %
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
Grain size (mm)


Sample 6
120
100
80
60
40
20
0
Percent %
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Grian size (mm)

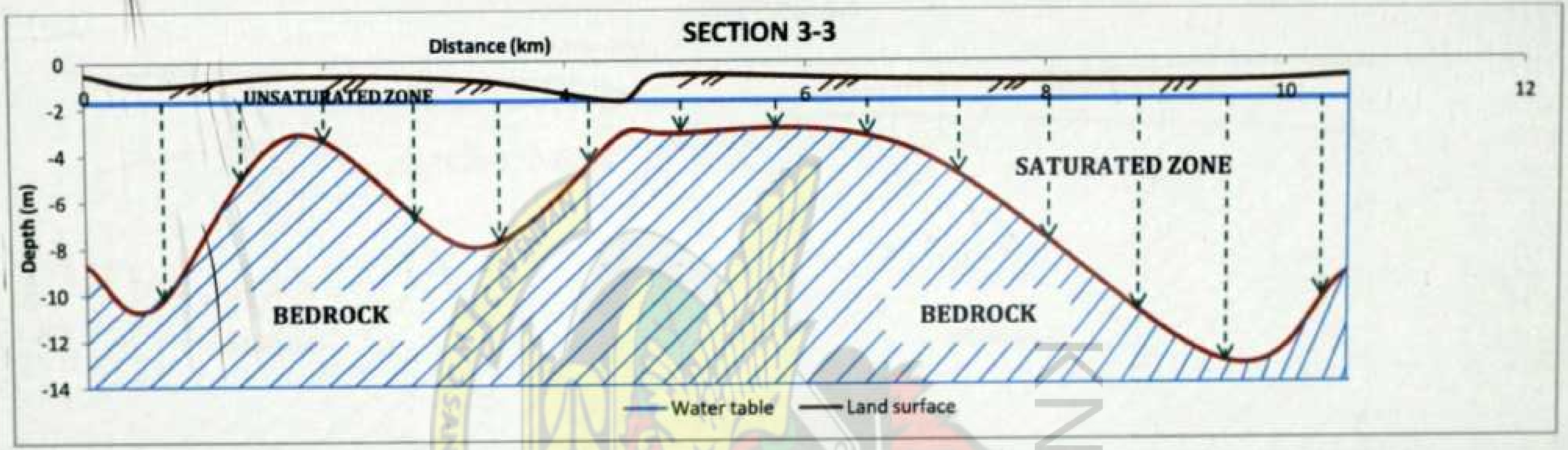

Sample 7
120
100
80
60
40
20
0
Percent %
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Grain size (mm)

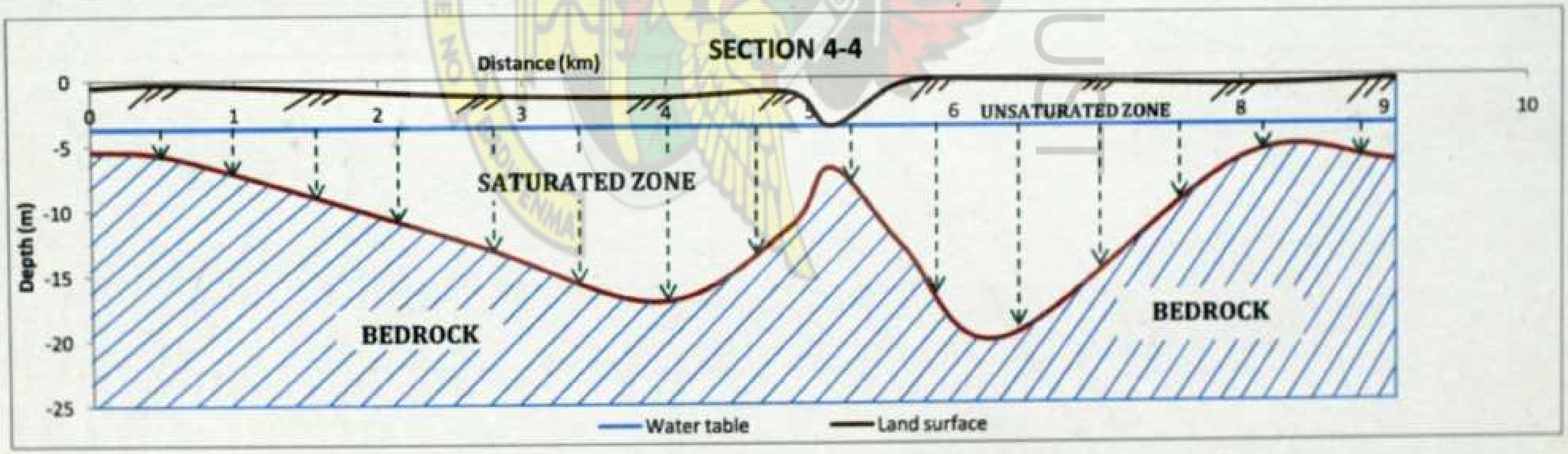

Sample 8
120
100
80
60
40
20
0
Percent %
0
0.2
0.4
0.6
0.8
1
1.2
Grian size (mm)

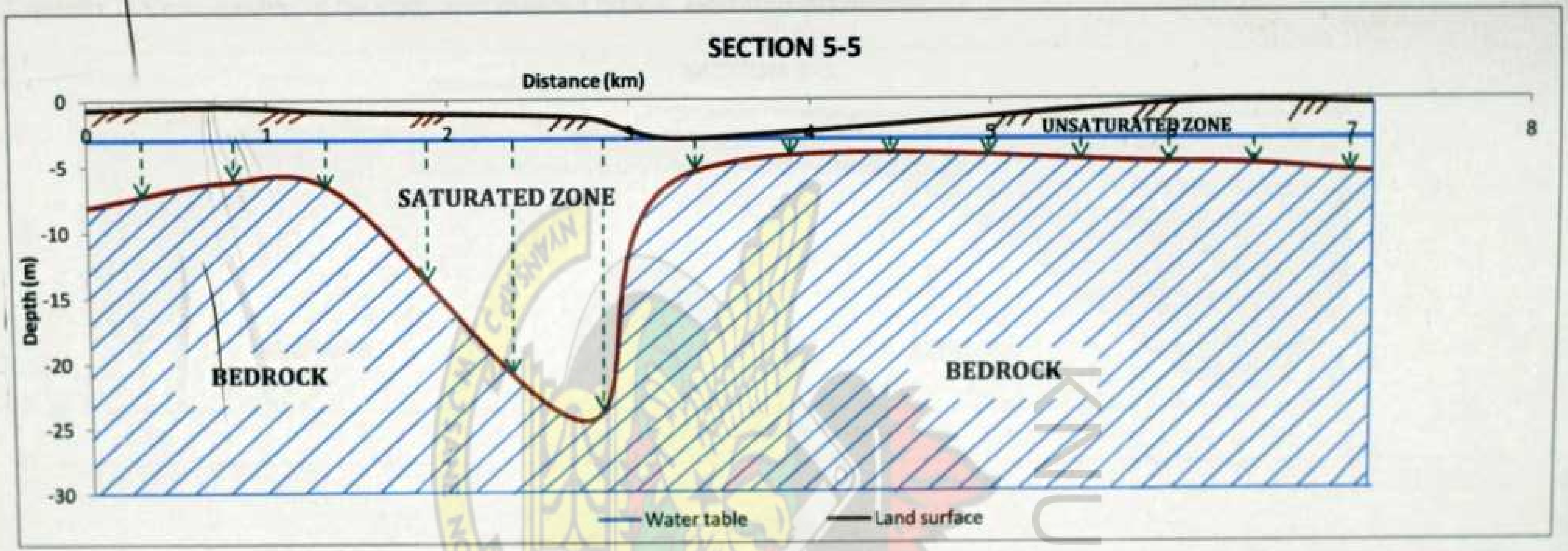
Appendix 5: Results of Hydraulic conductivity computations

SAMPLE NO.	LOCATION	I_0 (mm)	d_{10} (mm)	d_{50} (mm)	K (m/day)
1	Atankwidi	0.0021	0.0039	0.048	1.33×10^{-2}
2	Akoka	0.0023	0.0038	0.039	1.32×10^{-2}
3	Kaase	0.0022	0.004	0.053	1.52×10^{-2}
4	Kaase	0.0022	0.0039	0.047	1.40×10^{-2}
5	Akamo	0.0022	0.004	0.05	1.46×10^{-2}
6	Kurugu	0.0021	0.0037	0.045	1.28×10^{-2}
7	Sirigu	0.0023	0.0038	0.042	1.38×10^{-2}
8	Bembisi-Sirigu	0.0022	0.0039	0.04	1.25×10^{-2}

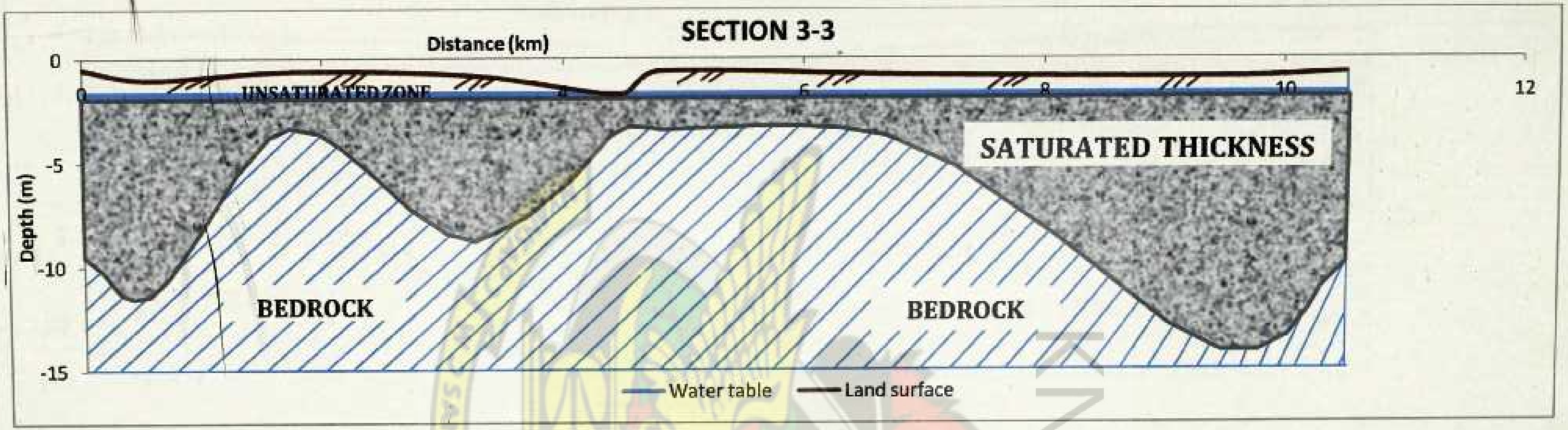
Appendix 6: Schematic diagram of cross-sections for the Simpsons rule

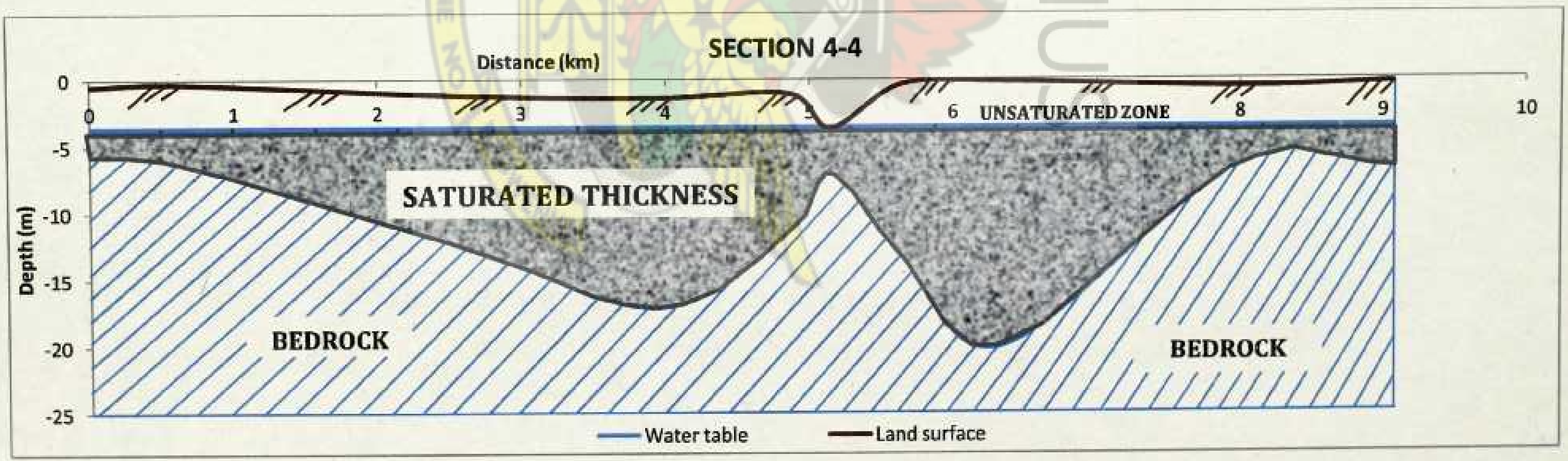


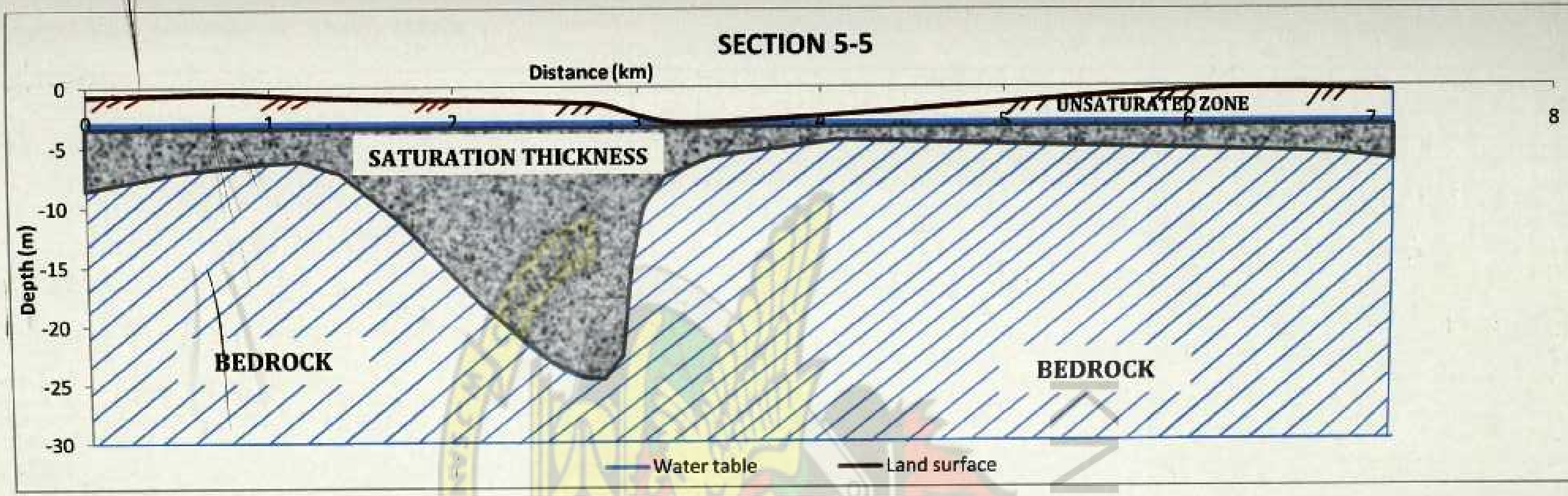



SECTION 5-5
Distance (km)
Depth (m)
0
-5
-10
-15
-20
-25
-30
0
1
2
4
5
7
8
SATURATED ZONE
UNSATURATED ZONE
BEDROCK
BEDROCK
Water table
Land surface

Appendix 7: Cross-sections of the study area showing typical saturation thicknesses






SECTION 5-5
Distance (km)
0
1
2
3
4
5
6
7
8
Depth (m)
0
-5
-10
-15
-20
-25
-30
UNSATURATED ZONE
SATURATION THICKNESS
BEDROCK
BEDROCK
Water table
Land surface

Appendix 8: Groundwater quality results

COMMUNITY	LONGITUDE	LATITUDE	Temp	pH	Cond	TDS	Sal.	Turb.	Br2	TSS	Tot. alk	Tot. H	Ca	Cl	NO2	NO3	PO4	SO4	Na
Atankwidi	10.83321°N	0.98616°W	27.9	7.12	277	152	0.1	42.1	1.06	34.0	116	50.0	8.8	3.0	0.019	2.10	0.010	4.0	25.0
Atankwidi	10.83256°N	0.98403°W	27.2	7.28	124	TDS	0.0	23.1	0.5	5.0	10.0	30.0	6.4	12.0	0.014	4.96	4.37	16.5	8.5
Akunka	10.83493°N	0.98079°W	27.6	7.37	306	168	0.1	74.1	1.17	97.0	142	86.0	15.2	20.0	0.008	0.430	3.23	9.0	30.6
Akunka	10.83646°N	0.98079°W	26.4	7.64	216	118.8	0.1	9.0	0.61	18.0	126	48.0	8.8	20.0	0.016	3.40	3.33	10.0	38.4
Akunka	10.83933°N	0.98126°W	27.7	7.43	475	261	0.2	16.4	0.58	29.0	212	100	29.7	28.0	<0.001	0.210	2.74	12.0	61
Akunka	10.83905°N	0.98039°W	27.3	7.07	226	124	0.0	92.3	0.04	58.0	42.0	32.0	5.6	16.9	0.043	0.823	4.63	22.0	18.0
Atiyurom	10.84632°N	0.96963°W	27.4	6.89	138	76	0.0	36.5	0.17	35.0	50.0	40.0	8.8	10.9	0.010	10.1	2.93	4.0	10.5
Atiyurom	10.84550	0.96971	27.4	6.90	136	75	0.0	36.0	0.07	11.0	50.0	38.0	8.0	8.7	0.120	0.596	3.49	7.2	9.2
Akodoor	10.85211	0.95675	27.7	7.36	291	160.1	0.1	26.7	0.17	36.0	146	66.0	16.0	10.2	0.002	0.220	1.83	22.0	15.0
Akodoor	10.85019	0.95678	27.5	7.29	207	113.9	0.0	62.8	0.05	45.0	118	62.0	15.2	9.0	0.014	0.001	2.05	5.0	36.4
Akunka	10.84330°N	0.97648°W	29.0	7.91	484	266	0.2	7.2	0.23	2.0	210	68.0	35.2	37.9	0.003	0.620	2.90	30.0	58.8
Atanpela	10.85194	0.95310	28.8	7.84	117	64	0.0	146	1.04	2.5	38.0	34.0	7.2	9.0	0.088	0.810	6.33	20.0	13.4
Akamo	10.85285	0.94422	30.6	7.78	278	153	0.0	316	0.5	273.0	126	108.0	23.2	11.0	0.030	1.60	2.97	8.0	10.1
Akamo (River bed)	10.85281	0.94617	29.8	7.93	315	173.3	0.1	235	0.04	164.0	134	84.0	20.0	22.0	0.038	0.420	4.43	12.0	25.6
Akamo	10.85713	0.94133	30.5	7.25	265	146	0.0	6.73	0.34	9.0	114	86.0	14.4	10.6	0.002	0.001	1.40	20.0	17.8
Kandiga Kurigu	10.87848	0.93203	32.0	7.49	383	211	0.1	2.13	0.65	1.0	162	130	32.1	22.0	0.001	0.150	1.63	50.0	34.4
Kandiga Kurigu	10.87499	0.93318	31.1	7.84	394	217	0.1	1.83	0.38	2.0	174	102	22.4	28.0	0.001	0.001	1.79	65.0	63.0
Kandiga Kurigu	10.87673	0.93248	32.2	7.72	249	137	0.0	1.75	0.5	15.0	104	66	17.6	14.6	0.012	0.430	2.41	30.0	28.0
Kandiga Kurigu	10.88066	0.93122	32.1	7.68	219	120	0.0	12.9	0.71	14.0	98.0	82.0	18.4	10.0	0.003	0.450	2.61	34.0	20.4
Kandiga Kurigu	10.88174	0.92981	31.3	7.26	124	68	-0.1	27.9	0.85	35.0	42.0	36.0	7.2	6.6	0.013	5.30	2.97	18.0	10.0
Kandiga Kurigu	10.89130	0.93356	30.3	7.06	479	263	0.2	2.6	1.15	4.0	202	180	40.9	44.0	0.003	0.240	0.57	84.0	70.9
Kandiga Kurigu	10.89717	0.93289	29.8	6.99	201	110.6	0.0	9.5	0.52	9.0	96.0	62.0	12.0	12.0	0.002	0.360	4.37	30.0	25.0
Longoh	10.90220	0.93438	29.2	7.06	255	140	0.0	10.3	0.56	17.0	110	82.0	20.0	13.9	0.002	0.150	2.71	42.0	28.9
Longoh	10.90387	0.93433	28.8	7.19	310	171	0.1	2.8	0.22	4.0	114	88.0	19.2	25.0	<0.001	0.670	1.89	55.0	39.6
Longoh	10.90621	0.93013	31.7	7.15	211	116	0.0	10.0	0.61	8.0	96.0	50.0	9.6	6.1	0.004	0.680	2.64	30.0	25.4
Bembiise	10.90814	0.93035	29.8	7.28	322	177	0.1	17.6	0.68	12.0	150	94.0	21.6	25.2	0.012	0.675	2.51	45.0	47.2
Bembiise	10.91631	0.93195	34.0	6.78	152	84	-0.1	67.8	0.21	13.0	44.0	38.0	7.2	5.0	0.028	0.260	3.88	25.0	10.4
Bembiise	10.91349	0.93150	32.4	6.93	184	101	0.0	21.8	0.34	41.0	66.0	40.0	9.6	8.0	0.016	1.60	2.48	16.0	15.8
Bembiise	10.92323	0.93154	33.7	7.27	233	128.2	0.0	76.9	1.98	26.0	74.0	52.0	19.2	27.9	0.060	0.160	5.80	20.0	23.4
Bembiise	10.92178	0.92993	31.6	7.22	100	55	-0.1	72.3	0.08	60.0	22.0	20.0	5.6	3.0	0.021	0.820	3.16	14.0	7.8
Sirigu (River bed)	10.92818	0.92977	31.5	7.11	178	98	0.0	186	0.08	105.0	74.0	60.0	20.0	7.9	0.074	0.250	6.26	13.0	10.8
Sirigu (River bed)	10.93058	0.92845	29.6	7.26	230	126.5	0	248	0.22	163.0	112	32.0	24.0	28.0	0.050	0.660	4.17	17.0	22.9
Sirigu	10.94187	0.91811	31.5	6.73	135	74.3	-0.1	84.0	0.08	75.0	30.0	24.0	5.6	12.9	0.028	0.320	9.46	15.0	12.2
Sirigu	10.94222	0.91827	28.9	7.01	224	123	0	35.0	0.06	15.0	82.0	68.0	15.2	20.0	0.013	0.360	2.93	22.0	17.8
Sirigu (River bed)	10.94110	0.91988	29.0	6.94	159	87.5	0.0	273	0	294.0	54.0	48.0	10.4	13.0	0.024	0.310	3.19	19.0	17.3
Sirigu	10.94348	0.91739	31.6	7.00	163	90	0	157	0.13	79.0	54.0	48.0	8.8	12.9	0.085	0.230	14.3	16.0	14.0
Sirigu	10.94381	0.91662	31.6	7.02	186	102.3	0.0	122	0.02	153.0	58.0	52.0	9.6	10.0	0.015	0.270	2.09	20.0	12.3
Sirigu	10.94400	0.91655	30.0	7.02	177	97	0	66.0	1.87	82.0	48.0	40.0	11.2	8.2	0.021	0.220	4.60	25.0	15.4
Sirigu	10.94472	0.91573	30.5	6.75	184	101	0.0	92.0	0.14	118	84.0	56.0	10.4	14.0	0.020	0.210	3.42	20.0	20.2
Sirigu	10.94486	0.91653	30.5	6.90	143	79	0.0	38.0	0.21	44.0	84.0	46.0	10.4	14.2	0.016	1.50	2.15	10.0	20.1

COMMUNITY	LONGITUDE	LATITUDE	K	F	HCO3	CaH	MgH	Mg	Mn	Fe	Zn	Cu	Pb	Ni	Cd	%diff	anions	cations	diff	sum
Atankwidi	10.83321°N	0.98616°W	7.5	0.210	142	22.0	28.0	6.8	0.007	0.611	0.009	<0.020	<0.005	<0.01	<0.002	5	2.5213	2.277627	0.2437	4.7990
Atankwidi	10.83256°N	0.98403°W	3.2	0.080	12.2	16.0	14.0	3.4	0.006	0.586	0.006	<0.020	<0.005	<0.01	<0.002	-4	0.9622	1.05055	-0.0884	2.0127
Akunka	10.83493°N	0.98079°W	14.5	0.400	173	38.1	47.9	11.6	0.013	0.099	0.007	<0.020	<0.005	<0.01	<0.002	3	3.5980	3.414329	0.1837	7.0123
Akunka	10.83646°N	0.98079°W	15.7	0.270	154	22.0	26.0	6.3	0.013	0.743	0.011	<0.020	<0.005	<0.01	<0.002	5	3.3468	3.029081	0.3177	6.3759
Akunka	10.83933°N	0.98126°W	11.8	0.520	259	74.3	25.7	6.2	0.018	0.150	0.016	<0.020	<0.005	<0.01	<0.002	3	5.2823	4.947144	0.3352	10.2295
Akunka	10.83905°N	0.98039°W	9.4	0.030	51.2	14.0	18.0	4.4	0.025	2.640	0.018	<0.020	<0.005	<0.01	<0.002	4	1.7881	1.664654	0.1235	3.4528
Atiyurom	10.84632°N	0.96963°W	5.7	0.040	61.0	22.0	18.0	4.4	0.025	0.604	0.018	<0.020	<0.005	<0.01	<0.002	5	1.5535	1.403475	0.1500	2.9570
Atiyurom	10.84550	0.96971	4.6	0.140	61.0	20.0	18.0	4.4	0.070	1.430	0.010	<0.020	<0.005	<0.01	<0.002	5	1.4048	1.278878	0.1259	2.6837
Akodoor	10.85211	0.95675	2.6	0.240	178	40.1	15.9	3.9	0.057	0.218	0.010	<0.020	<0.005	<0.01	<0.002	-2	1.7493	1.838118	-0.0888	3.5875
Akodoor	10.85019	0.95678	12.4	0.500	144	38.0	27.0	6.6	0.160	1.430	0.017	<0.020	<0.005	<0.01	<0.002	1	3.2774	3.201732	0.0757	6.4792
Akunka	10.84330°N	0.97648°W	25.3	0.650	256	72.0	18.0	4.4	0.007	0.125	0.010	<0.020	<0.005	<0.01	<0.002	5	5.9032	5.323057	0.5801	11.2262
Atanpela	10.85194	0.95310	5.7	<0.005	46.4	18.0	16.0	3.9	0.005	4.440	0.018	<0.020	<0.005	<0.01	<0.002	1	1.4434	1.408665	0.0347	2.8521
Akamo	10.85285	0.94422	5.6	0.550	154	58.1	49.9	12.1	0.045	5.610	0.062	<0.020	<0.005	<0.01	<0.002	5	3.0222	2.735326	0.2869	5.7576
Akamo (River b	10.85281	0.94617	16.8	0.260	183	50.0	34.0	8.3	0.022	2.160	0.014	<0.020	<0.005	<0.01	<0.002	5	3.5568	3.223768	0.3330	6.7806
Akamo	10.85713	0.94133	10.1	0.420	139	36.1	49.9	12.1	0.012	0.021	0.010	<0.020	<0.005	<0.01	<0.002	4	2.9952	2.746221	0.2489	5.7414
Kandiga Kurigu	10.87848	0.93203	12.6	0.560	198	80.2	49.9	12.1	0.029	0.028	0.013	<0.020	<0.005	<0.01	<0.002	5	4.9039	4.415476	0.4884	9.3193
Kandiga Kurigu	10.87499	0.93318	12.6	0.430	212	56.1	45.9	11.2	0.019	0.042	0.006	<0.020	<0.005	<0.01	<0.002	5	5.6231	5.10153	0.5216	10.7246
Kandiga Kurigu	10.87673	0.93248	13.0	0.320	127	44.1	21.9	5.3	0.023	0.544	0.016	<0.020	<0.005	<0.01	<0.002	4	3.1233	2.864522	0.2587	5.9878
Kandiga Kurigu	10.88066	0.93122	10.5	0.390	120	46.1	35.1	8.7	<0.005	0.083	0.016	<0.020	<0.005	<0.01	<0.002	3	2.9572	2.789533	0.1676	5.7467
Kandiga Kurigu	10.88174	0.92981	7.4	0.200	51.2	18.0	18.0	4.4	<0.005	0.426	0.027	<0.020	<0.005	<0.01	<0.002	5	1.4864	1.345354	0.1411	2.8318
Kandiga Kurigu	10.89130	0.93356	3.0	0.550	246	102.0	77.8	18.9	0.257	0.167	<0.005	<0.020	<0.005	<0.01	<0.002	2	7.0340	6.756106	0.2779	13.7901
Kandiga Kurigu	10.89717	0.93289	11.3	0.380	117	30.1	31.9	7.8	0.486	0.959	0.008	<0.020	<0.005	<0.01	<0.002	5	2.8888	2.616713	0.2721	5.5055
Longoh	10.90220	0.93438	12.6	0.450	134	50.1	31.9	7.8	0.438	0.808	0.010	<0.020	<0.005	<0.01	<0.002	4	3.4689	3.218804	0.2501	6.6877
Longoh	10.90387	0.93433	11.2	0.420	139	48.1	39.9	9.7	0.014	0.242	<0.005	<0.020	<0.005	<0.01	<0.002	5	4.1412	3.764792	0.3764	7.9060
Longoh	10.90621	0.93013	14.7	0.630	117	24.0	26.0	6.3	0.508	0.822	0.021	<0.020	<0.005	<0.01	<0.002	5	2.7275	2.477931	0.2496	5.2055
Bembiise	10.90814	0.93035	15.4	0.310	183	54.1	39.9	9.7	0.035	1.02	0.010	<0.020	<0.005	<0.01	<0.002	4	4.6585	4.322546	0.3360	8.9810
Bembiise	10.91631	0.93195	7.2	0.140	53.7	18.0	20.0	4.9	0.051	0.687	0.016	<0.020	<0.005	<0.01	<0.002	5	1.5458	1.39876	0.1470	2.9446
Bembiise	10.91349	0.93150	9.0	0.320	80.5	24.0	16.0	3.9	0.135	2.44	0.008	<0.020	<0.005	<0.01	<0.002	5	1.9045	1.717206	0.1873	3.6217
Bembiise	10.92323	0.93154	14.8	0.030	90.3	38.1	3.9	0.9	0.085	6.82	0.025	<0.020	<0.005	<0.01	<0.002	5	2.6859	2.428432	0.2575	5.1144
Bembiise	10.92178	0.92993	1.4	0.150	26.8	14.0	6.0	1.5	0.011	2.61	0.011	<0.020	<0.005	<0.01	<0.002	3	0.8294	0.777898	0.0515	1.6073
Sirigu (River be	10.92818	0.92977	4.2	<0.005	90.3	50.1	9.9	2.4	0.058	11.7	0.024	<0.020	<0.005	<0.01	<0.002	5	1.9774	1.77257	0.2048	3.7499
Sirigu (River be	10.93058	0.92845	17.5	<0.005	137	60.1	21.9	5.3	0.054	7.26	0.012	<0.020	<0.005	<0.01	<0.002	5	3.3942	3.077097	0.3171	6.4713
Sirigu	10.94187	0.91811	6.5	0.130	36.6	14.0	10.0	2.4	0.026	2.85	0.005	<0.020	<0.005	<0.01	<0.002	4	1.2814	1.173721	0.1077	2.4551
Sirigu	10.94222	0.91827	10.8	0.420	100	38.1	29.9	7.3	0.318	2.65	0.023	<0.020	<0.005	<0.01	<0.002	5	2.6679	2.409288	0.2586	5.0772
Sirigu (River be	10.94110	0.91988	2.3	0.090	65.9	26.1	21.9	5.3	0.040	2.97	0.013	<0.020	<0.005	<0.01	<0.002	2	1.8473	1.766193	0.0811	3.6135
Sirigu	10.94348	0.91739	3.3	<0.005	65.9	22.0	26.0	6.3	0.040	13.1	0.031	<0.020	<0.005	<0.01	<0.002	4	1.7807	1.650613	0.1301	3.4313
Sirigu	10.94381	0.91662	4.3	0.530	70.8	24.0	28.0	6.8	0.034	1.23	<0.005	<0.020	<0.005	<0.01	<0.002	5	1.8628	1.683273	0.1795	3.5461
Sirigu	10.94400	0.91655	11.1	0.410	58.6	28.1	11.9	2.9	0.645	3.22	0.018	<0.020	<0.005	<0.01	<0.002	-1	1.7154	1.751103	-0.0357	3.4665
Sirigu	10.94472	0.91573	11.4	0.510	102	26.1	29.9	7.3	0.600	4.32	0.007	<0.020	<0.005	<0.01	<0.002	4	2.4946	2.28951	0.2051	4.7841
Sirigu	10.94486	0.91653	11.5	0.180	102	26.1	19.9	4.8	0.141	2.09	0.009	<0.020	<0.005	<0.01	<0.002	5	2.3127	2.082117	0.2306	4.3948