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Hydrogeological Framework and Groundwater Recharge Estimation in the Tongo District of the Upper East Region of Ghana

By

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DECLARATION

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

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ABSTRACT

Surface water in most parts of the UER faces two challenges. The resource is mostly inadequate due to frequent failure and the uneven distribution of rainfall and sometimes also polluted due to anthropogenic activities. This situation has brought about the use of groundwater as a more reliable alternative for both domestic and agriculture purposes. The current reliance on groundwater has brought about a decline in the resource due to over abstraction from aquifers within the region which may potentially lead to depletion and give way to ecological challenges. There is therefore the need for good management of the aquifer by giving much consideration to its recharge areas and water sources. This study was conducted to assess the hydraulic conductivity and transmissivity characteristics of the soil overlying the aquifer in the Tongo district. This study also estimated the aquifer's geometry and the physio-chemical parameters of both surface water and groundwater in the area. The hydraulic conductivities estimated ranged between 0.54 m/d and 1.53 m/d indicating that the aquifer is an unconsolidated sedimentary soil. Analysis of grain-size distribution showed the overlying to be predominantly medium sand. The soil's transmissivities ranged between 1.82 m^2/d and 22.2 m^2/d. Even though the physico-chemical parameters indicate that the water in the aquifer is of good quality, the low soil transmissivity values suggests that not much water can be abstracted from the aquifer for local water supply. The geometry of the aquifer system within the region was delineated using the inverse distance weighting technique. The technique estimated that, depth to water table ranged between 0.6 and 23.7 m, and depth to bedrock between 4.5 and 40.8 m. The saturated aquifer thickness also ranged between 0.3 and 49.5 m. These parameters suggest that the aquifer is indeed shallow and can be susceptible to pollution.

Estimation of the aquifer recharge using the chloride mass balance method established a mean recharge rate of 109.3 mm/yr which suggests that only about 11% of precipitation in the area recharges the aquifer. This study recommends a long-term monitoring plan for early detection of groundwater contamination and aid to define the aquifer's geometry extensively. It is again recommends for communities to construct more open wells to recive direct recharge as well as ensuring good agricultural and sanitation practices to avoid groundwater pollution.

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CHAPTER 1: INTRODUCTION

1.1 Background

Water resources in Ghana contribute immensely in promoting quality livings standards and economic growth. They form a key role in ensuring food security and livelihood in mitigating poverty in the country. With the increasing population growth rate, Ghana is experiencing increasing demand for food production. The climate change influence in semi-arid areas are highly significant when compared to humid areas. Such conditions increases the stress on the available water resource which could affect the safety and sustenance of the environment in the possible future. Montoroi *et al.* (1999) indicated that global population expansion in the last century has created a massive dependency on water resources worldwide. Water harvesting techniques are seen as a safe measure to supply water for both food and agricultural production as a means in dealing with problems associated with varying rainfall and increasing population densities. A widely developed technique of water harvesting is the large catchment water harvesting where surface water is dammed and stored temporarily or permanently for use or as recharge for the groundwater resource.

The development of dams in Ghana has been part of the rural economic strategies to improve standards of living in such areas of the country. They are to offer a much reliable source of water and give a lifeline to rural communities in the semi-arid regions of the country, during the dry season. This for instance has seen the construction of 240 earth dams and dug-outs in northern Ghana (Acheampong *et al*. 2014) primarily to provide water for livestock and domestic uses. These dams and dug-out also are to mitigate recurrent drought impacts and serve as soil and water conservation measures in the region. Such an approach was presumed to be technically and politically attractive given that it had the capacity to hasten economic and social development through provision and supply of adequate water for domestic uses, irrigation and hydropower generation (Biswas and Tortojada, 2001).

The complexity of the natural existence of water (particularly surface water) and its current likelihood impacts from climate change makes groundwater the most reliable water source at all times for various users. In the sub-Saharan regions of Africa, groundwater is seen as a vital resource in the provision of potable water for domestic uses, watering of animals and dry season farming. Braune and Xu in 2010 estimated that these sub-regions reliance on groundwater for daily livelihood is about 50%. In Ghana, groundwater also continues to be the major supply source of potable water in both rural and peri-urban settlements. Surface water forms a fundamental part of groundwater flow systems in that they relate in almost all sceneries i.e from wetlands, lakes and small streams to main river valleys to seacoasts.

The groundwater resource has been a major source of water which has been exploited since the beginning of time with an estimate of about 700 billion m^3 mined yearly across all countries. Likewise in Ghana, groundwater is a major source for both rural and small towns' water supply schemes in Ghana. Gyau-Boakye and Dapaah-Siakwan cited in 2000 that the groundwater resource in rural settlements is an achievable and economical source of potable drinking water. The growing importance of groundwater and its rate of abstraction in Ghana makes it a necessity, to manage and improve the hydrologic cycle as a sub-system discreetly. There is the need to understand and identify the sources of recharge for a viable long-term groundwater development. The resource is easily within reach and does not necessitate major pipeline networking nor requires higher pumping, treatment and energy costs.

In comparing groundwater to surface water, the resource has a steady storage system that act as a buffer for regular discharge through springs and irregular rainfall which compensates for climatic variations such as drought by ensuring water supply during such periods. Groundwater is also better protected from massive pollution compared with surface water due to the presence of protective surficial geological formations with respect to the aquifer's depth and the filtering capacity.

The movement of both surface and groundwater is controlled largely by the topography and geological framework of the area. The general consideration is that high ground areas are considered as groundwater recharge areas whilst the low ground areas are groundwater discharge areas. Polluting one of resource affects the other because of the interchange of water between these two components of the hydrologic system (Sophocleous, 2002). The sources of water to and from the earth's surface in the water cycle are controlled by climate and thus requires some knowledge on the effects of both the climate and physiography on the movement of groundwater in order to understand the relations between surface water and groundwater systems.

1.2 Problem Statement

Gyau-Boakye and Dapaah-Siakwan in 2000 reported that rural settlements traditionally rely on surface water directly from rivers, lakes, streams, ponds and dugouts which are usually polluted by natural occurrences (e.g. sediment pollution) and anthropogenic activities which mostly result in water-borne diseases. . The resource is mostly inadequate due to frequent failure and the uneven distribution of rainfall and is becoming a threat to sustenance of life in the Upper East region. As an alternative to surface water, groundwater has become a more reliable source of water. The current reliance on groundwater for both domestic and agricultural activities in the region has brought about a decline in the resource as observed by Gyau-Boakye *et al,* 2000. Gyau-Boakye *et al*, 2000 and Subyani, 2004 cited that over abstraction of groundwater could cause significant water table decline which could cause increase in groundwater salinity, desertification of grazing and agricultural lands which may eventually lead to people migrating to major cities when the aquifer is depleted.

There is therefore the need for good management of the aquifer to improve sustainability of the resource for both domestic and agricultural use to improve the socio-economic developments in the region.

1.3 Justification

Rainfall in Upper East region has one modal season beginning from July and ending in September. The duration of rainfall within the period is often short and preceded by heavy rainstorms (Anayah and Kaluarachchi, 2009). These rains often exceed the soil's infiltration rates and causes surface runoff, without adequately replenishing moisture and groundwater (Liebe *et al*. 2005). These runoffs generate into transient and intermittent streams which are retained into man-made reservoirs for usage and further recharge of the aquifer. Most of the smaller reservoirs dry up and defeat the purpose of surface water storage during these dry spells. The lack of regular rainfall coupled with increasing economic growth in the region has led to the over-abstraction of the groundwater resource for sustenance which could cause a significant decline in water table and increase in groundwater salinity (Gyau-Boakye & Dapaah-Siakwan 2000; Subyani 2004).

The evaluation and management of groundwater resources for any use require an understanding of its occurrence and recharge. Knowledge about the aquifer's geometry and the overburden soil's characteristics such as the hydraulic conductivity and transmissivity should be known to ascertain or describe the aquifer's ability to transmit water into and out of the aquifer zone. It gives better insight to predict groundwater availability to develop the local and regional water plans in the future.

Therefore quality of groundwater, the source of recharge, flow path and quantity of groundwater which can be abstracted for socio-economic development must be known and documented for further studies.

1.4 Objectives

The main objective of this study is to estimate groundwater recharge and define the hydrogeological framework in the Tongo district.

The specific objectives are to:

- Estimate the hydraulic conductivity and transmissivity of the aquifer.
- Determine the aquifer geometry in the study area.
- Estimate groundwater recharge using the chloride mass balance method.

1.5 Scope of Work

The study seeks to investigate the hydrogeological framework and estimate groundwater recharge in the Tongo District of the Upper East Region of Ghana

CHAPTER 2: LITERATURE REVIEW

This chapter give the relevant literature review pertaining to the research to be carried out. This constitutes aquifer recharge, groundwater movement and evapotranspiration in semiarid areas, hydrogeological framework of Ghana, aquifer sections in Upper East region and groundwater use in the study area.

2.1 Hydrogeological Framework of Ghana

The hydrogeological regions in Ghana have characteristics similar to the local geological conditions due to its climatic zone. (Barnie *et al*. 2014)

The geological framework of Ghana has been convened into three broad geological units.

❖ The Precambrian Crystalline Basement Complex rocks

They underlie about 54% of the country's geological formation and are in a fairly heterogeneous environment. There are five (5) hydrogeological sub-divisions for the crystalline basement complex formations which are described in the table below.

Table 2.1 Hydrogeological sub-divisions of Precambrian Crystalline Complex rocks (Kankam-Yeboah *et al*, 2003)

Sub-division	Geology	Borehole yield range, m^3/h
Birimian system	They mostly constitute gneisses, granitic-gneiss, migmatites, phyllites, quartzites and schists.	0.4 – 30

Dahomeyan system	• They mostly constitute crystalline gneiss and migmatite. • The minor components consists of biotite schists and quartz.	1 – 3
Tarkwaian system	• They mostly constitute marginally metamorphosed shallow-water sedimentary strata; which mainly comprise conglomerate, shale, sandstone and quartzite.	0.7 – 24
	• They mostly constitute folded and metamorphosed arenaceous and argillaceous sedimentary strata; which comprise of indurated sandstone, schist, shale, phyllite and quartzite.	0.7 – 24
Togo series Buem formation	• They mostly constitute a thick sequence of sandstone, shale and some minor volcanic rock with conglomerate, grit and subordinate limestone.	0.7 – 24

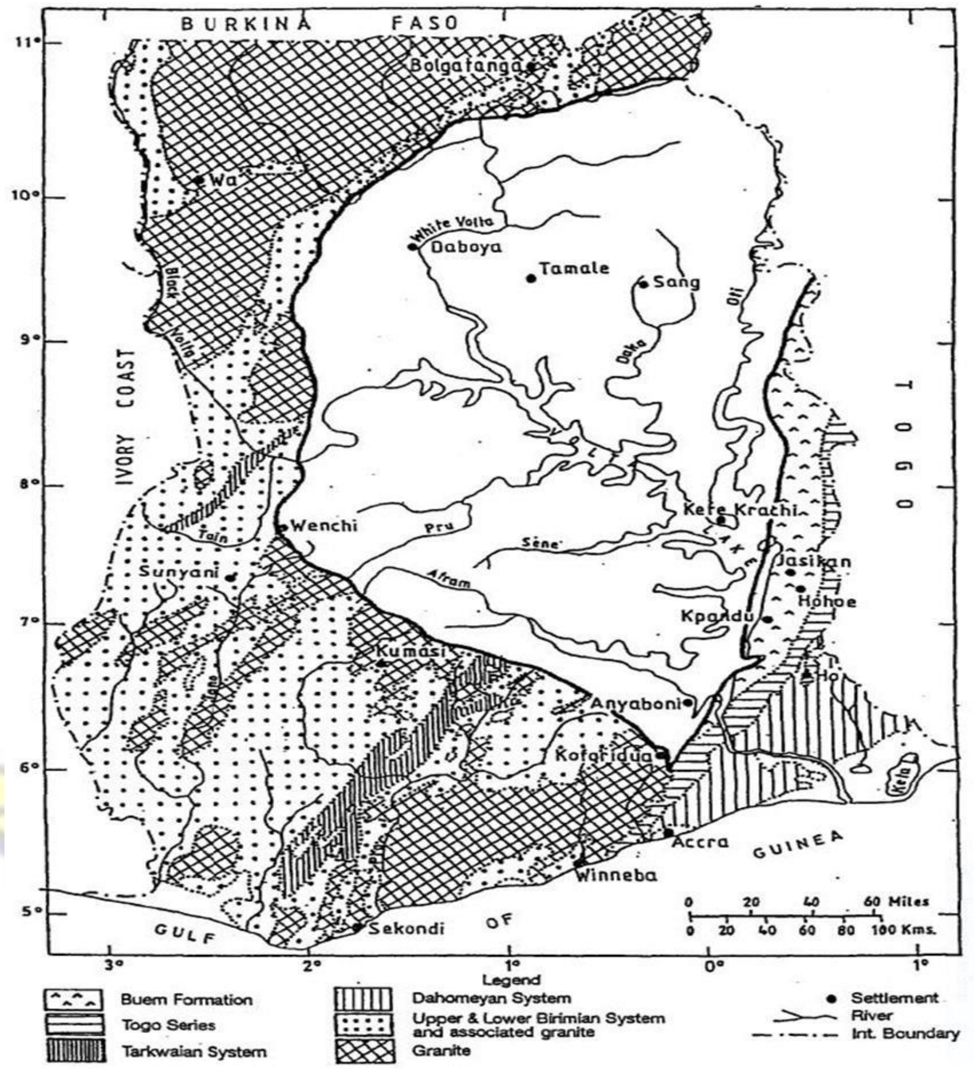

Figure 2.1 Hydrogeological sub-provinces of Ghana (Kankam-Yeboah *et al*, 2003)

❖ The Paleozoic consolidated sedimentary rocks.

They underlie about 45% of the country's geological formation and are in a considerably heterogeneous environment as well. These are the Voltaian formations which constitute gently folded rocks and well-consolidated rocks largely of arkose, limestone, sandstone, sandy and pebbly-beds shale, mudstone which have borehole yields ranging between 0.40 – 9.0 m^3/hr.

The minor minor geological provinces underlie about 1% of the country's geological formation and consists of Cenozoic/Mesozoic sedimentary strata and Quaternary alluvia (Table 2.2). These formations are found along narrow belts of major rivers and the coasts.

Table 2.2 Two minor geological provinces

Sub-division	Geology	Borehole yield range, m^3/h
Cretaceous to Lower Tertiary sedimentary rocks (found in the Tano Basin)	Consists of thick sections of alternating clay and sand with sporadic thin beds of gravel and fossiliferous limestone.	1 – 15
Tertiary to Eocene and Cretaceous unconsolidated alluvial sediments (found in the Keta Basin)	Consists of alternating limonitic sand, limestones, marine shales, sandy-clay and gravel.	10 – 32

The varied range of geological formations in Ghana has resulted into the variation rise of groundwater resources potential in reference to its occurrence, distribution, recharge, yield and other hydrogeological features. Abstraction of large amounts of groundwater from these aquifers within Ghana keeps increasing, therefore there is the need to undertake an in-depth recharge studies to estimate the amount of water that recharges these aquifers for groundwater sustainability for current and future use. Modelling of these aquifers will help to estimate the safe yield and to monitor pollution levels of the aquifers from the recharge areas.

2.2 Groundwater Development and Use in Northern Ghana

Groundwater use in Ghana is predominant where communities rely on simple unlined hand dug wells and boreholes to mine the resource. Gyau-Boakye and Dapaah-Siakwan (2000) indicates that, groundwater is the most economical and feasible source of potable drinking water in a rural areas given the dispersed nature of their settlements. The locations of the wells are determined using the trial-and-error method, hence water availability of previous years are important. Farmers also take into account the elevation of the area and moisture 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 begins from late September to late October with farmers 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 with reasons that animals could fall in, the rainy season erodes the area close to the well (which can cause 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 600 to 900 mm 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.

2.3 Groundwater Recharge and Estimation

Freeze and Cherry (1979) defined recharge as the entry of water available at the water table surface into the saturated zone, together with the allied flow away from the water table within the saturated zone. It is the process by which groundwater is replenished. Groundwater can be recharged both by precipitation and or surface water sources such as rivers and lakes infiltrating into the soil and rock layers of the ground (Bhattacharya *et al.*, 2003). Groundwater recharge can also be described as a hydrologic process which is an infinite transmission of water in various phases through the atmosphere, over and through land, to the ocean, and back to the atmosphere according to Sophocleous (2004).

Sophocleous adds that precipitation is brought into streams by land surface as overland flow into channels and tributaries, and in the subsurface as interflow and base flow ensuing from infiltration into the soil (Sophocleous, 2004). Ng *et al*, (2009) established that the prime controls on recharge which are soil properties, topography, vegetation and meteorology interrelate to create the unique conditions that result in recharge. De Vries and Simmers (2002), categorized recharge originating from precipitation as direct or diffused which infiltrates vertically from the land surface directly into the water table. In divergence, the indirect or localized recharge moves laterally on or near the land surface and eventually ends up in streams or topographic depressions before infiltration occurs. Both the diffused and localized recharge often travels as partisan flow through cracks or root tubules rather than exclusively through the soil matrix which makes it especially difficult to predict. Understanding of the movement of moisture downwards by precipitation and upward by evapotranspiration and root uptake is very relevant in groundwater recharge. (Ng *et al*, 2009). Groundwater recharge identification and quantity is very critical in its managements.

The rate of aquifer recharge is a most important factor in analysing and managing of groundwater resources in both arid and semi-arid area. Recharges in both these regions are difficult to estimate due to the vast variability of hydrogeological events in time and space. Recharge estimation in both areas again can be challenging given that such areas have generally low recharge when being related to the average annual rainfall or evapotranspiration, and makes it difficult to accurately quantify (Scanlon and Cook, 2002; Beekman *et al.*, 1996). Potential evapotranspiration surpasses average precipitation and indicates that recharge of groundwater is only in certain conditions since recharges are sporadic rather than continuous in such areas (Kinzelbach *et al*., 2002). Different methods such as water-balance techniques, empirical approaches, tracer techniques and Darcy's law in unsaturated zones along with other methods which depend highly on field situations and available data (Lerner *et al*., 1990; Edmunds *et al*., 2002), have been applied to estimate groundwater recharge. Commonly used methods are the chloride mass balance and environmental isotopes in water resource development and management (Subyani, 2004). Literature reviews done on recharge estimation methods used in a number of southern African countries by Beekman and Xu (2003) indicates that the chloride mass balance method is one of the methods often used with high accuracy in these regions. Numerical models are very useful in groundwater recharge estimation but many studies have cautioned against its application in semi-arid environment (Allison *et. al.*, 1994; Gee and Hillel, 1998). Direct recharge rates in these environments can be minute relative to both precipitation and evaporation given that they are very subtle to uncertain model parameterizations and input errors. The tracer-based recharge methods are preferable according to Allison *et al*. (1994) and, Gee and Hillel (1988) in the semi-arid areas. Natural tracers like meteoric chloride are mostly popular due to their permeating availability and increased sensitivity at lower recharge rates (Ng *et al*., 2009). The accuracy in quantifying the recharge rates is imperious to apt management and protection of the groundwater resources which is valuable. For proper management systems, the aquifer's recharge cannot easily be measured directly but rather estimated by indirect means (Lerner *et. al.*, 1990). The indirect estimation's accuracy is also not particularly difficult to determine, hence it is commended that such recharges should be estimated with multiple methods to obtain more unswerving values (Scanlon and Cook, 2002).

Recharge processes differ from one area to the other and gives no certain assurance that a method developed and used for one area will yield similar results for a different area. There is always the need to identify the feasible flow mechanisms and the imperative features influencing the potential area recharge prior to selecting a recharge method to use (Lerner *et al*, 1990). There exist a wide range of methods for estimating recharge and which can be classified per their hydro-geological provinces, hydrologic zones and their numeric modelling, physical, and tracer techniques. (Lerner *et al.*, 1990; Beekman *et al*, 1996, Scanlon and Cook, 2002). The hydrological zones are further classified by Scanlon and Cook (2002) into three zones as saturated zone, unsaturated zone and surface water. Each of these zones provides a perculiar set of data in estimating the groundwater recharge. The table below gives the common recharge techniques used and how they are categorized.

Table 2.3 Common aquifer recharge techniques

Category	Method
Direct Measurements	Lysimeters Soil moisture budget by neutron probe (TDR probes)
Water Balance and Hydrograph Methods	Soil moisture budgets River channel water balance Water table rise method River baseflow method Spring or river flow recession curves Rainfall-recharge relationships

	Cumulative Rainfall Departure Method
Darcyan Methods	Numerical flow model Saturated Zone Darcy law based on pumping tests and head measurements Unsaturated zone Darcy law based on measurements of matrix potential Unsaturated Zone: Solving Richards' equation
Tracer Methods	Bromide in unsaturated zone Carbon 14 Chloride method Chloride 36 in unsaturated zone (from fallout) New gas tracers CFC and SF_6 Stable isotopes D, ^{18}O Tritium method Tritium-Helium 3 method
Other Relevant Methods	Measuring evaporation fluxes (aerially, single trees) Remote sensing methods for indicators

Allison *et al* (1994) indicated that indirect physical approaches like the water balance method and Darcy flux measurements yield least successful results and add that employing the tracer methods such as Cl, ^{3}H and ^{36}Cl yield very successful result in estimating groundwater recharge in semi-arid areas. They added that chloride balance technique was the least expensive and much more universal for recharge estimation in comparison to other tracer methods available. To achieve proper management and adequate protection of the groundwater resource, there is the vital need for accurate quantification of the rate of recharge into the aquifer system.

2.3.1 Chloride Mass Balance

The chloride mass balance method was initially brought forward by Eriksson and Khunakasem (1969). The method bases on the mass conservation to estimate groundwater recharge. Chloride mass balance analysis works on the assumption that atmospheric chloride is the only significant source of chloride in groundwater. The approach also bases on the link between chloride in precipitation and chloride in groundwater. Dettinger in 1989 cited that conceptually, the chloride mass balance approach may be considered as occurring in the vadose zone of the soil where direct evaporation and plant transpiration can occur. Precipitation which contains chloride as a result of wet-fall thus chloride absorbed as a result of falling precipitation from the atmosphere and dry-fall which is the chloride deposits in the atmosphere kept on the land surface between precipitation events provides the water and chloride input to the balance zone.

The chloride mass balance method has been very reliable in the estimation of paleoclimate recharge rate dating back thousands of years (Murphy *et al*., 1996; Tyler *et al*., 1996). It has also been used in determining modern recharge rates particularly those with increased response changes to land-use with altered and deep-rooted trees vegetation rather than shallow-rooted grasses. The chloride mass balance is a direct method of calculating the mass flux of water reaching the water table which considers four parameters of chloride contents in precipitation (C_p), groundwater (C_{gw}), surface run-off (C_{sw}) and evapotranspiration (C_{et}).

The main pathway of water removal from the water balance zone is either through evapotranspiration, recharge and or surface runoff. Runoff is anticipated to occur at the ground surface and is probable to remove chloride away from the balance zone at almost the same concentration anticipated as present in precipitation (Mizell *et al.*, 2007). The evapotranspiration process only removes water and not chloride from the balance zone hence chloride concentrations in the recharge water must increase to preserve the chloride mass balance. The chloride mass balance method can be expressed mathematically as;

$$PC_P = RC_{gw} + SC_{sw} + ETC_{et} \tag{2.1}$$

Where:
P = Precipitation volume
R = Recharge volume
S = Surface runoff volume
ET = Evaporation and transpiration losses
Cp = Chloride concentration in precipitation
Cgw = Chloride concentration in groundwater
Csw = Chloride concentration in surface runoff
Cet = Chloride concentration in ET

Surface runoff is often neglected mainly due to lack of inadequate information on the runoff and also because most runoff from precipitation are not expected to reach beyond the area of groundwater recharge. Surface runoff does not remove chloride from the recharge area under normal runoff conditions but rather has the certainty to redistribute the chloride in the recharge area. Some estimated estimates of surface runoff can be determined from impounded water or reservoirs based on the knowledge about reservoir storage and evaporation index pertaining to the study area. Mizell *et al.,* (2007) stated that the magnitude and chemistry of the surface runoff if quantifiable can be used to estimate the surface runoff component of the equation above. Evapotranspiration removes water without the dissolved constituents hence the term ETC_{et} equals zero. Applying all these conditions, we deduce that recharge, R:

$$R = P\left(\frac{C_p}{C_{gw}}\right) \tag{2.2}$$

In the equation, the ratio Cgw/Cp describes the enrichment of chloride in groundwater related to chloride in precipitation. As a first approximation of groundwater recharge, the equation will result in a larger estimate than would be the case if surface runoff were quantified and included in the calculation. The chloride mass balance analysis attempts to indicate, qualitatively, the impact of this uncertainty by providing a range of recharge estimates based on a reasonable range for chloride in precipitation and extent of the contributing area.

The chloride mass balance method again assumes that there is no other source of chloride in groundwater beside precipitation for a good estimation of groundwater recharge. Even though weathering products from minerals and reworked sediments can make a significant contribution of chloride concentration in groundwater it was neglected in this study. Sampling for hand-dug wells and boreholes were done in granite and the weathered zone, where chloride is not known to be a major mineral (Yidana and Koffie, 2013). Also, chloride concentration as a result of sea-water intrusion is also neglected because the study area is far from the sea or ocean. The assumption that precipitation is the sole source of recharge is not a perceived challenge given that the study areas had little irrigation activity. This infers that the use of chemical fertilizer and other agricultural chemicals on farms is expected to be on a lower side. Owing to this reason, the contribution of chloride concentration from these sources may not have any significant influence on the groundwater.

2.3.2 Water Table Fluctuation

The water table is the surface in the soil at which the water pressure head is equal to the atmospheric pressure. It may be conveniently visualized as the 'surface' of the subsurface materials that are saturated with groundwater in a given area (Sophocleous, 2004). Waterlevel monitoring is an essential component of field studies associated with the analysis of artificial recharge. Sophocleous (2004) again cited that the main techniques used to estimate ground water recharge rates can be divided into physical methods and chemical methods (Foster, 1988). Among the physical methods, the water table fluctuation technique links the change in ground water storage with the resulting water table fluctuations through the specific yield in unconfined aquifer. This method is considered to be one of the most promising and attractive due to its accuracy, ease of use and low cost of application in semiarid areas according to Beekman and Xu (2003). Water-level fluctuations mainly result from a wide variety of hydrologic phenomenon caused either by natural and/or by anthropogenic means. The water table fluctuation method is among the most widely-applied methods for estimating recharge rates given the abundance of available groundwater-level data and the simplicity of estimating recharge rates from temporal fluctuations or spatial patterns of groundwater levels. The method requires information on specific yield and changes in water levels over time to be applied. The method, based on the assumption that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table and is best applied to aquifer systems with shallow groundwater levels showing quick responses to precipitation events (Scanlon and Cook, 2002). Water table fluctuations were used to estimate recharge from the waterlevel rise in a well multiplied by the specific yield of the aquifer (Rasmussen and Andreasen, 1959). Recharge is determined as:

$$R = S_y \times \frac{dh}{dt} \tag{2.3}$$

Where:
R = Recharge from precipitation (mm/yr)
Sy = Specific Yield dh = Annual rise in
Water Table (mm)
dt = Period of time of Annual Rise (yr)

This method actually measures the effect of recharge at the water table and should provide estimates that correspond closely to the definition of recharge. Albeit this, the appropriate value of specific yield must be known to translate the measured water-level fluctuations into estimates of recharge. Specific yield denoted as Sy, is defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of an aquifer, per unit decline in the water table (Freeze and Cherry, 1979).

The specific yield of an aquifer can either be determined using laboratory methods or aquifer test approach. The laboratory method determines specific yield base on porosity and specific retention (Johnson, 1967). Values of Sy and transmissivity (T), for unconfined aquifers are commonly obtained from the analysis of aquifer tests conducted over a period of hours or days. Drawdown- versus-time data from observation wells are matched against theoretical type curves developed using the aquifer test approach (Neuman, 1972). Specific yield of an aquifer varies with texture of aquifer materials as shown below.

Table 2.4 Statistics on specific yield from 17 studies (compiled by Johnson, 1967)

Texture	**Av. Sy**	**Coefficient of variation (%)**	**Min. Sy**	**Max. Sy**	**No. of determinations**
Clay	0.02	59	0	0.05	15
Silt	0.08	60	0.03	0.19	16
Sandy clay	0.07	44	0.03	0.12	12
Fine sand	0.21	32	0.1	0.28	17
Medium sand	0.26	18	0.15	0.32	17
Coarse sand	0.27	18	0.2	0.35	17
Gravelly sand	0.25	21	0.2	0.35	15
Fine gravel	0.25	18	0.21	0.35	17
Medium gravel	0.23	14	0.13	0.26	14
Coarse gravel	0.22	20	0.12	0.26	13

Shirahatti *et al.*, (2012) cited some challenges with application of the method. They related to determining a representative value for specific yield and ensuring that fluctuating in water levels are due to recharge and are not the result of changes in atmospheric pressure, or the presence of entrapped air, or other phenomena (such as pumping). Healy and Cooks (2002) also indicated that this method for groundwater estimation has its own limitation and stated that:

- The water table fluctuation method is ideal for shallow water table systems that indicate sharp water-level rises and decline. Deep aquifers may not display sharp rises because wetting fronts tend to disperse over long distances. The method could also be applicable to systems with thick unsaturated zones that display only seasonal water level fluctuations.
- The wells should be located such that the monitored water levels are representative of the catchment as a whole given that recharge rates vary substantially within a basin, owing to differences in elevation, geology, land surface slope, vegetation, and other factors.
- Method does not account for a steady rate of recharge thus for a constant rate of recharge equal to the rate of drainage away from the water table, the water levels would not change and the water table fluctuation method would predict no recharge.
- Some other difficulties with identifying the cause of water-level fluctuations and the calculation of a value for specific yield (Beekman and Xu, 2003).

2.4 Aquifer Characteristics

Aquifers generally have characteristics that control groundwater occurrence with respect to storage, movement and yield. They characterise the basic ability of an aquifer's recharge and discharge at a given time under prevailing conditions. The hydraulic and hydrogeological quantities used to characterize aquifers include;

- Capillarity
- Capillary fringe
- Discharge velocity
- Drawdown
- Groundwater velocity
- Hydraulic conductivity
- Hydraulic head
- Permeability
- Porosity
- Transmissivity

Hydraulic conductivity can be defined as the rate of discharge of water under laminar flow conditions through a unit cross-sectional area of porous medium under a unit hydraulic gradient and standard temperature conditions. The main aquifer hydraulic characteristics are the horizontal hydraulic conductivity, vertical hydraulic conductivity and specific storage (storage coefficient). Field testing procedures are mostly based on the vertical well methods which are the pumping, slug, pressure pulse and constant injection tests. The pumping test which comprises the withdrawal of groundwater at a constant rate from one well and observing the temporal variation of the water level in the pumping well and the nearby observation well. Transmissivity refers to the rate at which groundwater flows horizontally through a unit width of an aquifer under a unit hydraulic gradient. It is often expressed as the product of the hydraulic conductivity and the full saturated thickness of the aquifer which is expressed as m^3/day/m.

Both the hydraulic conductivity and transmissivity describe the aquifer's ability to transmit water into and out of the aquifer zone and gives better insight to predict groundwater availability to develop local and regional water plans in the future. Todd and Mays (2005) outlined techniques including field methods such as pumping test of wells, laboratory methods and the use of empirical formulae to determine some aquifer characteristics. However an accurate estimation of hydraulic conductivity using the field methods is limited due to inadequate knowledge of the aquifer's hydraulic boundaries and geometry (Uma *et al*. 1989). The financial implication the field methods in lieu of procedures and their related wells constructions can make it exorbitant. Likewise the laboratory mothods also present daunting problems with obtaining representative samples and most often due to long testing times in order to attain results. Alternatively, procedures of estimating hydraulic conductivity using empirical formulae mostly based on grain-size distribution properties have been established and used to overcome these problems (Odong, 2007). These hydraulic conductivity and transmissivity of an aquifer can be estimated from empirical relations.

2.4.1 Estimation of hydraulic conductivity based on grain-size distribution analysis

Grain-size distribution analysis was introduced in 1934 by Krumbein and has been in used worldwide by most geologist. The analysis distinguishes 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 (Alyamani and Sen, 1993). Various techniques including field and laboratory methods and have been employed to determine the soil's hydraulic conductivity. The accuracy in estimating the hydraulic conductivity by the field methods according to Uma *et al* in 1989, is limited by the lack of precise knowledge of aquifer geometry and its hydraulic boundaries. The cost associated with these field methods can also be very expensive to use. The laboratory methods yields some difficulty in obtaining representative samples and much 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 associated with both field and laboratory methods according to Odong in 2007. Grain- size methods unlike the others do not depend on the aquifer's geometry and hydraulic boundaries, and are comparably less expensive. Given that information about the textural properties of soils can be easily obtained, the grain-size distribution method can be a probable alternative for estimating the aquifer's hydraulic conductivity.

The diameter of soil's pores are more beneficial to characterise than the diameter the soil's grains. The pore size distribution would be very challenging to determine and thus the approximation of the hydraulic properties would be based mostly on their grain-size distribution which is easier to measure. Hydraulic conductivity (K) can be estimated using the grain-size analysis of the sediment samples by aid of empirical equations relating its hydraulic conductivity to some size property of the sediment. Some established empirical formulae are detailed below:

Vukovic and Soro (1992) summarized the empirical methods from several studies and submitted a general formula for K as;

$$K = \frac{g}{v} \times C \times f(n) \times d_e^2 \quad (2.4)$$

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

The kinematic viscosity (v) relates to dynamic viscosity (μ) and the water or fluid density (ρ) which is determined as;

$$v = \frac{\mu}{\rho} \quad (2.5)$$

The values of de, C and f(n) depend on the method being employed for the analysis. Vukovic and Soro (1992) cited that porosity (n) could be derived from the empirical relationship with the coefficient of grain uniformity (U) given as;

$$n = 0.255 \, x \, (1 + 0.83^{U}) \quad (2.6)$$

With U determined as

$$U = \left(\frac{d_{60}}{d_{10}}\right) \quad (2.7)$$

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

Hazen formula, originally was developed in determining the hydraulic conductivity of uniformly graded sand (Hazen, 1892). It is useful in determining K for soil within the fine sand to gravel range provided the soil has a uniformity coefficient less than 5 and effective grain size within 0.1 and 3mm.

Hazen formulae has varying de, C and f (n) values and their purviews of applicability.

$$K = \frac{g}{v} \times 6 \times 10^{-4}[1 + 10(n - 0.26)]\ d_{10}^{2} \tag{2.8}$$

The Kozeny-Carman equation is one of the most commonly used and accepted derivations of permeability as a function of the soil medium's characteristics. Kozeny's original equation in 1927 was reviewed and revised by Carman in 1937/1956 to form the KozenyCarman equation. This approach is consider not ideal for clayey soils or soil with effective size above 3mm according to Carrier 2003.

$$K = \frac{g}{v} \times 8.3 \times 10^{-3} \left[\frac{n^3}{(1-n)^2}\right] d_{10}^{2} \tag{2.9}$$

The Breyer formula is regularly considered very suitable for materials with heterogeneous distributions and poorly arranged grains with a coefficient of grain uniformity ranging between 1 to 20, and an effective grain size ranging between 0.06 to 0.6mm. This method does not factor porosity, hence a value of 1 is given.

$$K = \frac{g}{v} \times 6 \times 10^{-4}\ log \frac{500}{U}\ d_{10}^{2} \tag{2.10}$$

The Slitcher formula is most applicable for grain-size between 0.01mm and 5mm.

$$K = \frac{g}{v} \times 1 \times 10^{-2}\ n^{3.287}\ d_{10}^{2} \tag{2.11}$$

Terzaghi formula is also much applicable for large-grain sand according to Cheng and Chen 2007.

$$K = \frac{g}{v} \times C_t \left[\frac{n - 0.13}{\sqrt[3]{1-n}}\right]^2 d_{10}^{2} \tag{2.12}$$

Where the C_t = sorting coefficient and ranges between 6.1 x 10^{-3} and 10.7 x 10^{-3}

U.S. Bureau of Reclamation (USBR) formula computes the hydraulic conductivity using the effective grain size (d_{20}) and is not dependent on porosity. The formula is most suitable for medium-grain sand with uniformity coefficient less than 5 according to Cheng and Chen 2007.

$$K = \frac{g}{v} \times 4.8 \times 10^{-4}\, d_{20}^{0.3} \times d_{20}^{2} \tag{2.13}$$

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$$K = 1300\,[I_o + 0.025(d_{50} - d_{10})]^2 \tag{2.14}$$

Where

Io = the intercept (mm) of the line formed by d_{50} and d_{10} with the grain-size axis.

d_{50} = the median grain diameter (mm). d_{10} = the effective grain diameter (mm).

This is one of the much known and used equations that depends on grain-size analysis.

This method considers both grain sizes of d_{10} and d_{50} and their sorting characteristics.

2.4.2 Estimation of aquifer parameters from geophysical methods

Geophysicists over the years have indicate that the assimilation of aquifer characteristics estimated from boreholes and surface resistivity measurements can be very effective. According to Ward in 1990, resistivity techniques are generally used to resolve a variety of environmental, geological and geotechnical subsurface detection problems. The prime purpose of these well-established methods is to quantity the potential differences at the surface as a result of the current flow within the ground. The electrical and hydraulic conductivities depend on each other given that the mechanisms that control electrical current, conduction and fluid flow are largely directed by the same physical parameters and lithological attributes. The measured resistivity values are usually relative and not absolute implying that only relative conclusions of an area's hydraulic parameters can be made. Owing to this, surface geophysical methods have been employed in aquifer zone delineation and the valuation of the aquifer's geophysical character various locations worldwide (Khalil, 2006).

CHAPTER 3: METHODOLOGY

The research methodology and data sampling methods used for the research is reported in this chapter. The methodology adopted consists of details on desk study, field work and data collection, soil sampling, water sampling, methods used and laboratory analysis.

3.1 Desk Study

Relevant reports and information of the Tongo district was sourced from the Talensi District Assembly in Bolgatanga, as well as from relevant literature available. Information was also gathered for dams, dug outs, wells and boreholes within the study area from the

Talensi District Assembly and other relevant organizations found within the study area. All information particularly on the dams (with respect to design and purpose) were obtained from Ghana Irrigation Development Authority (GiDA), Bolgatanta. Further studies carried out on the topographic and geological maps as well as data on boreholes and shallow wells available in the region from Water Research Institute, Accra.

3.1.1 Study Location

Tongo is the capital sub-district of the Talensi District, which is one of the recently formed districts in the Upper East region from the then Talensi-Nabdam-District Assembly in 2012. Established by Local Government (Talensi District Assembly; Establishment instrument 2012, L.I.2110), the district is located in the Upper East Region of Ghana. It is bordered to the North by the Bolgatanga Municipal, South by the West and East Mamprusi Districts (both in the Northern Region), Kassena-Nankana District to the West and the Bawku west and Nabdam District to the East. The district lies between latitude 10°15′ and 10°60′ north and, longitude 0°31′ and 1°0.5′ west. The district occupies a total land area of about 838.4 km^2 and indicates a large area which requires many socio-economic infrastructures in terms of the geographical spread of the district. The area covered by the district makes it difficult to ensure fair distribution of facilities and makes it almost impossible for many people to have easy access to services provided. To increase geographical access and to ensure effective health service delivery and administration, the district has been divided into eight administrative sub-districts namely; Datoku, Duusi Gbane, Gorogo Tengzuk, Pwalugu, Namolgo Kpatia, Tongo, Tolla Nungu and Winkongo sub-districts.

Figure 3.1 Location map of study area.

3.1.2 Hydrogeology

The Voltaian formation is characterized essentially by little or no primary porosity. Therefore, groundwater occurrences are associated with the occurrence of secondary porosities caused by fracturing, faulting, jointing and weathering (Yidana *et al*., 2007). Aquifers in the study area are generally semi-confined and structurally controlled and developed by secondary porosity in the form of fractures (Dapaah-Siakwan and GyauBoakye, 2000). Acheampong (1998) cited that the hydrogeological parameters in the study area are based on secondary permeability in the form of joints, which were developed after the primary porosities had been destroyed by rock compaction and slight metamorphism. This has resulted to the relatively poor success of drilling in these aquifers. The secondary porosity which results from jointing, shearing, fracturing and weathering has given rise to two main types of aquifers in the Voltaian; the weathered zone aquifer and the fractured zone aquifers. The weathered zone aquifers usually occur at the base of the thick weathered layer while the fractured zone aquifers usually occur at some depth beneath the weathered zone (Kortatsi, 1994). Wardrop and Associates in 1980 stated that analysis of the available hydrogeological and lithological data from wells drilled in the study area indicates that fractured aquifer provides most of the wells with water. The nature, aperture and degree of interconnection between joints determine the hydrogeological fortunes of the rocks. The structural grain is made of NNE–SSW fracture systems, which control the hydrogeological character of the Voltaian sedimentary rocks in general (Yidana *et al*., 2007). Borehole yields within the fractured zone are determined by the extent and degree of fracturing and therefore a formation which combines a thick weathered zone with a well fractured bedrock zone may provide the most productive aquifer situation.

Within the Middle Voltaian formation, the success rate for drilling boreholes is about 56%, and the borehole yield ranges between 0.41 m^3/h and 9 m^3/h with an average yield of about 6.2 m^3/h (Dapaah-Siakwan and Gyau-Boakye, 2000). The groundwater fortunes of this terrain have been extensively investigated (Agyekum, 2004) and has been established that recharge to all the aquifer systems is mainly by direct infiltration of precipitation through fracture and fault zones along the highland fronts and also through the sandy portions of the weathered zone while some amount of recharge may also occur through seepage from ephemeral streams channels during rainy seasons.

Transmissivity is a fundamental property of aquifers and water-bearing materials. In homogeneous aquifers, transmissivity (T) is the product of hydraulic conductivity (K) and the saturated aquifer thickness (b), that is:

$$T = K \times b \qquad (3.1)$$

According to Yidana and Koffie (2013), the transmissivity within the formation ranges from 1 m^2/d to 71.6 m^2/d with an average of 15.9 m^2/d. The aquifer transmissivity among the sandstones is in the range of 0.1 m^2/d to 52.0 m^2/d, and in the siltstone and mudstone aquifers, transmissivity is in the range of 0.2 m^2/d to 16.0 m^2/d. They again added that the recharge rate computed in the Voltaian ranges between 2.07 x 10^{-5} m/day and 2.85 x10^{-4} m/day which is about 0.3% to 4.1% of the annual precipitation in the area (Yidana and Koffie, 2013).

3.1.3 Land Use and Vegetation

The vegetation is guinea savannah woodland consisting of short widely spread deciduous trees and a ground flora of grass, which get burnt by fire or the scorch sun during the long dry season. This situation affects the amount of rainfall in the area and hence with negative implication on the quantity of water underground and the yield of water from many water point. The extreme temperatures' and prolong dry season facilitate bush burning, affect rejuvenation processes and promotes land degradation. As people try to cope during the long dry season, they attempt alternative livelihood mean by depending on the environment by adopting various unsustainable practices; the common practices being hunting with fire, firewood harvesting and charcoal production among others. As a typical agrarian economy, the long dry season affect the food security of many families resulting in most people migrating to cater for the food gap; which has the tendency of withdrawing the strong and energetic farm labour from the communities and creating social deviants in other cases. The implication of this respond is inimical mainly to women, children and the aged as they are always left vulnerable to hunger, abuse and the children dropping out from school.

The district is located in an area where soil is predominantly light in texture on the surface horizon, with low inherent fertility due to the deficiency in organic matter contents, nitrogen and potassium content. For this, the soils are generally susceptible to erosion and declining fertility, given the least negative land use practices. Due to the common nature of these unsustainable land use practices therefore, the soils in the district are impoverished in humus and other soils nutrient properties. High on the list of the negative human practices are burning and the competition of man with land for plants and animal residue. Practices which prevent the accumulation of organic matter and further weaken the natural regeneration capacity of the soils; thus rendering many lands unproductive. Thus land degradation is inevitable in the district if much concern is not put to the environment. The implication of this impoverishment of land from degradation is low yield in agricultural production. The district has one gazetted forest reserves covering a total area of 261.55 km^2. The district has an upland soil mainly developed from granite rock. It is shallow and low in soil fertility, weak with low organic matter content and predominantly coarse textured. Valley areas have soils ranging from sandy loams to salty clays which are difficult to till and prone to water logging and floods; negatively affecting agricultural productivity.

3.1.4 Climate and Drainage

Ghana lies within sub-Saharan West Africa wich is located in the savanna zone. This zone is sub divided from north to south into Sahel, Sudan, and Guinea-Savanna zones (Laube *et al*., 2008). Windmeijer and Andriesse in 1993 stated that the Upper East region is located in the area between the southern Sudan Savanna zone and the northern Guinea

Savanna zone with prevailing semi-arid conditions. The region has uni-modal rainy season from July to September often characterized by short duration intense rains preceded by heavy storms. Consequently, rapid runoff is generated into ephemeral and intermittent streams and then captured by artificial dams, primarily used for irrigation. The average annual rainfall, potential evapo-transpiration, and temperature at Navrongo in the Upper East region are 986 mm, 2050 mm, and 28.6°C, respectively (Ghana Meteorological Services, Navrongo). The average annual temperature is 29^{o}C. The mean daily minimum temperature is 25^{o}C, coinciding with the peak of the rainy season, and rises to a maximum of 34^{o}C in April. Relative humidity is highest during the rainy season with an average value of 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.

The Upper East region is mainly drained by the Volta River system and a stream network of perennial and intermittent streams and rivers. The four major rivers are White Volta, Red Volta, Sisili, and Tono River (Liebe, 2002). The drainage system of the Upper East region is part of the White Volta sub basin. The sub-basin is named after White Volta because it is the largest river downstream to the other three rivers coming from Burkina Faso. It should be mentioned that the stream flow of White Volta is influenced from the releases of the Bagre Dam in Burkina Faso and thus causing large variation in annual runoff (Ledger, 1964). The Tongo district is drained mainly by the Red and White Volta and their tributaries. These physical characters has given rise to dry season farming activities along some parts of the Volta basin stretches of the district. Similarly, the existence of the mineral deposits (gold) has resulted in existence of small scale artisanal mining and medium scale investor activities in the district while the rock out crops has resulted in the establishment of quarries. The farming activities along the Volta basin however has caused the silting of the river course, resulting in flooding during the raining season. While the mining activities are a source of extensive environment degradation.

3.2 Field Work and Data Collection

A reconnaissance survey was conducted to first find out locations of water sources existing within and closer to the Tongo District to be sampled for the research work. Specific locations of these water sources were taken with a hand-held GPS to determine the proximity of the wells to the dams. Visits were made to areas like Baare, Gaare, Tongo Zubiongo, Tongo Beo, Gambibigo, Shiega, Pelungu, Gbani and Tindongo for sampling.

Figure 3.2 Aerial view of study area

3.3 Soil Sampling

Soil samples were taken at locations closer to the hand-dug wells and boreholes within the study area. 27 disturbed soil samples were taken in January, 2015 during the dry periods using an augur drill at depths between 0 to 3 m into transparent zip-lock bags and labelled accordingly. Each sample weighed about 1kg and was kept in zip-lock polyethylene bags and labelled. They were further transported to the Soil Laboratory of the Water Research Institute, Accra for the grain-size distribution analysis. The samples were tested in accordance with standard procedures of British Standards Institution
Methods of Test for Soils for Civil Engineering Purposes (BS1377).

3.3.1 Grain-Size Distribution Analysis

The dry sieve method was used to analyse soil sampled from the field. Sieves ranging from 10 mm to 0.05 mm were used according to the British Soil Classification System 5930 code (BS 5930) to determine the grain-size distribution of the soil. A semi-logarithm graph was used to plots the soil's distribution to obtain the grain-size distribution curve which was used to classify each sample's particle size as a means to determine the soil's basic parameters. The system classifies the soil into basic soil type groups as either fine, medium or coarse sub-groups according to size. These classifications were obtained from the grain-size distribution curve analysis done.

3.3.2 Determination of Hydraulic Conductivity

Information extracted from the semi-logarithmic graph plots from the grain-size distribution curves were further analysed to determine the hydraulic conductivity of the aquifer's over-burden soil. Three empirical formulae; Equations (2.8), (2.9) and (2.14) were employed to estimate hydraulic conductivity for the over-lying soil for the aquifer. Parameters such as the porosity (n) and grain uniformity (U) were computed from the empirical formulae (see Equations 2.6 and 2.7 above). The intercept (I) and diameters of particle size at 10%, 20%, 50% and 60% were deduced from the plotted grain-size distribution curves.

3.3.3 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 $T = K \times b$

Where;
T is the Transmissivity (m^2/day) K is the
Hydraulic Conductivity (m/day) b is the
Saturated Aquifer Thickness (m).

3.4 Determination of Aquifer Geometry

Data from 636 (Figure 4.2) wells in Upper East region were obtained in February, 2015 from Water Research Institute of Ghana, (Groundwater Section) Accra. The data was analysed to obtain the aquifer configuration which includes estimated yield, static water levels, aquifer zone and depth to bedrock within the Tongo district and other surrounding areas. The static water levels deduced from the borehole data were used to determine depths to water table. The saturated thickness of aquifer in the area was determined from the difference between the depth to the bedrock and the depth to water table.

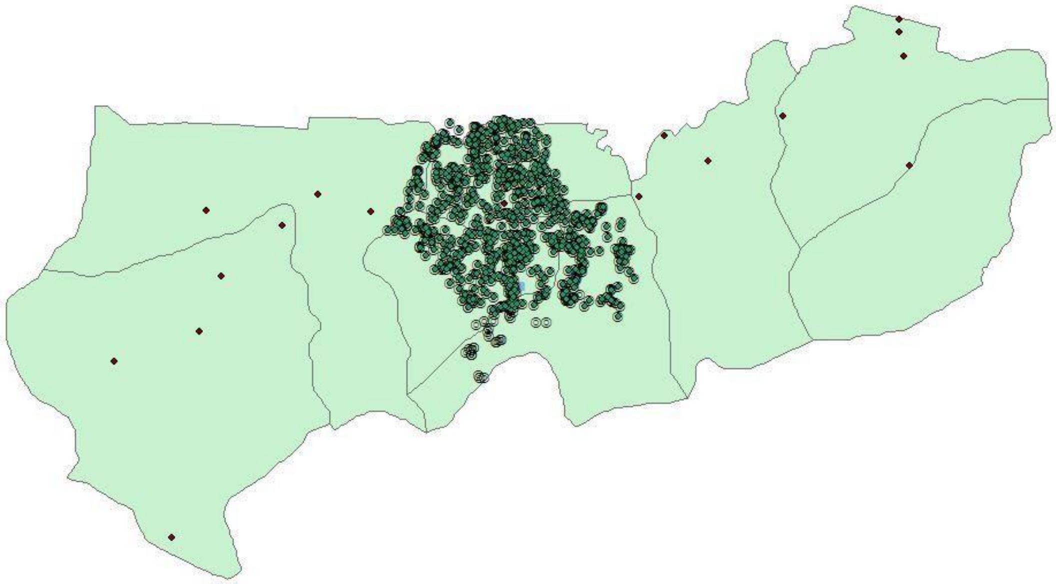

Figure 3.3 Plotted locations of borehole data from WRI in Upper East Region

3.5 Water Sampling

Water samples were collected in January, 2015 from reservoirs, hand-dug wells and boreholes within the study area. A good representation of samples were collected from available hand-dug wells and boreholes in the areas (see Figure 4.1 above) to ensure even distribution of data as much as possible. A total of 37 water samples were collected, of with 13 were from boreholes (Appendix D: Plate 6.1), 11 from hand-dug wells (Appendix D: Plates 6.2 and 6.3), 4 from both reservoirs and 9 from rain water, in accordance with standard protocols as described by Duncan *et al*. (2007). In sampling from the hand pumps for both hand-dug wells and boreholes, purging was done for about two (2) minutes to flush the stagnant water retained in pipes. The two (2) open hand-dug wells without pump systems were properly checked and confirmed for regular usage. This was to ensure that stale and stagnant water was not sampled. Sampling was done in consideration with standard protocols described by U.S. Geological Survey (2006), and Duncan *et al* (2007).

All samples were collected at each site into 250 ml pre-sterilized translucent polyethylene bottles and labelled. The samples were transported to the National Nuclear Research Institute (NNRI) of the Ghana Atomic Energy Commission's Chemistry laboratory for chloride analysis using the ion chromatograph. The samples were filtered with a white 0.45 μm membrane place in a filter holder. The potable EC meter (Hach Sension 5) was used to measure some field parameters like total dissolved solids (TDS), salinity and electrical conductivity, and the potable pH meter (Hach Sension 1) were also used to measure pH and redox potential in situ.

Rainwater harvested directly from rain gauges were sampled into 250 ml translucent polyethylene bottles upon request, from the Ghana Meteorological Agency in Navrongo.

Chloride Mass Balance

The chloride mass-balance method relies on the salt-balance and the salt-age equations. Allison and Hughes (1983) cited that the salt-balance equation is used to determine groundwater recharge rates (see Equation 2.1 above). Chloride concentration in the groundwater and precipitation collected in the field was determined by laboratory analysis. An average of chloride concentration in groundwater (C_{gw}) and precipitation (C_p) were determined. The average precipitation value in mm/year for the study area was obtained from literature as 1000 mm/year (Yidana and Koffie, 2013). The chloride mass balance assumes that the only source of chloride entering the unconfined aquifer is rainwater and generally the chloride concentration in shallow well are consistently higher than rainwater and indicate that these concentrated values are a direct result of evapotranspiration occurring from the top of the water table.

CHAPTER 4: RESULTS AND DISCUSIONS

4.1 Analysis of Aquifer Characteristics

4.1.1 Hydraulic Conductivity and Transmissivity

The easy movement of water through aquifer fractures and soil pore spaces 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). The flow patterns of groundwater through the aquifer is affected by its magnitude, variability and pattern. Hydraulic conductivities determined from grain size analysis using the three formulae (Equations 2.7, 2.8 and 2.13). As shown in Table 5.1 below, the Hazen emperical formula ranges from 1.733 m/d to 1.879 m/d with a mean of 1.812m/d, the Kozeny-Carman formula ranges from 0.541m/d to 1.529 m/d with an average of 1.172 m/d and the Alyamani and Sen formula ranges from 1.358 m/d to 1.718 m/d with an average of 1.518 m/d.

The Hazen formula bases its analysis only on particle size 10 (d_{10}) whereas the Kozeny-Carman formula bases its analysis on the entire particle size distribution and particle shape (Carrier, 2003). This according to Carrier (2003) makes Hazen's formula less accurate in contrast to the Kozeny- Carman formula. The Alyamani and Sen method is more accurate for samples which are well graded given that it is subtle to the shape of the grading curve. On these bases the estimations by Kozeny-Carman would be considered best formula to be used for this study, thus estimated values of hydraulic conductivities ranges between 0.541 m/d and 1.529 m/d with an average of 1.172 m/d.

The estimated hydraulic conductivity in the study area indicates that the aquifer is an unconsolidated sedimentary soil with medium sand material. Also the estimated hydraulic conductivity values are lower since they fall within 10^{-2} – 10^{2} m/yr (web.ead.anl.gov). These values suggest that movement of water through the soil's pore spaces is slow.

The transmissivity values in the study are ranged between 1.8 m^2/d and 22.2 m^2/d with an average value of 5.26 m^2/d. These values again suggest low transmissivity of aquifers in the study area (Krasny, 1993). Krasny (1993) in classifying transmissivity magnitudes indicate that values within this range have the potential to withdraw groundwater in small quantities for local water supply.

4.1.2 Grain Analysis

The soil's grain size distribution is a key property which has the tendency to affect its hydrogeological conductivity. According to Fetter (2001), soil samples with larger grains distribution will likely have a high hydraulic conductivity whereas those with a mixture of grain sizes (i.e. multi-graded soil) will have a lower hydraulic conductivity and porosity because the void between the larger grains will be filled up by smaller grains. Analysis were done on the plotted grain-size distribution curves for each sample to help classify them as either fine, medium or coarse particle sizes in accordance with BS 5930. The classifications analysis indicated that 50 to 60% were within medium and fine sand, with medium sand being the predominant type. (Table 4.1).

Sample	Soil Classification	d_{10} (mm)	d_{20} (mm)	d_{50} (mm)	d_{60} (mm)	U	n	Io (mm)	Equ. 2.7 (m/day)	Equ. 2.8 (m/day)	Equ. 2.13 (m/day)
BS1,0.0	medium sand	0.044	0.055	0.18	0.23	5.227	0.351	0.031			
BS1,0.5	medium sand	0.043	0.052	0.18	0.2	4.651	0.362	0.03	1.879	0.703	1.452
BS1,1.0	medium sand	0.043	0.052	0.18	0.21	4.884	0.358	0.03	1.837	0.674	1.452
BS2,0.0	medium sand	0.046	0.06	0.2	0.3	6.522	0.331	0.031	1.815	0.597	1.579
BS2,0.5	medium sand	0.044	0.057	0.19	0.29	6.591	0.330	0.03	1.651	0.541	1.472
BS2,1.0	medium sand	0.045	0.06	0.2	0.31	6.889	0.326	0.031	1.686	1.069	1.581
BS3,0.0	medium sand	0.042	0.054	0.18	0.21	5.000	0.355	0.029	1.733	1.326	1.369
BS3,0.5	medium sand	0.045	0.056	0.18	0.23	5.111	0.353	0.031	1.968	1.486	1.536
BS3,1.0	medium sand	0.046	0.059	0.19	0.28	6.087	0.337	0.031	1.883	1.281	1.556
BS4,0.0	medium sand	0.044	0.055	0.18	0.21	4.773	0.360	0.03	1.944	1.529	1.450
BS4,0.5	medium sand	0.044	0.055	0.18	0.22	5.000	0.355	0.03	1.902	1.455	1.450
BS4,1.0	medium sand	0.043	0.054	0.18	0.2	4.651	0.362	0.03	1.879	1.501	1.452
BS5,0.0	medium sand	0.043	0.053	0.17	0.2	4.651	0.362	0.03	1.879	1.501	1.431
BS5,0.5	medium sand	0.042	0.052	0.15	0.2	4.762	0.360	0.03	1.773	1.397	1.390
BS5,1.0	medium sand	0.044	0.056	0.18	0.23	5.227	0.351	0.031	1.861	1.386	1.538
GS1,0.0	medium sand	0.046	0.06	0.22	0.32	6.957	0.325	0.032	1.752	1.105	1.718
GS2,0.0	medium sand	0.046	0.06	0.2	0.3	6.522	0.331	0.031	1.815	1.187	1.579
GS2,0.5	medium sand	0.044	0.055	0.19	0.24	5.455	0.347	0.031	1.822	1.323	1.561
GS3,0.0	medium sand	0.043	0.057	0.19	0.25	5.814	0.341	0.03	1.685	1.178	1.474
GS3,0.5	medium sand	0.048	0.062	0.22	0.35	7.292	0.321	0.031	1.859	1.143	1.620
GS3,1.0	medium sand	0.046	0.062	0.21	0.31	6.739	0.328	0.031	1.783	1.145	1.602
GS4,0.0	medium sand	0.043	0.054	0.18	0.21	4.884	0.358	0.03	1.837	1.425	1.452
GS4,0.5	medium sand	0.046	0.06	0.19	0.31	6.739	0.328	0.032	1.783	1.145	1.648
GS4,1.0	medium sand	0.046	0.062	0.22	0.34	7.391	0.319	0.032	1.694	1.034	1.718
GS5,0.0	medium sand	0.042	0.052	0.175	0.2	4.762	0.360	0.029	1.773	1.397	1.358
GS5,0.5	medium sand	0.045	0.059	0.19	0.28	6.222	0.335	0.031	1.781	1.197	1.559

GS5,1.0	medium sand	0.044	0.056	0.18	0.25	5.682	0.343	0.03	1.785	1.265	1.450

Table 4.1 Computation of Hydraulic Conductivities from Grain-Size Distribution Analysis

									1.861	0.666	1.538

4.2 Analysis of Aquifer Geometry

Analysis drawn from the 636 borehole data obtained (see Figure 3.3 above) for the region to delineate the aquifer within and around the Tongo district. The depth to water table, depth to bedrock and saturated aquifer thickness have been determined below.

4.2.1 Depth to Water Table

The summary of depths to water table or aquifer top is shown in the Table 4.2 below. These depths ranged between 0.6 and 23.7 m with the mean depth of 6.88 m and standard deviation of 4.56 m.

Table 4.2 Depth to Water Table of study area

Depth Ranges, m	Frequency	Percentage, %
0 – 2	36	5.86
2 – 4	111	18.08
4 – 6	139	22.64
6 – 8	133	21.66
8 – 10	90	14.66
10 – 12	48	7.82
12 – 14	32	5.21
14 – 16	13	2.12
16 – 18	9	1.47
18 – 25	3	0.49
TOTAL	614	100

The areas as indicated from the table above show that the region generally has shallow water table levels with most ranged between 2 and 8 m signifying about 62%.

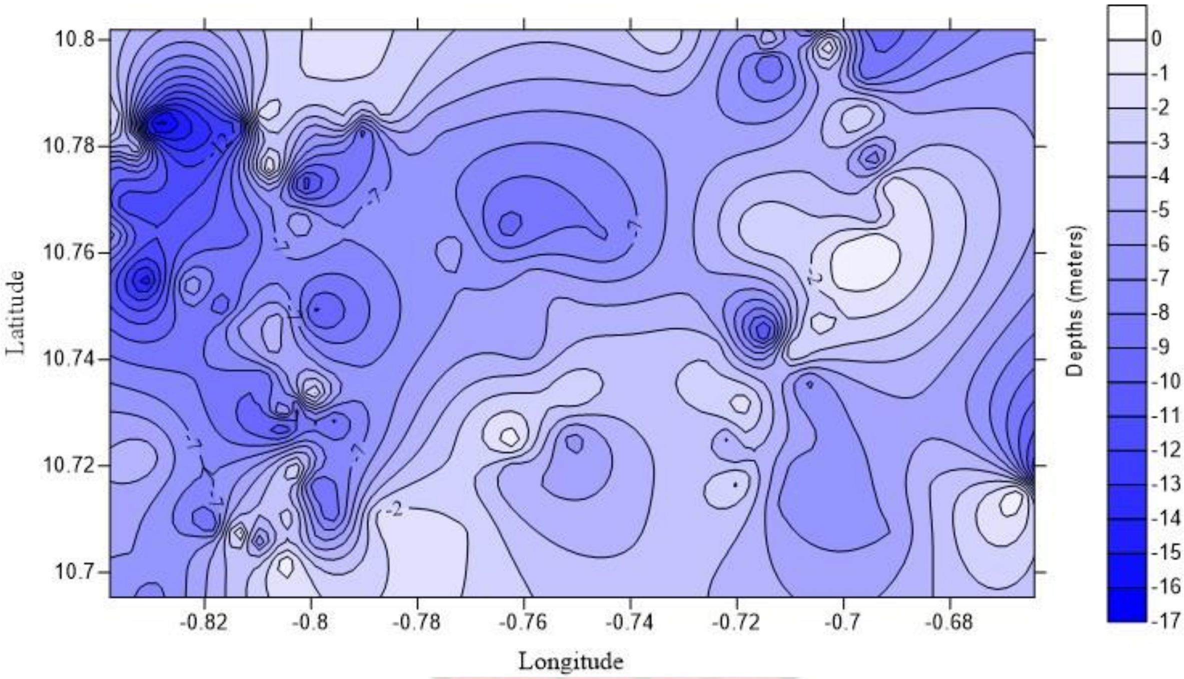

Figure 4.1 Contour map showing depths to water table

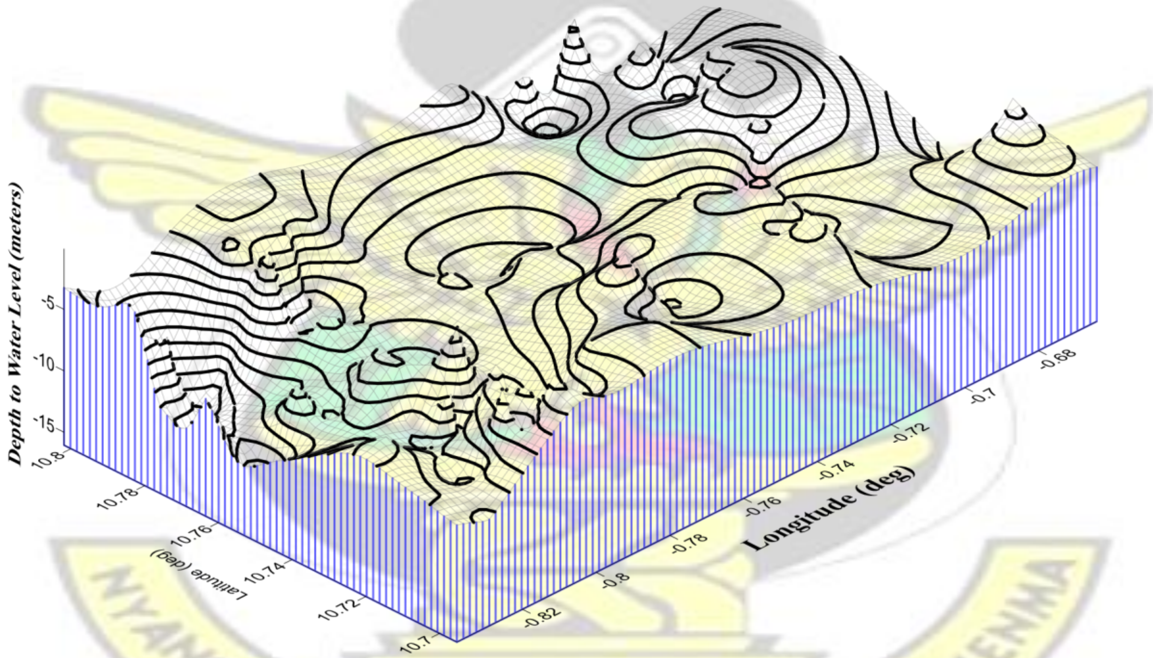

Figure 4.2 Wireframe map of surface depth to water levels.

4.2.2 Depth to Bedrock

This study area generally has depths to bedrock ranging from 4.5 – 40.8 m with a mean value of 16.75 m and standard deviation values of 5.6 m. The summary of the various depths to the bedrock in the study area is presented in the Table 4.3.

Table 4.3 Depth to Bedrock

Depth Ranges, m	**Frequency**	**Percentage, %**
0 – 5	1	0.20
5 –10	50	9.96
10 – 15	138	27.49
15 – 20	176	35.06
20 – 25	92	18.33
25 – 30	29	5.78
30 – 35	8	1.59
35 – 40	7	1.39
40 – 45	1	0.20
TOTAL	502	100

Analysis from Table 4.3 above indicate that about 62% of the area had depths to bedrock between 15 – 20m whilst just about 3% of the area have depth to bedrock exceeding 30m.

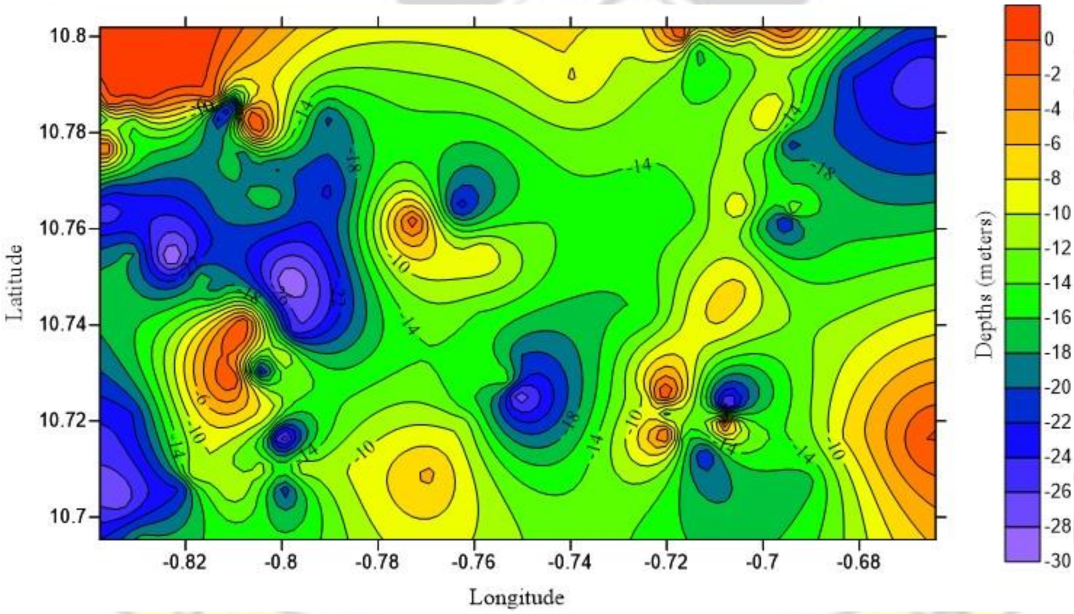

Figure 4.3 Contour map of Depth to Bedrock

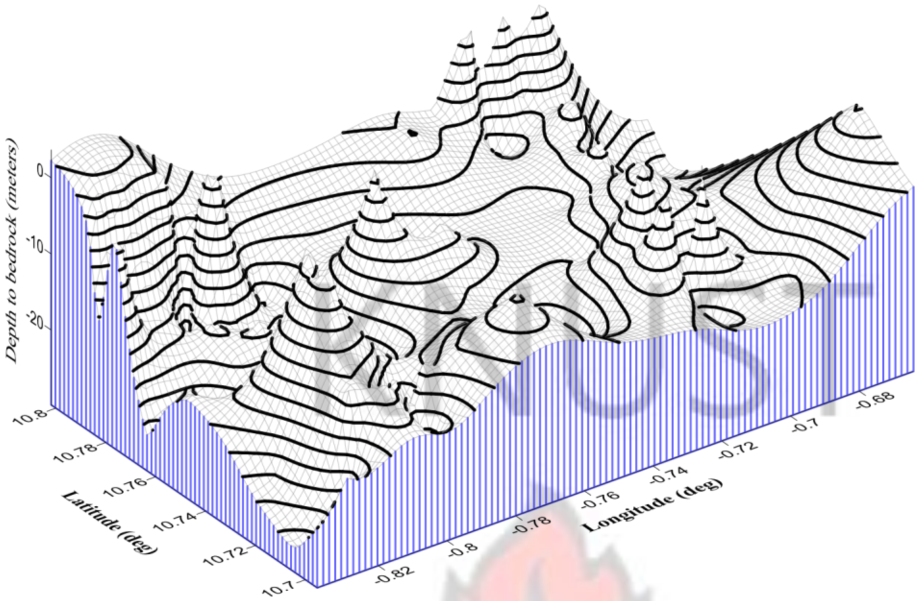

Figure 4.4 Wireframe map of Depth to Bedrock

4.2.3 Saturated Aquifer Thickness

The saturated aquifer thickness of the area ranges from 0.3 to 49.5 m with an average value of 6.5 m and standard deviation of 4.2 m. The summary is given in the Table 4.4 below.

Table 4.4 Saturated aquifer thickness of the study

Depth Ranges, m	Frequency	Percentage, %
0 – 5	104	20.12
5 –10	371	71.76
10 – 15	22	4.26
15 – 20	14	2.71
25 – 30	4	0.77
45 – 45	2	0.39
TOTAL	517	100

It can be realised from Table 4.4 above that about 91% of the areas have a saturated thickness between 0 – 10 m with only 1 % showing thickness exceeding 30 m.

4.3 Estimation of Groundwater Recharge

4.3.1 Summary of physico-chemical water analysis

The total dissolved solids (TDS) composition in water consist of certain dissolved amounts of organic matter and inorganic salts. According to WHO (2004), water classified as of good quality should have a TDS concentration less than 600 mg/l. TDS of sampled water sources in the study area indicates that values for groundwater sampled (Appendix A) ranges between 139 to 314 mg/l with a mean of 206.29 mg/l. Likewise the TDS values for surface water sampled ranges between 69 to 161 mg/l with a mean of 115 mg/l. The measured concentrations are significantly lower and are within the recommended range by WHO (2004). In lieu of the measured TDS values, both the groundwater and surface water quality in the area can therefore be considered to be of very good quality for drinking. Salinity hazard is a measure of TDS expressed in the unit of electrical conductance (EC) which is considered as one of the most influential water quality guideline on crop productivity. A high EC denotes less water availability to plants, even though the soil may appear wet. Bauder et al. (2007) classifies water based on their EC with a range between 250 to 750 µS/cm as good or ≤250 µS/cm as excellent quality. Both groundwater and surface water sources estimates a mean value of 321 µS/cm and therefore indicates the quality of water in the area as good. The EC values also suggests that the groundwater resource is relatively fresh (Yidana and Koffie, 2013). These values also suggest that the groundwater had not remained in the aquifer system for too long and so had not dissolved much solute to have increased the chloride composition of the ground water. The study areas are not noted for any significant industrial activity that might affect the chloride increase in groundwater in the study and hence the assumption that precipitation is the major source of chloride is justified.

Both surface and groundwater sources have a mean pH of 7.25 which indicates a neutral condition for acidity or alkalinity, given that the optimum pH has a range of

6.5 to 9.5. The inorganic components and chemical contaminants in water may affect its taste given certain temperature conditions. High water temperature heightens the growth of microorganisms and impacts adequacy of various inorganic components which may cause increases in colour, taste, corrosive issues and odour. Cool water is generally more palatable than warm water.

4.3.2 Recharge estimation using chloride mass balance method

Quantification of groundwater recharge and its spatial trends are very important in groundwater resource management plans. It also serves as the bases to depict the physical system of the study area as much as possible for proper management. The chloride concentrations for each water sample shown in Table 4.5 below were obtain from laboratory analysis using the ion chromatograph setup. The chloride mass balance method was used to quantify the groundwater recharge (Table 4.6) using the relation:

$R = P\left(\frac{C_p}{C_{gw}}\right)$(See Equation 2.2 above).

Table 4.5 Estimated ground water recharge using chloride mass balance method.

Water Source	**Well ID**	**Cl Conc. (mg/l)**	**Recharge (mm/yr)**
Borehole	B1	12.63	68.00
		13.67	62.83
		11.46	74.95
		11.06	77.66
		11.85	72.48
		10.57	81.26
		14.65	58.63
		15.76	54.50
		14.26	60.23
		15.76	54.50
		13.23	64.92
Borehole	B12	9.48	90.60
Borehole	B2		
Borehole	B3		
Borehole	B4		
Borehole	B5		

Borehole	B6		
Borehole	B7		
Borehole	B8		
Borehole	B9		
Borehole	B10		
Borehole	B11		
Borehole	B13	8.24	104.23
Hand Dug Well	W1	7.03	122.17
Hand Dug Well	W2	3.05	281.60
Hand Dug Well	W3	4.65	184.71
Hand Dug Well	W4	3.56	241.26
Hand Dug Well	W5	5.04	170.41
Hand Dug Well	W6	8.54	100.57
Hand Dug Well	W7	18.62	46.13
Hand Dug Well	W8	17.22	49.88
Hand Dug Well	W9	10.72	80.12
Hand Dug Well	W10	7.56	113.61
Hand Dug Well	W11	2.78	308.95
Baare Dam	DM1	2.01	427.31
Baare Dam	DM2	1.96	438.21
Gaare Dam	DM3	3.82	224.84
Gaare Dam	DM4	3.81	225.43

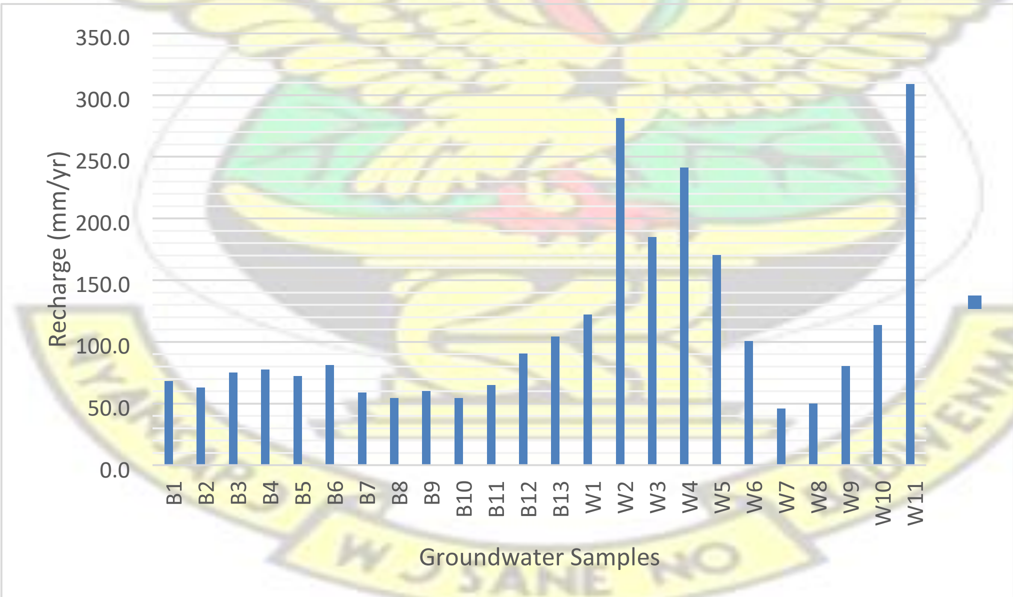

Figure 4.5 Bar chart estimated groundwater recharge rate at sampling points.

Figures 4.6 and 4.7 below represent the maps showing the spatial variation of the groundwater recharge from precipitation in the study area using the chloride mass balance approach. The highly recharge areas are located in the southwest (towards the Baare dam) and the northeast (towards the Gaare dam) of the study area as envisaged. The recharge distribution in the area is uneven and unpredictable in the sense that it does not really show a distinct spatial pattern. The Golden Surfer 10 software was used to deduce the spatial variation of the recharge.

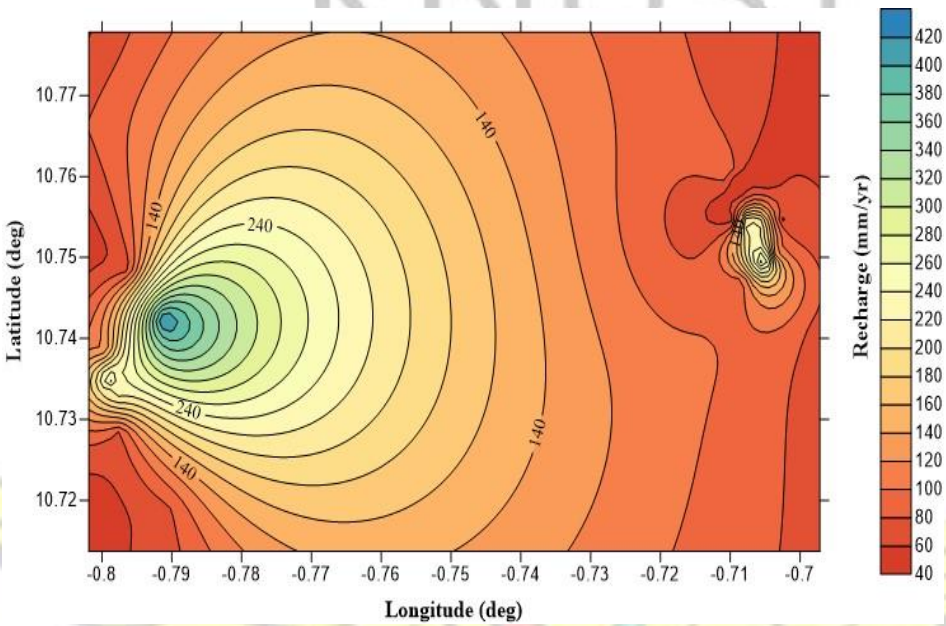

Figure 4.6 Contour map of estimated groundwater recharge from precipitation.

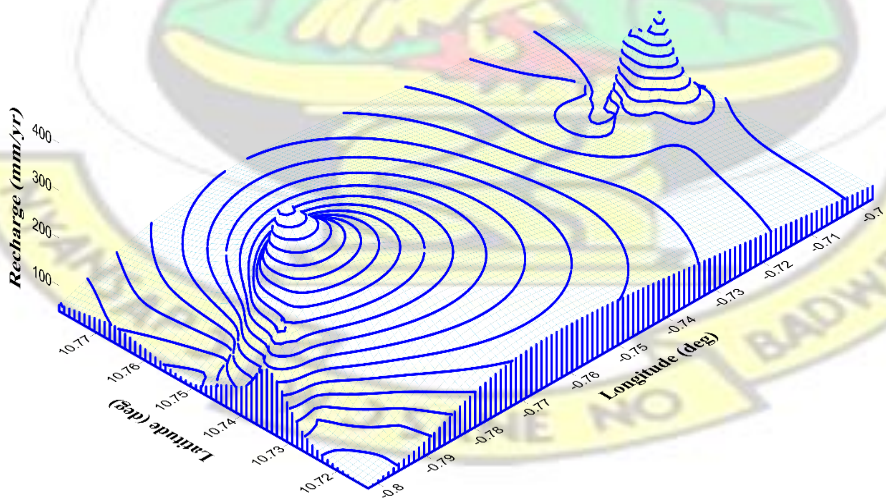

Figure 4.7 Predicted wireframe map of groundwater recharge from precipitation.

The average annual rainfall in the Northern Region of Ghana is estimated to be 1000 mm/yr (Yidana and Koffie, 2013). The average groundwater recharge based on the above assumptions using chloride mass balance is estimated to be 109.3 mm/yr which ranges between 46.1 mm/y and 218.6 mm/yr. Lowest value was from W7 in Gaare area and highest was from W11 in also in the Gaare area. The estimated groundwater recharge mean value of 109.3 mm/yr indicates that only about 10.9 % of total precipitation recharges the study area. This seeks to suggest that averagely, about 89 % of the precipitations in the area is lost through either evapo-transpiration and or by surface runoff.

It also reveals that about 911 mm/yr of the annual rainfall is lost through evapotranspiration and runoff as anticipated from literature in Northern Ghana. The Water Resource Commission of Ghana in the White Volta Basin in 2008 estimated that the evapotranspiration in the 3 (three) Northern regions thus in Tamale, Yendi and Bole were 913 mm/yr, 910 mm/yr and 908 mm/yr. Most of the precipitated water is lost due to evapotranspiration because the study area lies beneath rocks of the Middle Voltaian which constitutes the Oti and Obosum beds, which are well fused and are generally flat lying and therefore are very likely to reduce the rate of percolation. According to Dapaah-Siakwan and Gyau-Boakye (2000), these beds are of interbedded mudstones/siltstones, arkose and conglomerates. Dickson and Benneh (1985) also confirmed that rains of high intensity during the rainy seasons result in minimal soil recharge given that most of it lost through runoff and evapotranspiration.

The wide variation in the chloride concentration of the groundwater which has led to a wide variation in groundwater recharge rate in the study area (Figure 5.5 and 5.6) may be attributed to the differences in the local vegetation near the respective well location, which directly affects the amounts of evapotranspiration that would occur. It may also be as a result of the thickness of the vadose zone and thus the amount of water that can evapo-transpire from the top of water table. Most of the high recharged points are found to be open wells which are recharged directly from rainfall without significant evapo-transpiration. As a result, the chloride concentration in those wells are very low and based on chloride mass balance method, it can be stated that low chloride concentrations in the groundwater indicate higher recharge and vice versa.

Generally the recharge rate of groundwater in the study area is very low because of the shallow aquifer systems and slow rate of percolation. The geological formations are inherently impermeable and this can be attributed to compaction and metamorphism of the rocks (Dapaah-Siakwan and Gyau-Boakye, 2000). The hydrogeological conditions in the area are generally controlled by the secondary permeability in the form of fractures, fissures and crevice. Erde`lyi (1964) found that the Voltaian formation for most part consists of clayey sediments even the best of the sandstones are unsuitable for storing groundwater. These properties of the aquifer make the recharging water vulnerable to fractionation by evaporation. Thus before the percolation water gets to the saturated zone much of the percolation water might have been lost due to intense sun radiation thereby reducing the amount of water that get to the water table.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This research focused on the estimation of groundwater recharge and defined the hydrogeological framework in the Tongo district. The study highlighted on general aquifer recharge and the prospect of management of the resource.

The geometry of aquifer systems delineated in the district estimates that the groundwater system is shallow and can be susceptible to pollution. The hydraulic conductivities estimated within the aquifer does not give a wide range of values and suggests that the geological formations in the area is homogeneous. Again the low hydraulic conductivity values indicates that vertical flow within the aquifer is restricted, and will result in limiting percolation and expose the potential aquifer recharge water to severe evaporation. The mean transmissivity value of 5.26 m2/d also indicates the supply potency for small groundwater redraws. The recharge distribution in the district estimated from the chloride mass balance techniques does not show a distinct spatial pattern. The estimated mean groundwater recharge value of 109 mm/yr indicates that about 11% of the annual precipitation recharges the area. The relatively lower electrical conductivity (EC) values implies that the water had not stayed in the aquifer for long to have dissolved enough solute in the groundwater. The EC values also indicates that the quality of water in the area is good.

5.2 Recommendations

The results and main findings of the study suggest the following recommendations:

- There should be a long-term monitoring plan of groundwater levels to ascertain consistency of groundwater levels over a period of time to define aquifer geometry extensively. Groundwater quality should also be monitored to ensure early detection and intervention of any pollution or contamination that may occur.
- Communities should construct more open wells to receive direct recharge from precipitation and adopt proper management practices to protect the recharge areas identified in the communities.
- Good agricultural practices and proper sanitation measures must be encourages to protect the minute recharge rates from precipitation from being polluted to avoid groundwater pollution.
- Similar research on should be conducted in other parts of the country to delineate aquifer geometries and estimate groundwater recharge potency in the country.

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APPENDICES

Appendix A: Physical Water Parameters and Chloride Concentrations

Community	Well ID	EC	Temp.	TDS	Salinity	pH	EH	Latitude	Longitude	El, m	Cl (mg/l)
Baare Dam	DM1	115.6	25.5	69	0	7.94	-71.3	N10°44'32.5"	W0°47'28.4"	200	2.01
Baare Dam	DM2	115.5	25	69	0	7.93	-70.1	N10°44'32.5"	W0°47'28.4"	201	1.96
Baare	B1	289	31.5	173	0	7.049	-20.7	N10°44'26.3"	W0°41'49.8"	199	12.63
Baare	W1	227	30.5	136	0	6.88	-8.4	N10°44'18.8"	W0°47'58.4"	197	7.03
Baare	W2	523	30.4	314	0.2	6.74	0.5	N10°44'05.2"	W0°47'55.7"	186	3.05
Baare	W3	467	22.7	282	0.1	7.73	-58.4	N10°44'03.8"	W0°47'54.6"	186	4.65
Baare	W4	360	27.4	216	0.1	7.3	-33.2	N10°44'00.8"	W0°47'53.4"	188	3.56
Baare	W5	418	28.1	251	0.1	7.38	-36.7	N10°43'51.9"	W0°47'51.8"	190	5.04
Tongo Zuboogo	B2	457	32.3	274	0.1	7.08	-19.8	N10°42'49.3"	W0°47'42.0"	212	13.67
Tongo zubiongo	B3	352	31.6	211	0.1	7.02	-15.1	N10°43'07.6"	W0°47'26.4"	219	11.46
Baare	B4	257	31.9	165	0	6.91	-9.3	N10°43'42.5"	W0°47'50.8"	209	11.06
Baare Tabaha	B5	367	31.4	220	0.1	7.44	-41.3	N10°44'55.0"	W0°47'46.6"	202	11.85
Tongo Beo	B6	377	31.2	226	0.1	7.01	-15.4	N10°45'58.6"	W0°48'06.8"	204	10.57
Tongo Beo	B7	393	30.3	236	0.1	6.78	-1.6	N10°46'40.2"	W0°48'06.7"	201	14.65
Gaare Dam	DM3	269	21.1	161	0	8.39	-97.1	N10°45'15.6"	W0°42'29.1"	196	3.82
Gaare Dam	DM4	268	21.1	161	0	8.39	-98	N10°45'15.3"	W0°42'20.7"	214	3.81
Gaare Primary	B8	385	29.1	231	0.1	7.46	-42.4	N10°45'15.8"	W0°42'34.0"	229	15.76
Gaare Chief palace	W6	262	29.6	157	0	6.79	-3.1	N10°45'36.7"	W0°42'36.0"	231	8.54
Gaare Chief palace	B9	335	30.4	201	0.1	7.26	-30.8	N10°45'36.3"	W0°42'35.5"	231	14.26
Gaare	W7	245	29.6	147	0	6.98	-14.2	N10°45'36.3"	W0°42'30.7"	224	18.62
Gaare Yaar	W8	429	30.8	257	0.1	7.18	-25.7	N10°45'32.2"	W0°42'17.9"	227	17.22
Gaare (Under Baobab)	B10	365	29.7	219	0.1	7.11	-21.5	N10°45'16.7"	W0°42'09.1"	229	15.76

Gaare	W9	275	25.9	165	0	7.12	-22.3	N10°45'19.0"	W0°42'04.1"	227	10.72
Gaare	B11	370	31.6	222	0.1	7.34	-35.3	N10°45'32.6"	W0°42'03.2"	231	13.23
Gbani	W10	300	29.2	180	0.1	7.02	-16.3	N10°45'02.7"	W0°42'12.3"		7.56
Gbani	W11	232	28.8	139	0	6.97	-13.1	N10°44'58.7"	W0°42'18.6"	212	2.78
Gbani	B12	292	30.8	175	0.1	6.87	-7.6	N10°44'49.3"	W0°42'29.6"	210	9.48
Tindongo	B13	257	31.2	154	0	7.09	-20.3	N10°44'20.1"	W0°42'50.8"	211	8.24

Appendix B: Chloride Concentrations in Precipitation from Navrongo Meteorological Station

Sample Date	Amount, mm	Cl (mg/l)
10/09/2014	10	0.6
16/09/2014	49	1.2
17/09/2014	10.4	0.58
23/09/2014	7.6	0.9
26/09/2014	16.9	0.8
27/09/2014	7.1	0.71
29/09/2014	23.1	0.84
7/10/2014	14.2	1
19/11/2014	28.6	1.1
Average	18.54	0.86

Appendix C: Table of Seive Analysis from Grain-Size Distribution

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
BS1, 0.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	534	544	10	10	1.19%	98.81%
0.0 - 0.5m	1.25	515	537	22	32	3.82%	94.98%
	0.63	492	521	29	61	7.29%	87.69%
	0.5	462	470	8	69	8.24%	79.45%
	0.315	448	462	14	83	9.92%	69.53%
	0.2	441	457	16	99	11.83%	57.71%
	0.16	435	440	5	104	12.43%	45.28%
	0.071	423	437	14	118	14.10%	31.18%
	0.05	414	421	7	125	14.93%	16.25%
	less	245	256	11	136	16.25%	0.00%
	Total			136	837	100.00%	
BS1, 0.5	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	534	540	6	6	0.72%	99.28%
0.5 - 1.0 m	1.25	515	538	23	29	3.47%	95.81%
	0.63	492	521	29	58	6.94%	88.88%
	0.5	462	470	8	66	7.89%	80.98%
	0.315	448	462	14	80	9.57%	71.41%
	0.2	441	458	17	97	11.60%	59.81%

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
	0.16	435	441	6	103	12.32%	47.49%
	0.071	423	441	18	121	14.47%	33.01%
	0.05	414	424	10	131	15.67%	17.34%
	less	245	259	14	145	17.34%	0.00%
	Total			145	836	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
BS1, 1.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation above	2.5	557	563	6	6	0.71%	99.29%
1.0 m	1.25	511	536	25	31	3.65%	95.65%
	0.63	485	514	29	60	7.06%	88.59%
	0.5	460	477	17	77	9.06%	79.53%
	0.315	462	466	4	81	9.53%	70.00%
	0.2	442	459	17	98	11.53%	58.47%
	0.16	440	445	5	103	12.12%	46.35%
	0.071	429	447	18	121	14.24%	32.12%
	0.05	424	431	7	128	15.06%	17.06%
	less	245	262	17	145	17.06%	0.00%
	Total			145	850	100.00%	
BS2, 0.0	10			0	0	0.00%	100.00%
	5	560	570	10	10	0.76%	99.24%
excavation within	2.5	534	572	38	48	3.64%	95.60%
0.0 - 0.5m	1.25	515	548	33	81	6.14%	89.46%
	0.63	492	524	32	113	8.57%	80.89%
	0.5	462	470	8	121	9.17%	71.72%

	0.315	448	460	12	133	10.08%	61.64%
	0.2	441	455	14	147	11.14%	50.49%
	0.16	435	439	4	151	11.45%	39.04%
	0.071	423	435	12	163	12.36%	26.69%
	0.05	414	420	6	169	12.81%	13.87%
	less	245	259	14	183	13.87%	0.00%
	Total			183.00	1319	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
BS2, 0.5	10			0	0	0.00%	100.00%
	5	560	564	4	4	0.33%	99.67%
excavation within	2.5	557	586	29	33	2.72%	96.95%
0.5 - 1.0 m	1.25	511	545	34	67	5.51%	91.44%
	0.63	485	518	33	100	8.23%	83.21%
	0.5	460	476	16	116	9.55%	73.66%
	0.315	462	466	4	120	9.88%	63.79%
	0.2	442	457	15	135	11.11%	52.67%
	0.16	440	444	4	139	11.44%	41.23%
	0.071	429	443	14	153	12.59%	28.64%
	0.05	424	432	8	161	13.25%	15.39%
	less	245	271	26	187	15.39%	0.00%
	Total			187	1215	100.00%	
BS2, 1.0	10			0	0	0.00%	100.00%
	5	560	573	13	13	0.97%	99.03%
excavation above	2.5	557	595	38	51	3.81%	95.21%
1.0 m	1.25	511	544	33	84	6.28%	88.93%

	0.63	485	516	31	115	8.60%	80.33%
	0.5	460	474	14	129	9.65%	70.68%
	0.315	462	466	4	133	9.95%	60.73%
	0.2	442	456	14	147	10.99%	49.74%
	0.16	440	444	4	151	11.29%	38.44%
	0.071	429	441	12	163	12.19%	26.25%
	0.05	424	430	6	169	12.64%	13.61%
	less	245	258	13	182	13.61%	0.00%
	Total			182	1337	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
BS3, 0.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	557	562	5	5	0.56%	99.44%
0.0 - 0.5m	1.25	511	532	21	26	2.90%	96.54%
	0.63	485	522	37	63	7.02%	89.52%
	0.5	460	479	19	82	9.14%	80.38%
	0.315	462	467	5	87	9.70%	70.68%
	0.2	442	460	18	105	11.71%	58.97%
	0.16	440	445	5	110	12.26%	46.71%
	0.071	429	447	18	128	14.27%	32.44%
	0.05	424	433	9	137	15.27%	17.17%
	less	245	262	17	154	17.17%	0.00%
	Total			154.00	897	100.00%	
BS3, 0.5	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%

excavation within 0.5 - 1.0 m	2.5	557	562	5	5	0.56%	99.44%
	1.25	511	540	29	34	3.78%	95.67%
	0.63	485	520	35	69	7.67%	88.00%
	0.5	460	478	18	87	9.67%	78.33%
	0.315	462	467	5	92	10.22%	68.11%
	0.2	442	457	15	107	11.89%	56.22%
	0.16	440	444	4	111	12.33%	43.89%
	0.071	429	443	14	125	13.89%	30.00%
	0.05	424	429	5	130	14.44%	15.56%
	less	245	255	10	140	15.56%	0.00%
	Total			140	900	100.00%	

Sample Detail	**Sieve Diameter [mm]**	**Wg of Sieve [g]**	**Wg of Sample and Sieve [g]**	**Wg on Sieve [g]**	**Cumulative Weight [g]**	**Percentage Retained [%]**	**Percentage Passing [%]**
BS3, 1.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation above 1.0 m	2.5	557	574	17	17	1.74%	98.26%
	1.25	511	550	39	56	5.73%	92.53%
	0.63	485	513	28	84	8.60%	83.93%
	0.5	460	473	13	97	9.93%	74.00%
	0.315	462	466	4	101	10.34%	63.66%
	0.2	442	453	11	112	11.46%	52.20%
	0.16	440	444	4	116	11.87%	40.33%
	0.071	429	439	10	126	12.90%	27.43%
	0.05	424	429	5	131	13.41%	14.02%
	less	245	251	6	137	14.02%	0.00%
	Total			137	977	100.00%	

BS4, 0.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	534	541	7	7	0.93%	99.07%
0.0 - 0.5m	1.25	515	533	18	25	3.31%	95.76%
	0.63	492	521	29	54	7.15%	88.61%
	0.5	462	470	8	62	8.21%	80.40%
	0.315	448	461	13	75	9.93%	70.46%
	0.2	441	455	14	89	11.79%	58.68%
	0.16	435	440	5	94	12.45%	46.23%
	0.071	423	437	14	108	14.30%	31.92%
	0.05	414	422	8	116	15.36%	16.56%
	less	245	254	9	125	16.56%	0.00%
	Total			125.00	755	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
BS4, 0.5	10			0	0	0.00%	100.00%
	5	560	562	2	2	0.26%	99.74%
excavation within	2.5	557	565	8	10	1.31%	98.43%
0.5 - 1.0 m	1.25	511	531	20	30	3.94%	94.49%
	0.63	485	511	26	56	7.35%	87.14%
	0.5	460	474	14	70	9.19%	77.95%
	0.315	462	466	4	74	9.71%	68.24%
	0.2	442	455	13	87	11.42%	56.82%
	0.16	440	444	4	91	11.94%	44.88%
	0.071	429	444	15	106	13.91%	30.97%
	0.05	424	432	8	114	14.96%	16.01%

	less	245	253	8	122	16.01%	0.00%
	Total			122	762	100.00%	
BS4, 1.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation above	2.5	534	540	6	6	0.66%	99.34%
1.0 m	1.25	515	540	25	31	3.42%	95.92%
	0.63	492	526	34	65	7.17%	88.75%
	0.5	462	471	9	74	8.16%	80.60%
	0.315	448	462	14	88	9.70%	70.89%
	0.2	441	458	17	105	11.58%	59.32%
	0.16	435	441	6	111	12.24%	47.08%
	0.071	423	443	20	131	14.44%	32.64%
	0.05	414	425	11	142	15.66%	16.98%
	less	245	257	12	154	16.98%	0.00%
	Total			154	907	100.00%	

Sample Detail	**Sieve Diameter [mm]**	**Wg of Sieve [g]**	**Wg of Sample and Sieve [g]**	**Wg on Sieve [g]**	**Cumulative Weight [g]**	**Percentage Retained [%]**	**Percentage Passing [%]**
BS5, 0.0	10			0	0	0.00%	100.00%
	5	560	561	1	1	0.13%	99.87%
excavation within	2.5	534	540	6	7	0.93%	98.94%
0.0 - 0.5m	1.25	515	533	18	25	3.32%	95.62%
	0.63	492	517	25	50	6.64%	88.98%
	0.5	462	470	8	58	7.70%	81.27%
	0.315	448	461	13	71	9.43%	71.85%
	0.2	441	458	17	88	11.69%	60.16%
	0.16	435	441	6	94	12.48%	47.68%

	0.071	423	440	17	111	14.74%	32.93%
	0.05	414	422	8	119	15.80%	17.13%
	less	245	255	10	129	17.13%	0.00%
	Total			129.00	753	100.00%	
BS5, 0.5	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	557	558	1	1	0.15%	99.85%
0.5 - 1.0 m	1.25	511	524	13	14	2.13%	97.72%
	0.63	485	515	30	44	6.70%	91.02%
	0.5	460	476	16	60	9.13%	81.89%
	0.315	462	466	4	64	9.74%	72.15%
	0.2	442	456	14	78	11.87%	60.27%
	0.16	440	444	4	82	12.48%	47.79%
	0.071	429	443	14	96	14.61%	33.18%
	0.05	424	431	7	103	15.68%	17.50%
	less	245	257	12	115	17.50%	0.00%
	Total			115	657	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
BS5, 1.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation above	2.5	534	540	6	6	0.64%	99.36%
1.0 m	1.25	515	546	31	37	3.95%	95.41%
	0.63	492	529	37	74	7.91%	87.50%
	0.5	462	471	9	83	8.87%	78.63%
	0.315	448	462	14	97	10.36%	68.27%
	0.2	441	456	15	112	11.97%	56.30%

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
	0.16	435	439	4	116	12.39%	43.91%
	0.071	423	437	14	130	13.89%	30.02%
	0.05	414	421	7	137	14.64%	15.38%
	less	245	252	7	144	15.38%	0.00%
	Total			144	936	100.00%	
GS1, 0.0	10			0	0	0.00%	100.00%
	5	560	588	28	28	2.95%	97.05%
excavation within	2.5	557	575	18	46	4.85%	92.19%
0.0 - 0.5m	1.25	511	527	16	62	6.54%	85.65%
	0.63	485	500	15	77	8.12%	77.53%
	0.5	460	469	9	86	9.07%	68.46%
	0.315	462	465	3	89	9.39%	59.07%
	0.2	442	453	11	100	10.55%	48.52%
	0.16	440	443	3	103	10.86%	37.66%
	0.071	429	439	10	113	11.92%	25.74%
	0.05	424	429	5	118	12.45%	13.29%
	less	245	253	8	126	13.29%	0.00%
	Total			126	948	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
GS2, 0.0	10			0	0	0.00%	100.00%
	5	560	582	22	22	2.32%	97.68%
excavation within	2.5	534	547	13	35	3.69%	93.99%
0.0 - 0.5m	1.25	515	538	23	58	6.12%	87.87%
	0.63	492	513	21	79	8.33%	79.54%
	0.5	462	468	6	85	8.97%	70.57%

	0.315	448	456	8	93	9.81%	60.76%
	0.2	441	450	9	102	10.76%	50.00%
	0.16	435	442	7	109	11.50%	38.50%
	0.071	423	432	9	118	12.45%	26.05%
	0.05	414	417	3	121	12.76%	13.29%
	less	245	250	5	126	13.29%	0.00%
	Total			126	948	100.00%	
GS2, 0.5	10			0	0	0.00%	100.00%
	5	560	562	2	2	0.25%	99.75%
excavation within	2.5	557	568	11	13	1.61%	98.15%
0.5 - 1.0 m	1.25	511	533	22	35	4.33%	93.82%
	0.63	485	511	26	61	7.54%	86.28%
	0.5	460	474	14	75	9.27%	77.01%
	0.315	462	465	3	78	9.64%	67.37%
	0.2	442	455	13	91	11.25%	56.12%
	0.16	440	445	5	96	11.87%	44.25%
	0.071	429	443	14	110	13.60%	30.66%
	0.05	424	433	9	119	14.71%	15.95%
	less	245	255	10	129	15.95%	0.00%
	Total			129	809	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
GS3, 0.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	557	572	15	15	1.74%	98.26%
0.0 - 0.5m	1.25	511	541	30	45	5.21%	93.05%

	0.63	485	509	24	69	8.00%	85.05%
	0.5	460	472	12	81	9.39%	75.67%
	0.315	462	466	4	85	9.85%	65.82%
	0.2	442	454	12	97	11.24%	54.58%
	0.16	440	445	5	102	11.82%	42.76%
	0.071	429	443	14	116	13.44%	29.32%
	0.05	424	429	5	121	14.02%	15.30%
	less	245	256	11	132	15.30%	0.00%
	Total			132.00	863	100.00%	
GS3, 0.5	10			0	0	0.00%	100.00%
	5	560	575	15	15	1.26%	98.74%
excavation within	2.5	557	593	36	51	4.27%	94.48%
0.5 - 1.0 m	1.25	511	545	34	85	7.11%	87.36%
	0.63	485	509	24	109	9.12%	78.24%
	0.5	460	470	10	119	9.96%	68.28%
	0.315	462	465	3	122	10.21%	58.08%
	0.2	442	451	9	131	10.96%	47.11%
	0.16	440	442	2	133	11.13%	35.98%
	0.071	429	436	7	140	11.72%	24.27%
	0.05	424	427	3	143	11.97%	12.30%
	less	245	249	4	147	12.30%	0.00%
	Total			147	1195	100.00%	

Sample Detail	**Sieve Diameter [mm]**	**Wg of Sieve [g]**	**Wg of Sample and Sieve [g]**	**Wg on Sieve [g]**	**Cumulative Weight [g]**	**Percentage Retained [%]**	**Percentage Passing [%]**
GS3, 1.0	10			0	0	0.00%	100.00%
	5	560	563	3	3	0.72%	99.28%

excavation above 1.0 m	2.5	557	567	10	13	3.13%	96.14%
	1.25	511	526	15	28	6.75%	89.40%
	0.63	485	495	10	38	9.16%	80.24%
	0.5	460	464	4	42	10.12%	70.12%
	0.315	462	463	1	43	10.36%	59.76%
	0.2	442	446	4	47	11.33%	48.43%
	0.16	440	441	1	48	11.57%	36.87%
	0.071	429	431	2	50	12.05%	24.82%
	0.05	424	425	1	51	12.29%	12.53%
	less	245	246	1	52	12.53%	0.00%
	Total			52	415	100.00%	
GS4, 0.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within 0.0 - 0.5m	2.5	534	542	8	8	0.88%	99.12%
	1.25	515	544	29	37	4.09%	95.02%
	0.63	492	523	31	68	7.52%	87.50%
	0.5	462	469	7	75	8.30%	79.20%
	0.315	448	459	11	86	9.51%	69.69%
	0.2	441	456	15	101	11.17%	58.52%
	0.16	435	445	10	111	12.28%	46.24%
	0.071	423	445	22	133	14.71%	31.53%
	0.05	414	419	5	138	15.27%	16.26%
	less	245	254	9	147	16.26%	0.00%
	Total			147	904	100.00%	

Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]

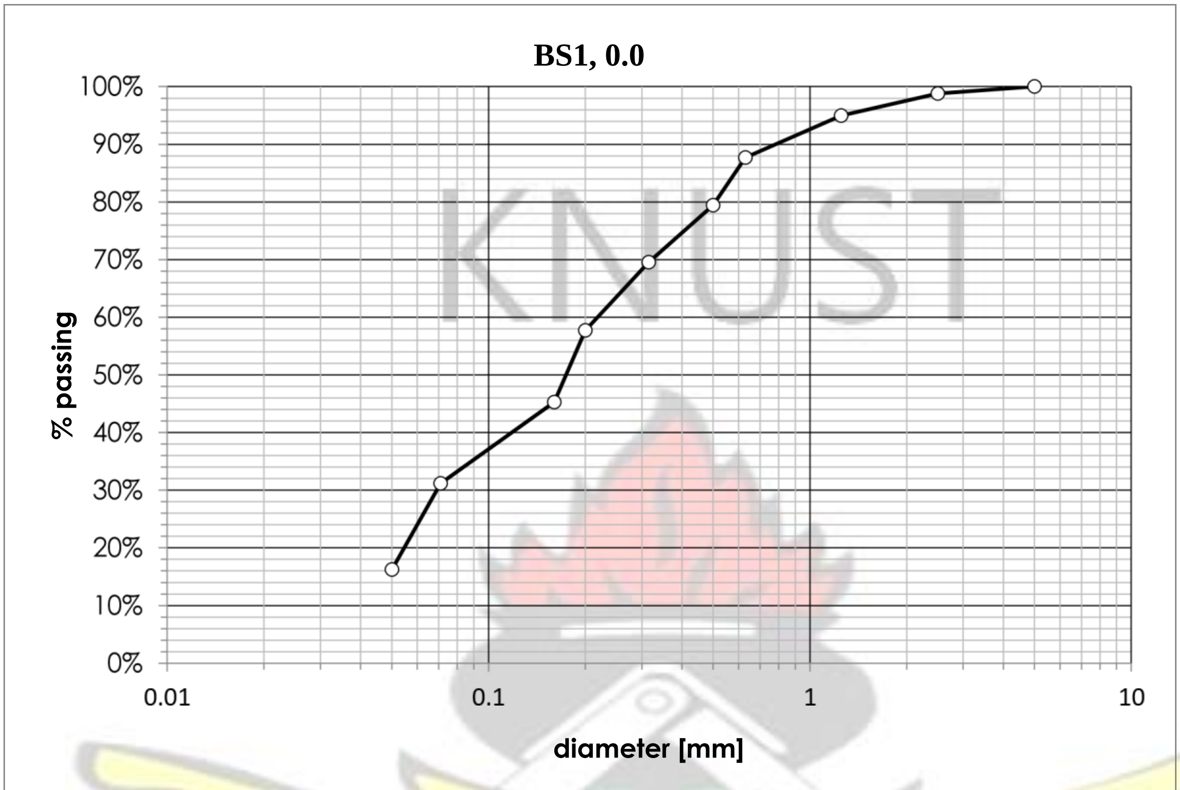
GS4, 0.5	10			0	0	0.00%	100.00%
	5	560	567	7	7	0.57%	99.43%
excavation within	2.5	534	568	34	41	3.36%	96.07%
0.5 - 1.0 m	1.25	515	557	42	83	6.80%	89.27%
	0.63	492	520	28	111	9.09%	80.18%
	0.5	462	468	6	117	9.58%	70.60%
	0.315	448	457	9	126	10.32%	60.28%
	0.2	441	451	10	136	11.14%	49.14%
	0.16	435	438	3	139	11.38%	37.76%
	0.071	423	433	10	149	12.20%	25.55%
	0.05	414	418	4	153	12.53%	13.02%
	less	245	251	6	159	13.02%	0.00%
	Total			159	1221	100.00%	
GS4, 1.0	10			0	0	0.00%	100.00%
	5	560	570	10	10	0.84%	99.16%
excavation above	2.5	534	567	33	43	3.62%	95.54%
1.0 m	1.25	515	558	43	86	7.24%	88.30%
	0.63	492	519	27	113	9.51%	78.79%
	0.5	462	467	5	118	9.93%	68.86%
	0.315	448	455	7	125	10.52%	58.33%
	0.2	441	448	7	132	11.11%	47.22%
	0.16	435	437	2	134	11.28%	35.94%
	0.071	423	428	5	139	11.70%	24.24%
	0.05	414	417	3	142	11.95%	12.29%
	less	245	249	4	146	12.29%	0.00%
	Total			146	1188	100.00%	

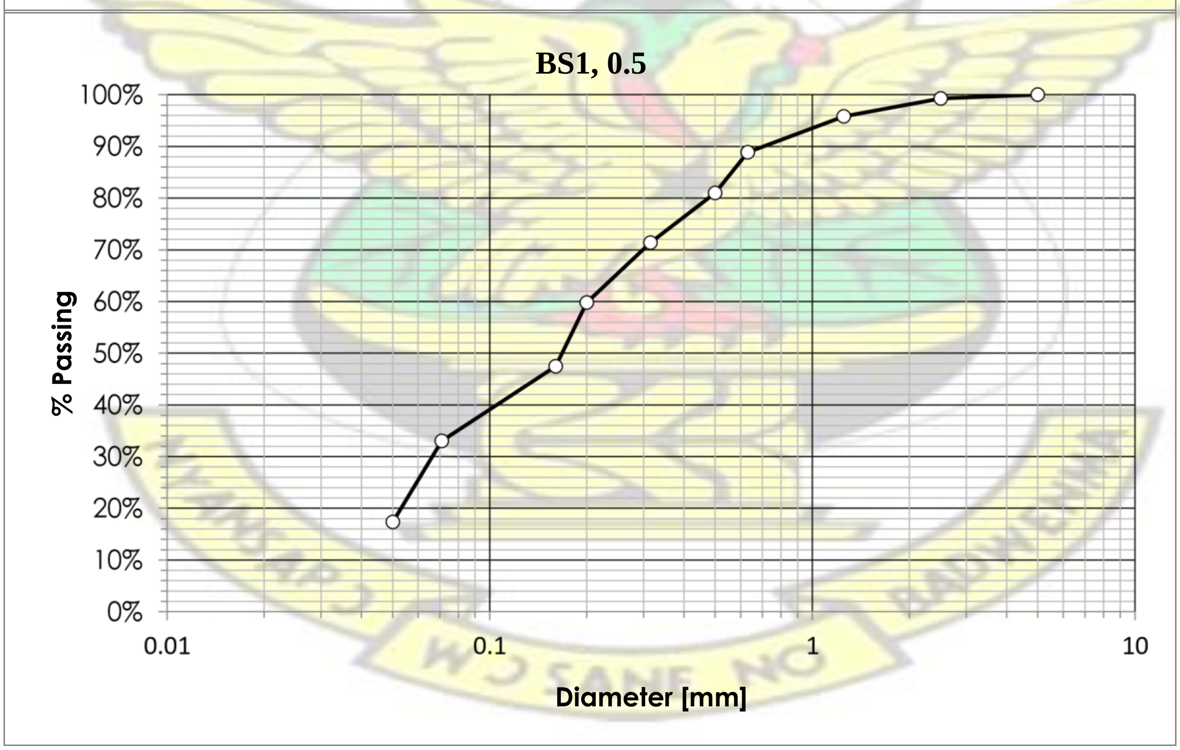
Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
GS5, 0.0	10			0	0	0.00%	100.00%
	5	560	560	0	0	0.00%	100.00%
excavation within	2.5	534	539	5	5	0.82%	99.18%
0.0 - 0.5m	1.25	515	530	15	20	3.28%	95.89%
	0.63	492	512	20	40	6.57%	89.33%
	0.5	462	468	6	46	7.55%	81.77%
	0.315	448	459	11	57	9.36%	72.41%
	0.2	441	455	14	71	11.66%	60.76%
	0.16	435	440	5	76	12.48%	48.28%
	0.071	423	436	13	89	14.61%	33.66%
	0.05	414	420	6	95	15.60%	18.06%
	less	245	260	15	110	18.06%	0.00%
	Total			110	609	100.00%	
GS5, 0.5	10			0	0	0.00%	100.00%
	5	560	563	3	3	0.34%	99.66%
excavation within	2.5	534	549	15	18	2.03%	97.63%
0.5 - 1.0 m	1.25	515	548	33	51	5.76%	91.86%
	0.63	492	517	25	76	8.59%	83.28%
	0.5	462	468	6	82	9.27%	74.01%
	0.315	448	457	9	91	10.28%	63.73%
	0.2	441	451	10	101	11.41%	52.32%
	0.16	435	438	3	104	11.75%	40.56%
	0.071	423	433	10	114	12.88%	27.68%
	0.05	414	418	4	118	13.33%	14.35%
	less	245	254	9	127	14.35%	0.00%

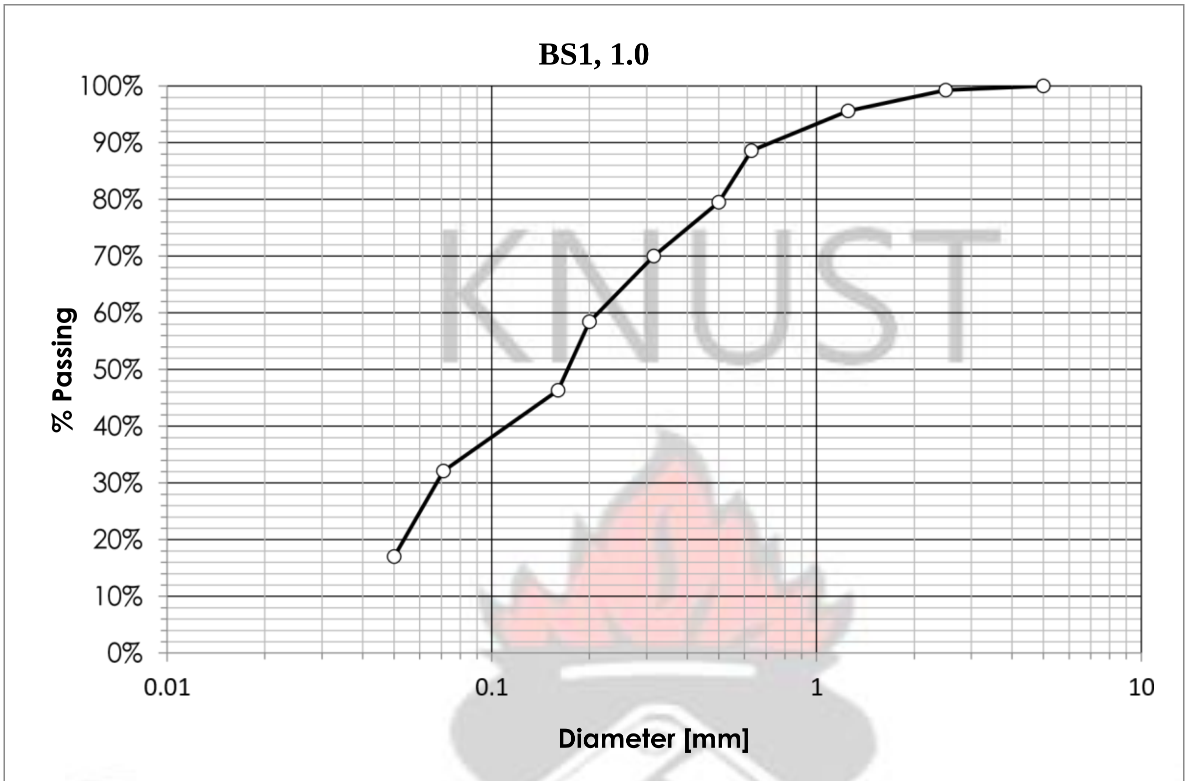
	Total			127	885	100.00%	

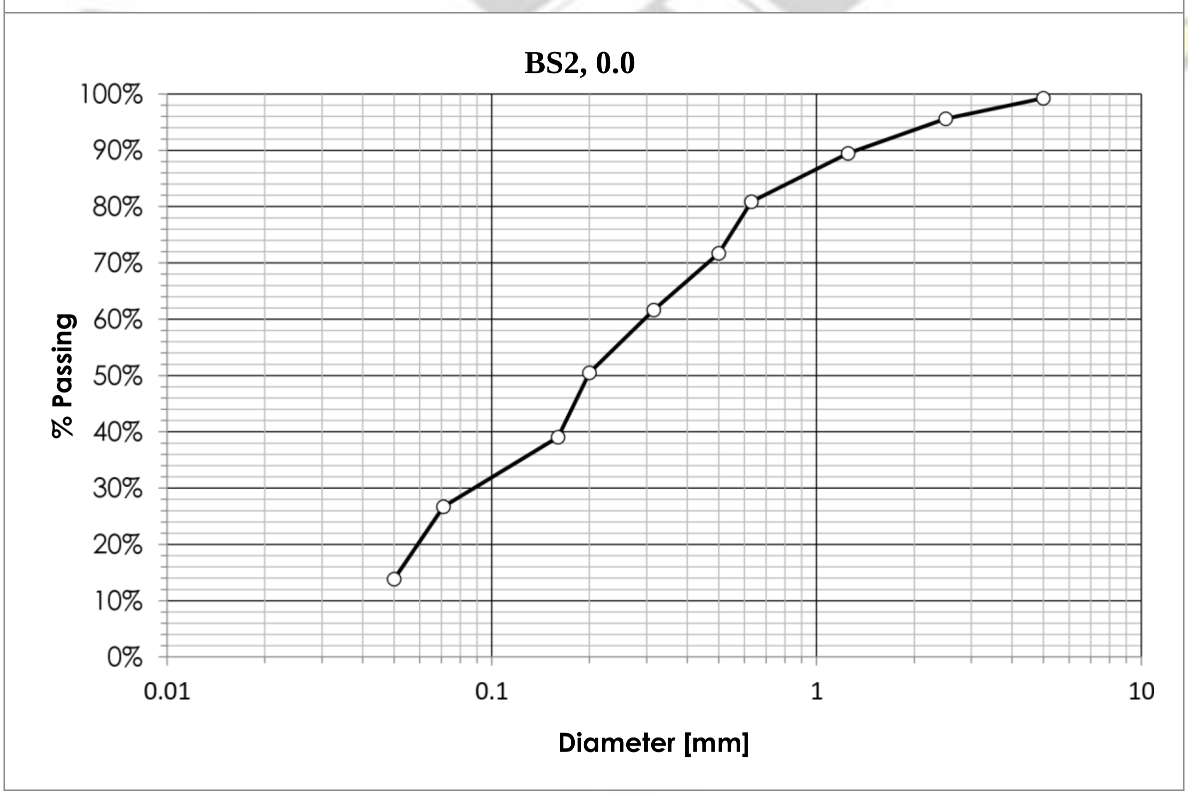
Sample Detail	Sieve Diameter [mm]	Wg of Sieve [g]	Wg of Sample and Sieve [g]	Wg on Sieve [g]	Cumulative Weight [g]	Percentage Retained [%]	Percentage Passing [%]
GS5, 1.0	10			0	0	0.00%	100.00%
	5	560	561	1	1	0.12%	99.88%
excavation above	2.5	534	545	11	12	1.45%	98.43%
1.0 m	1.25	515	546	31	43	5.21%	93.22%
	0.63	492	516	24	67	8.11%	85.11%
	0.5	462	468	6	73	8.84%	76.27%
	0.315	448	457	9	82	9.93%	66.34%
	0.2	441	453	12	94	11.38%	54.96%
	0.16	435	439	4	98	11.86%	43.10%
	0.071	423	436	13	111	13.44%	29.66%
	0.05	414	420	6	117	14.16%	15.50%
	less	245	256	11	128	15.50%	0.00%
	Total			128	826	100.00%	

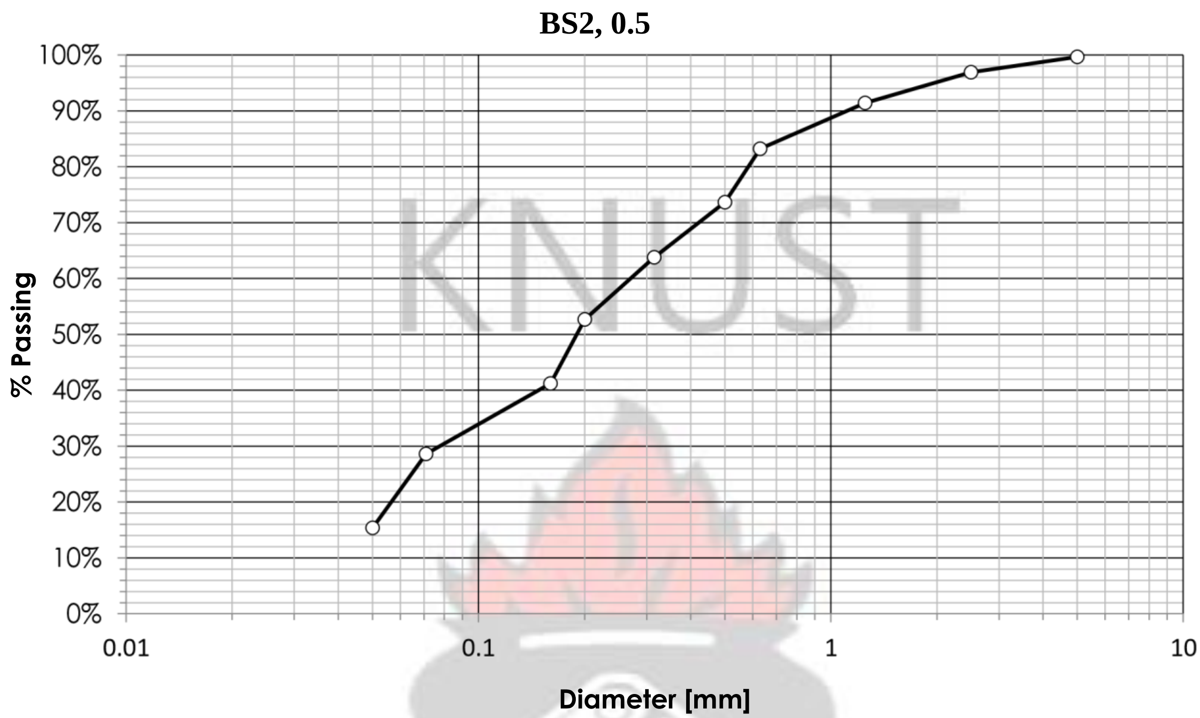
Appendix D: Grain-Size Distribution Curves for Soil Samples

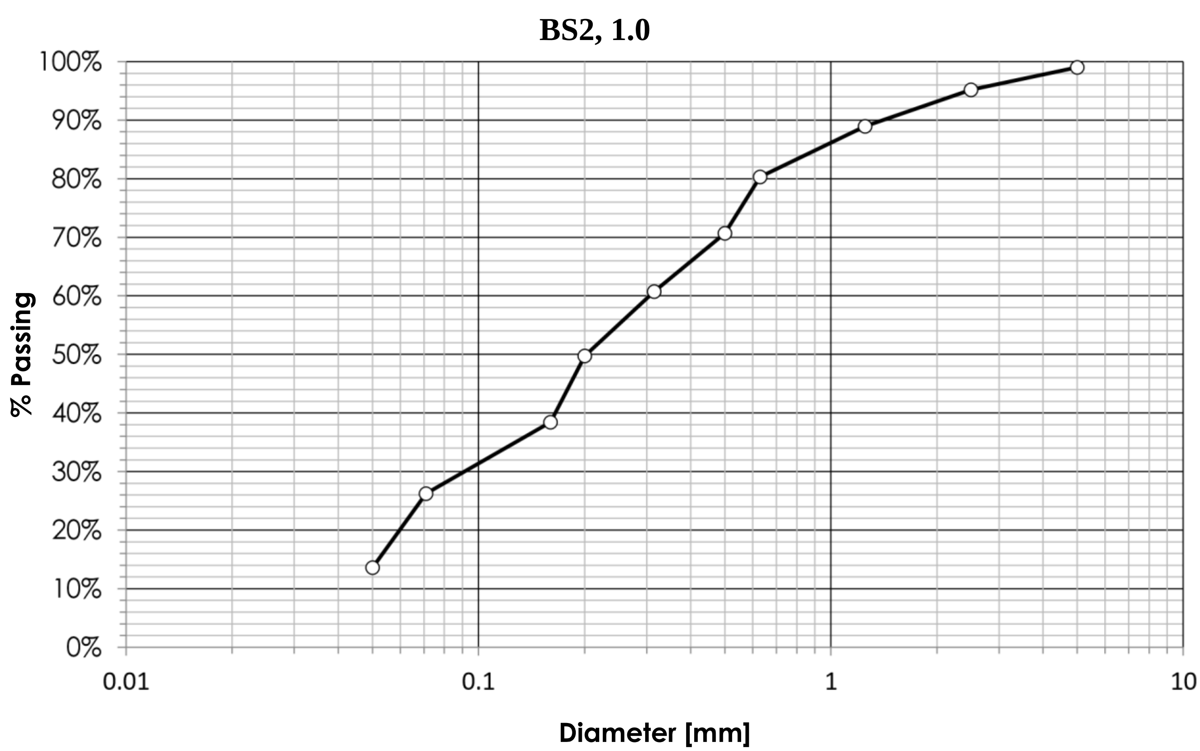


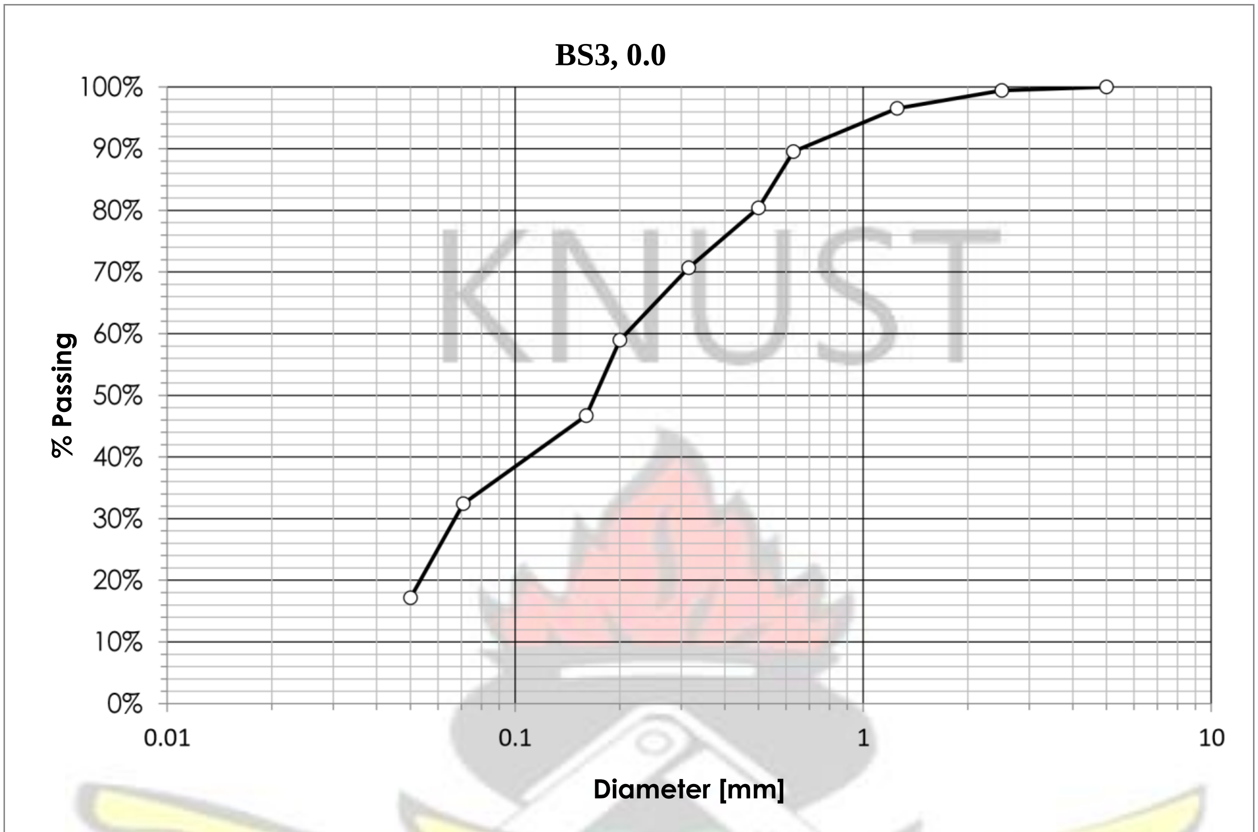


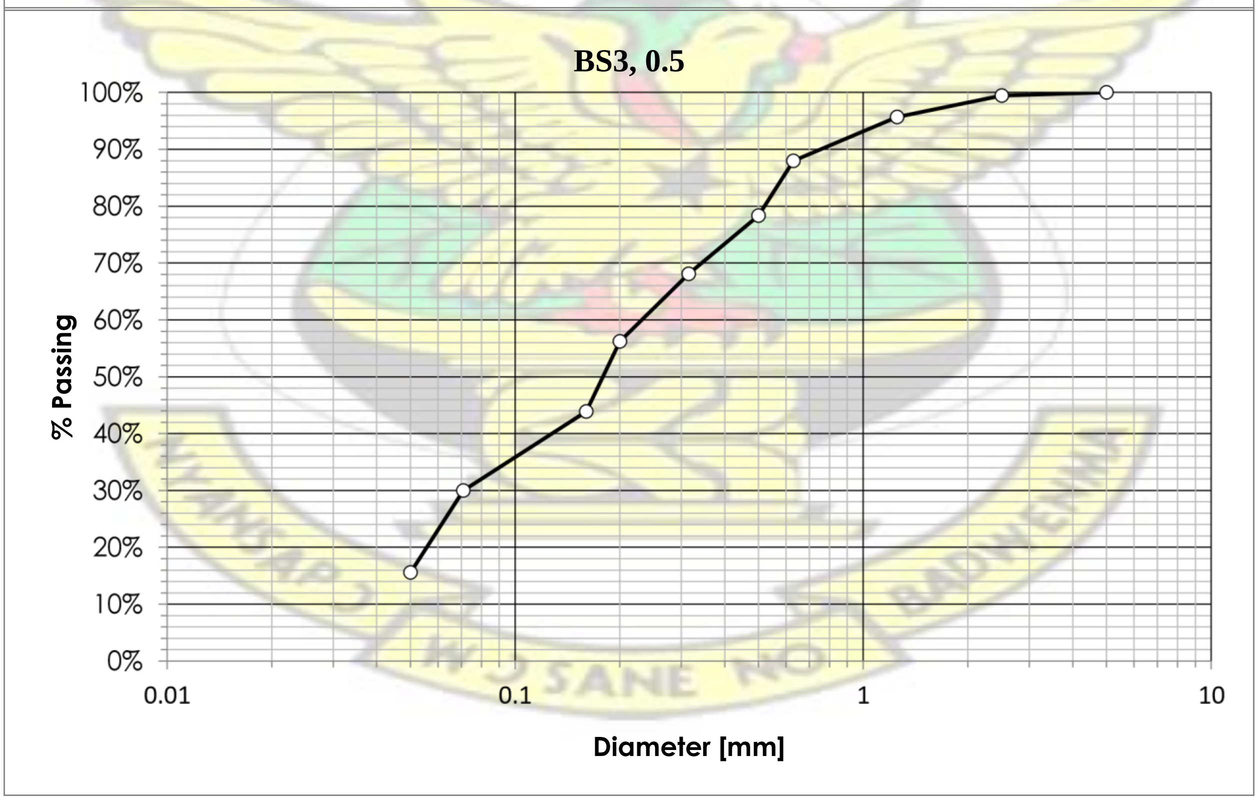

BS1, 1.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

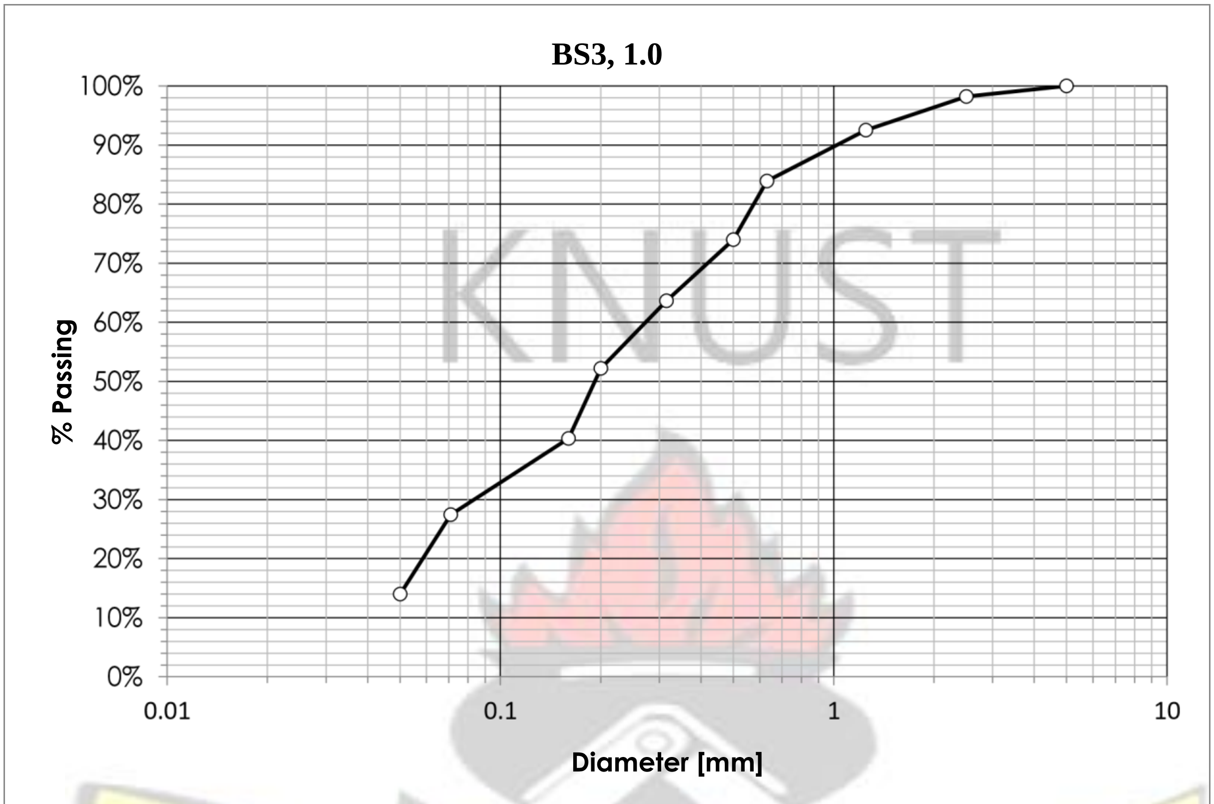

BS2, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

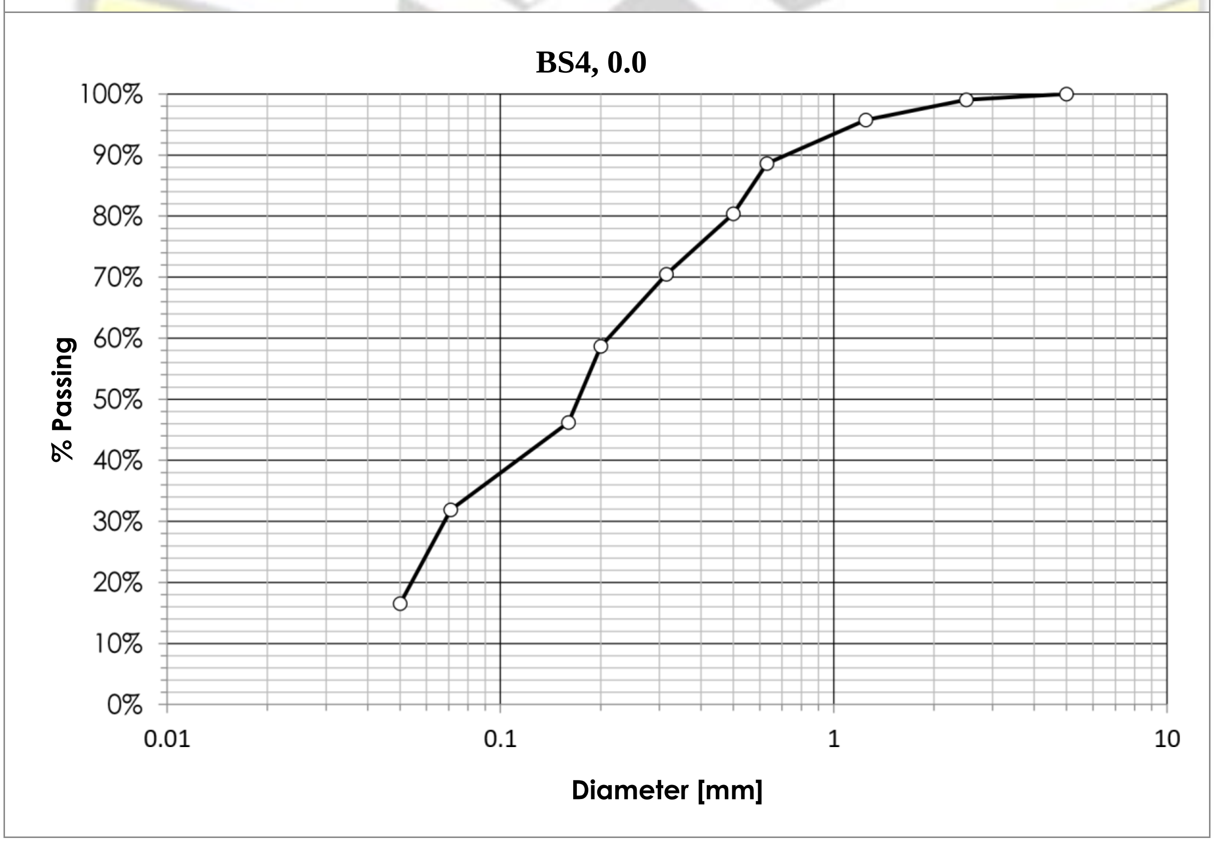

BS2, 0.5
% Passing
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.01
0.1
1
10
Diameter [mm]

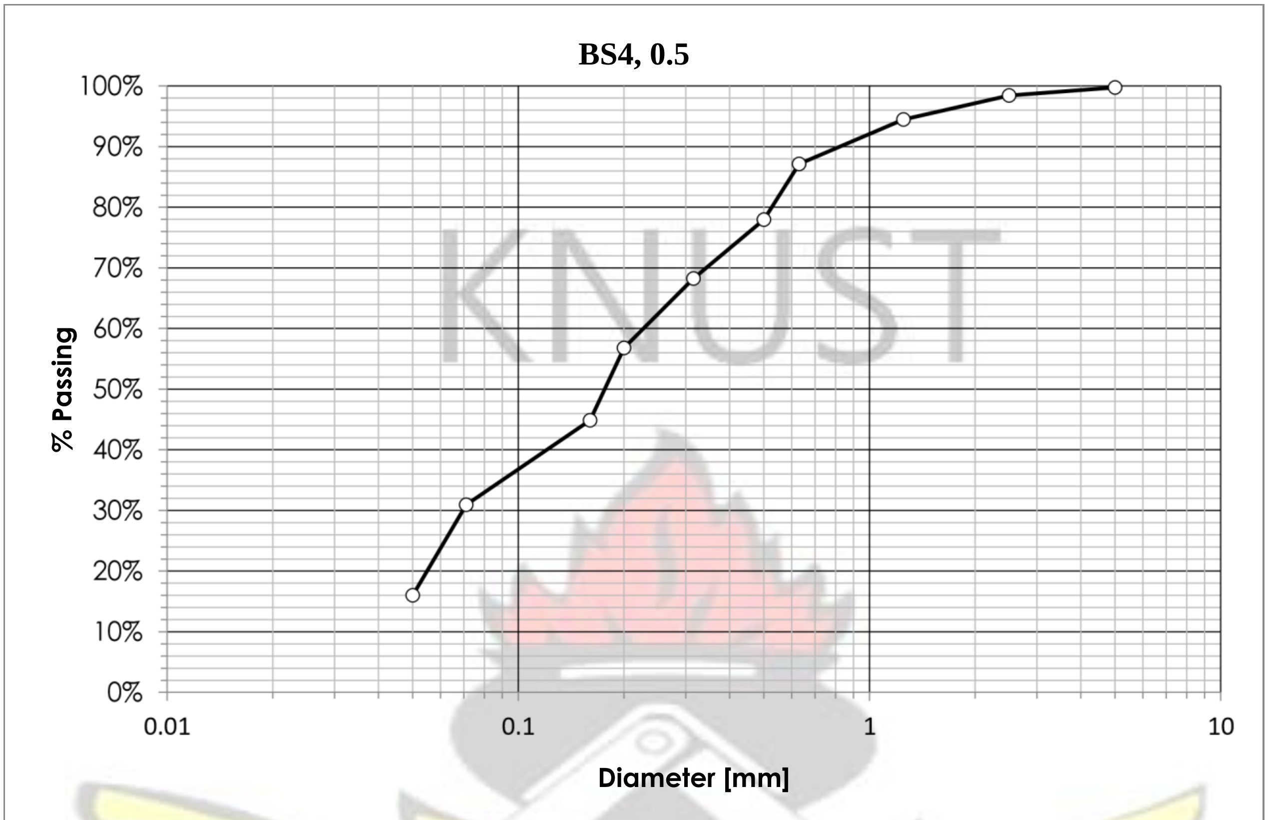

BS2, 1.0
% Passing
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.01
0.1
1
10
Diameter [mm]


BS3, 0.0
% Passing
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.01
0.1
1
10
Diameter [mm]

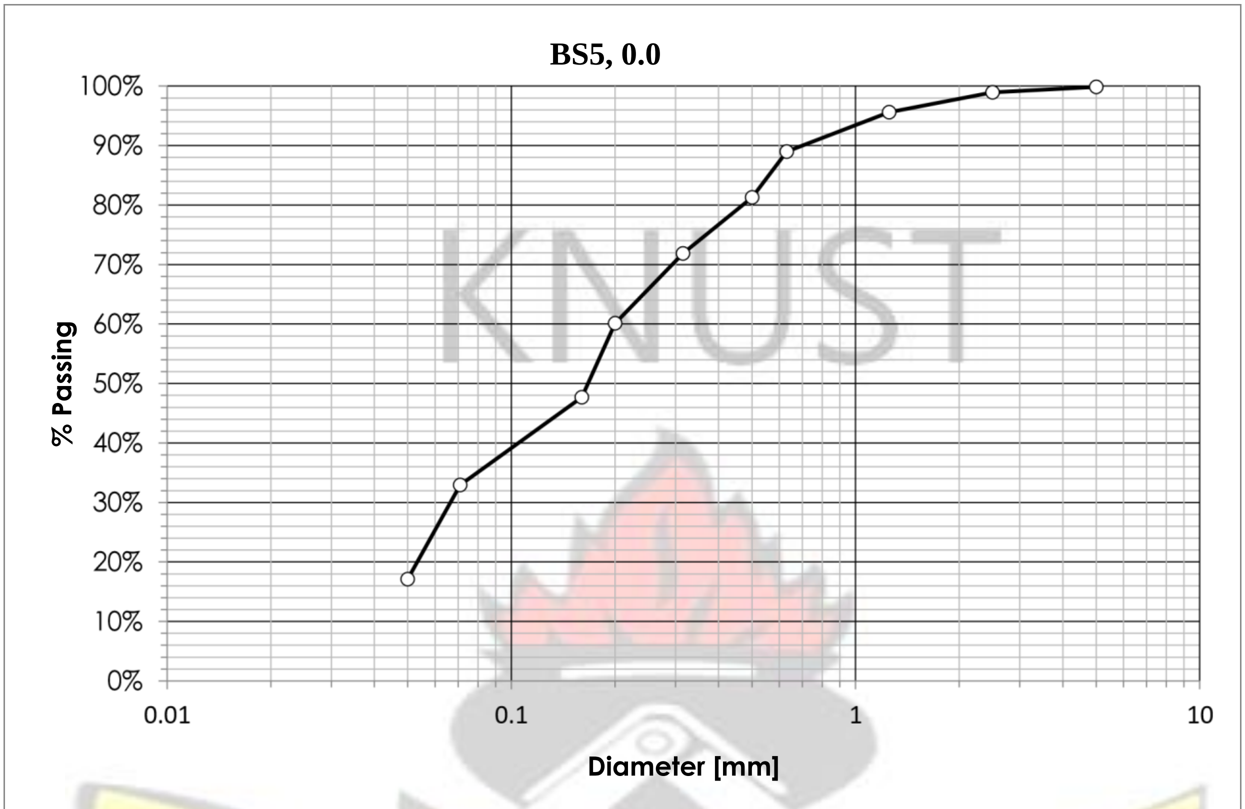

BS3, 0.5
% Passing
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.01
0.1
1
10
Diameter [mm]


BS3, 1.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

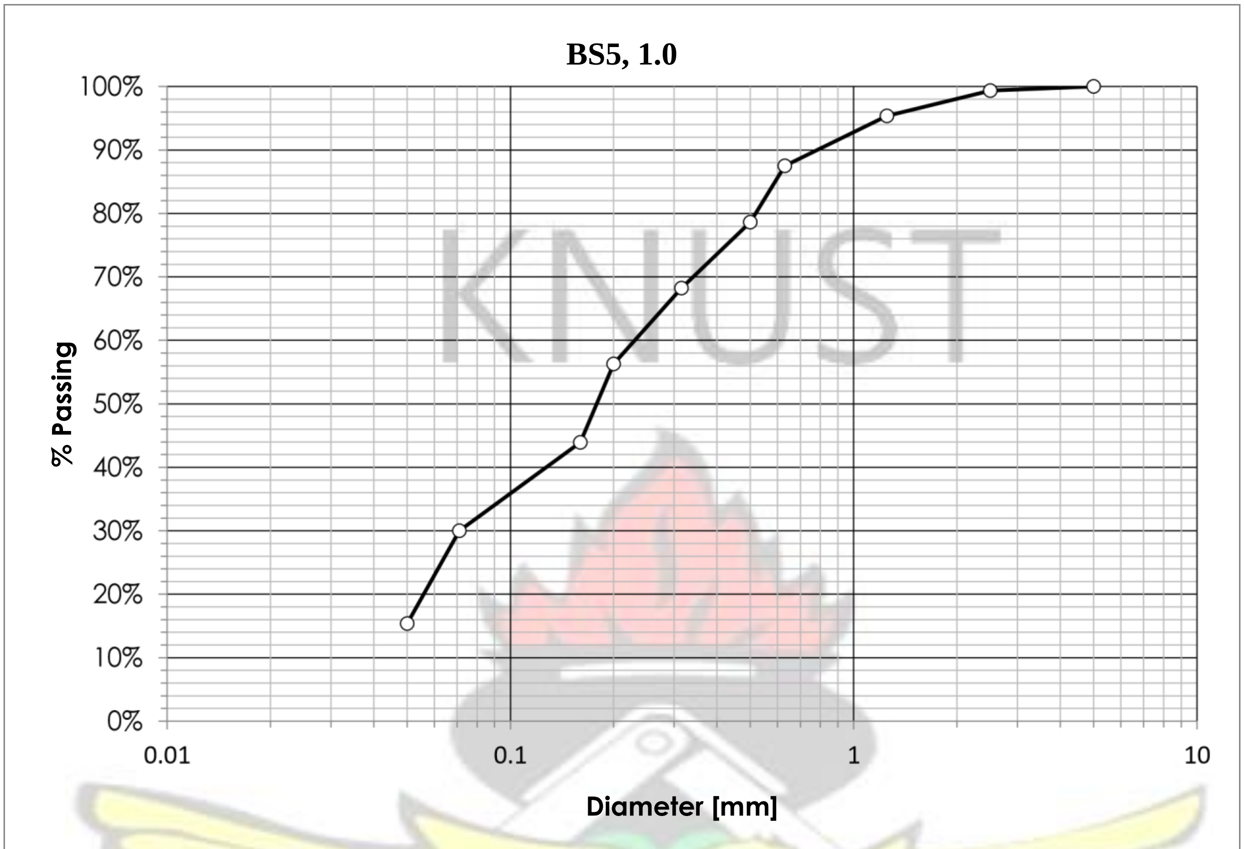

BS4, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]


BS4, 0.5
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

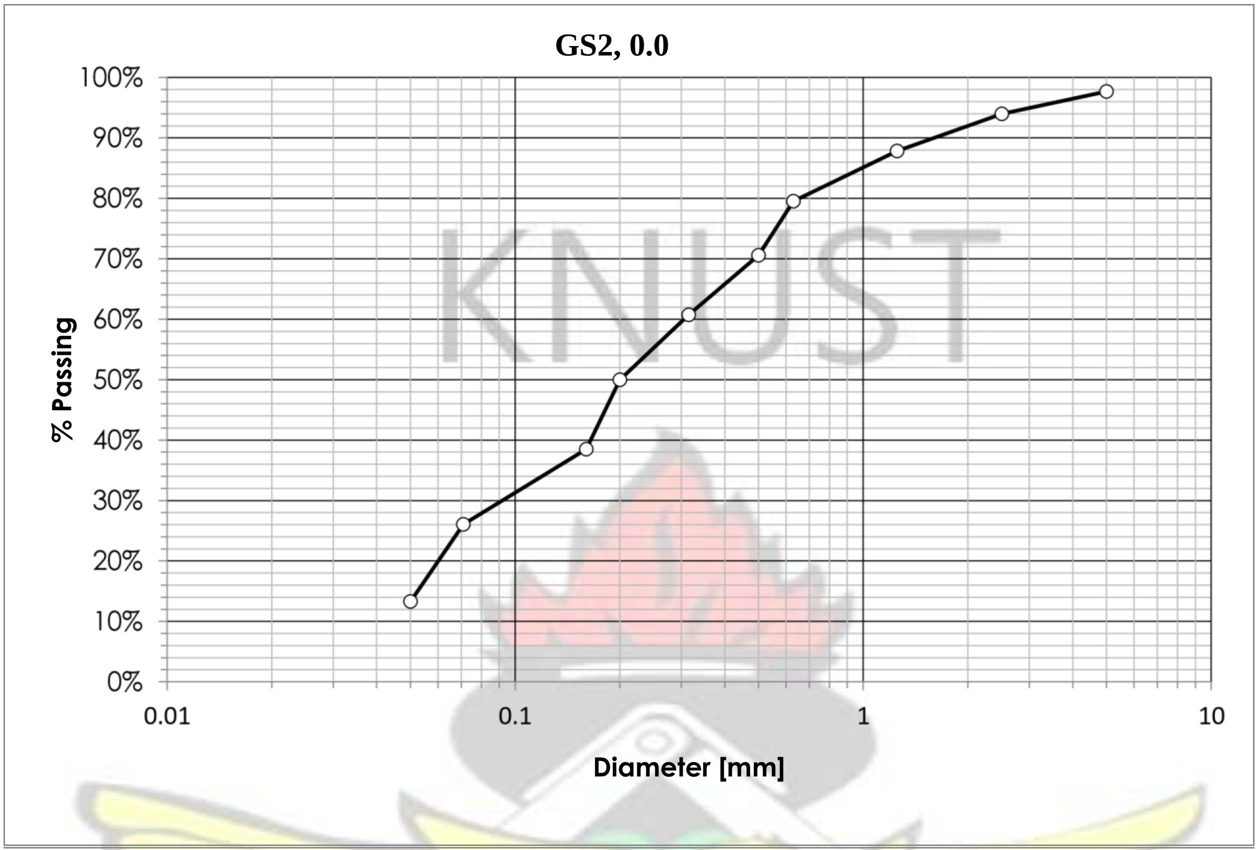

BS4, 1.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

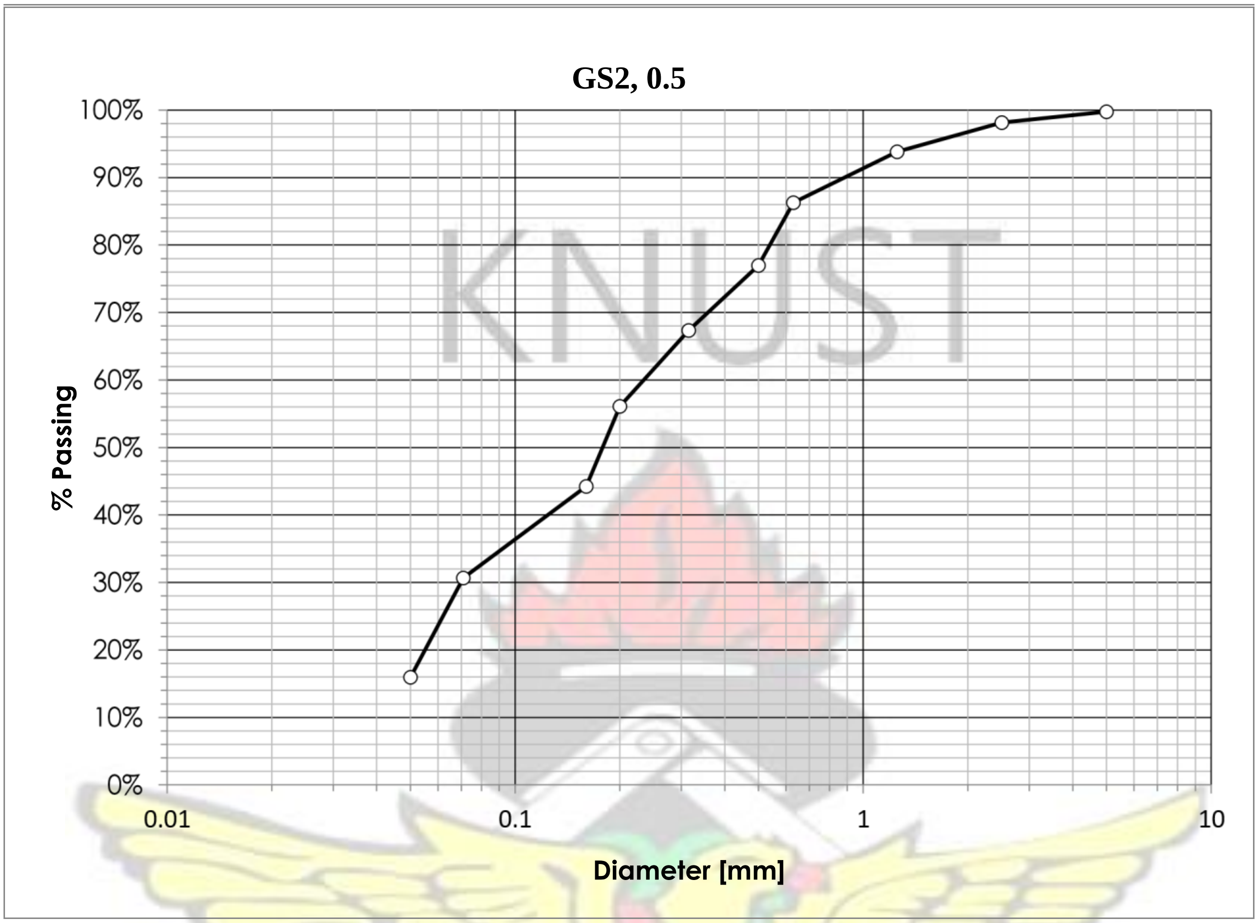

BS5, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

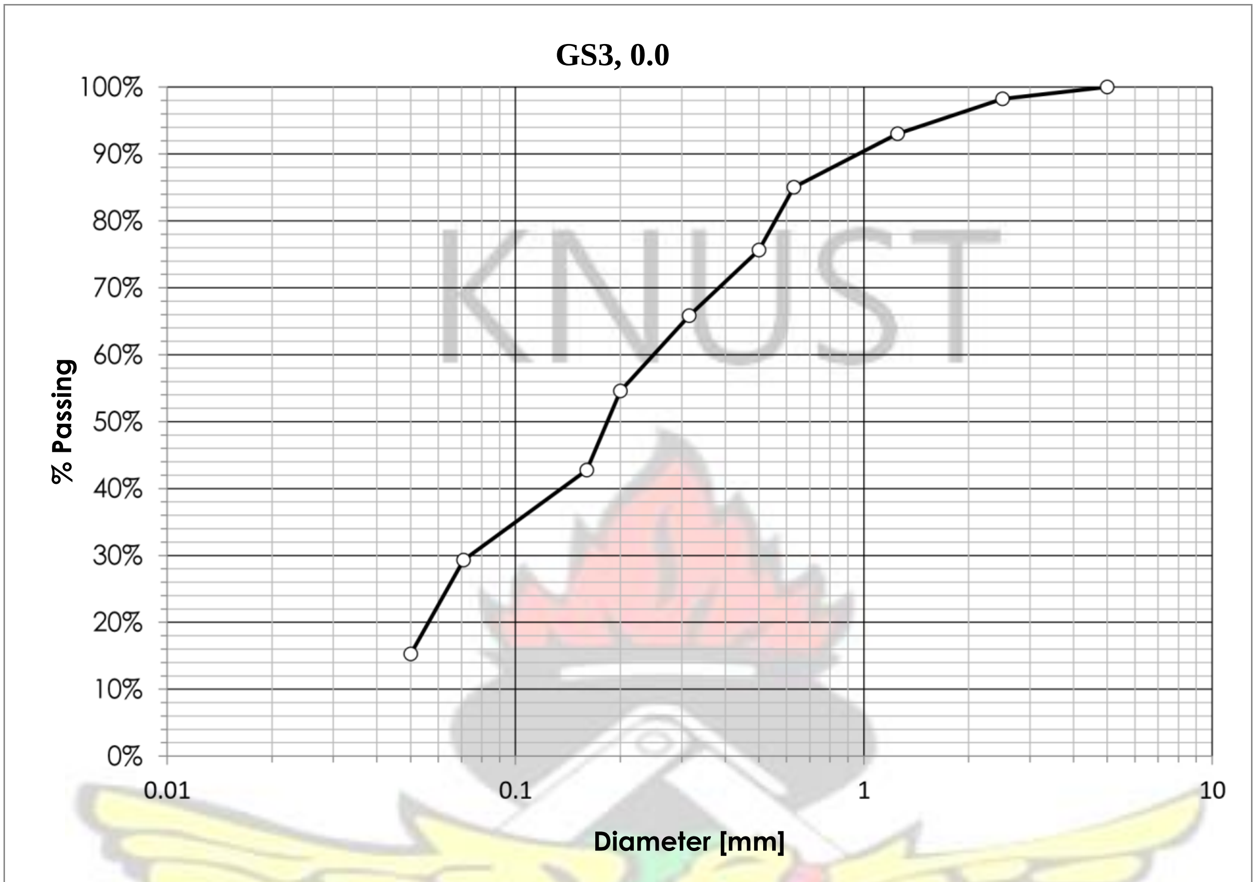

BS5, 0.5
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

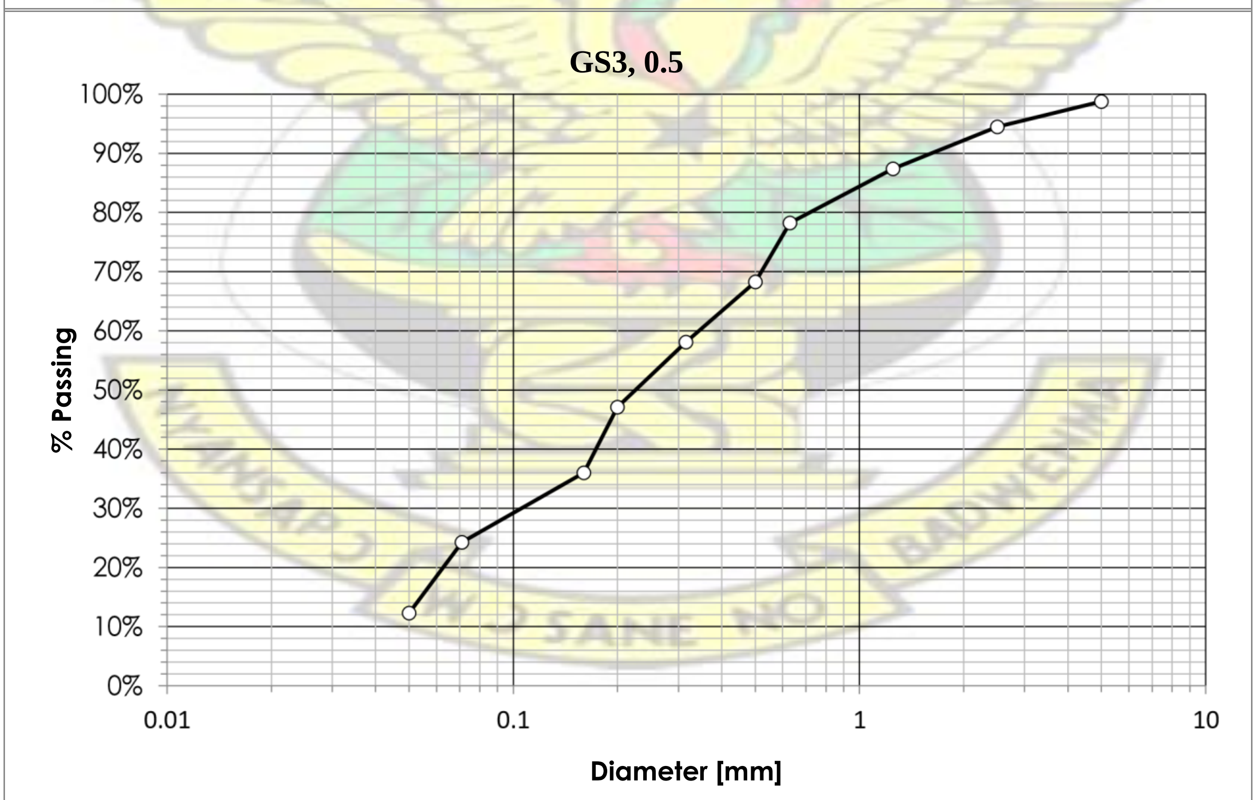

BS5, 1.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

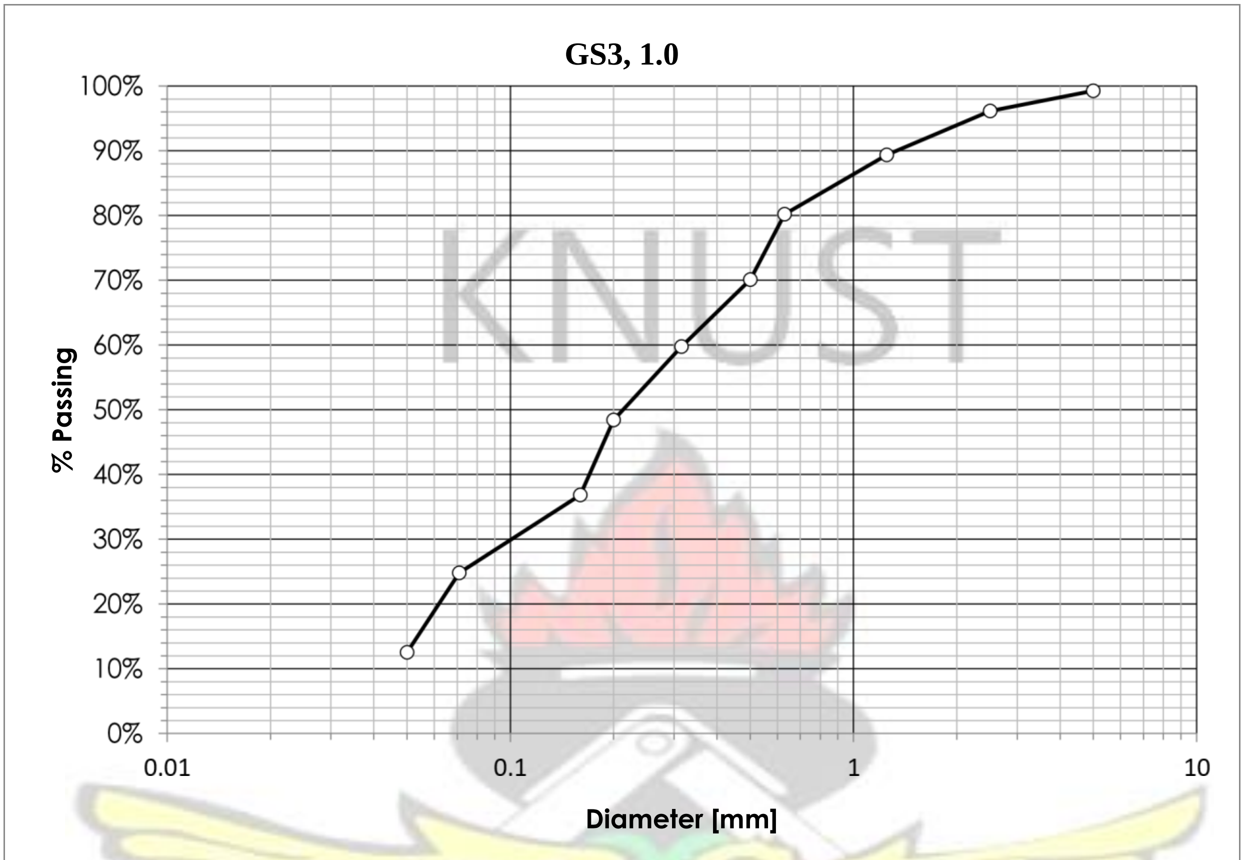

GS1, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]


GS2, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

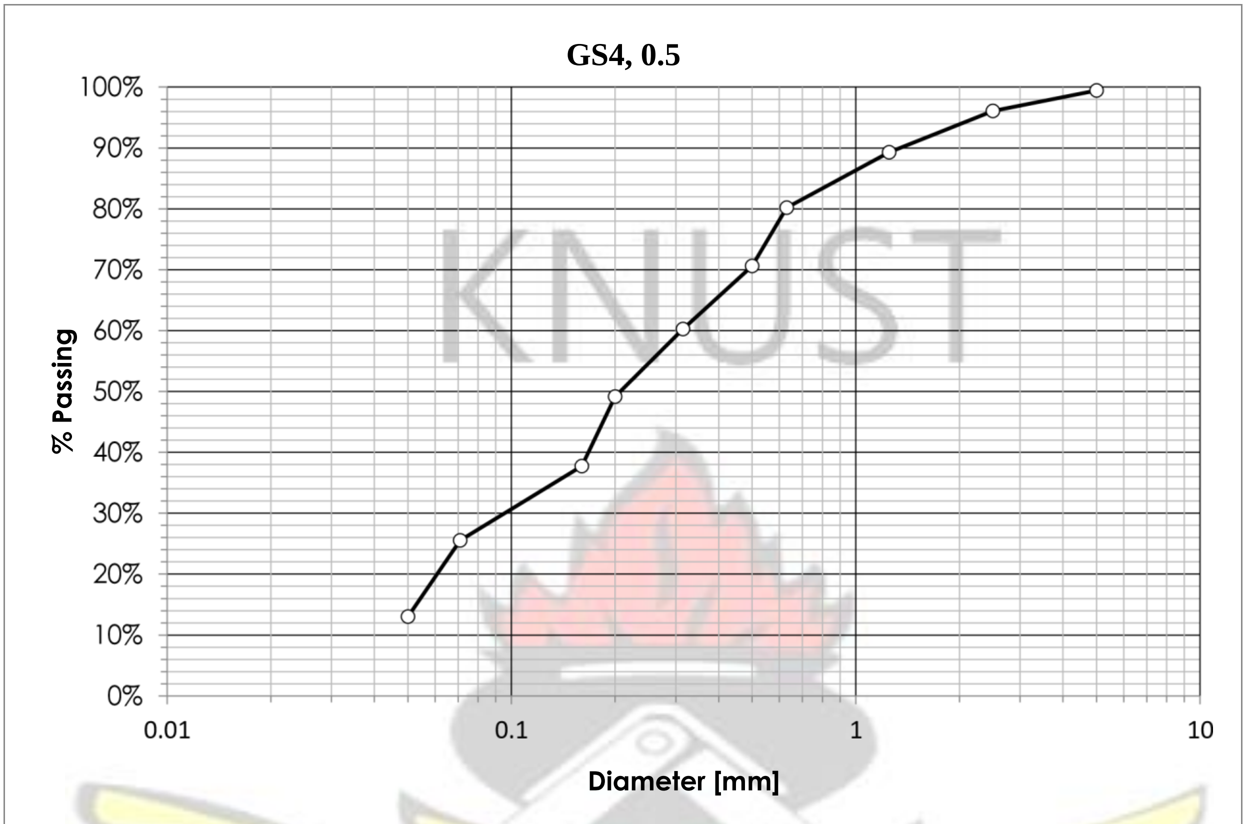

GS2, 0.5
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

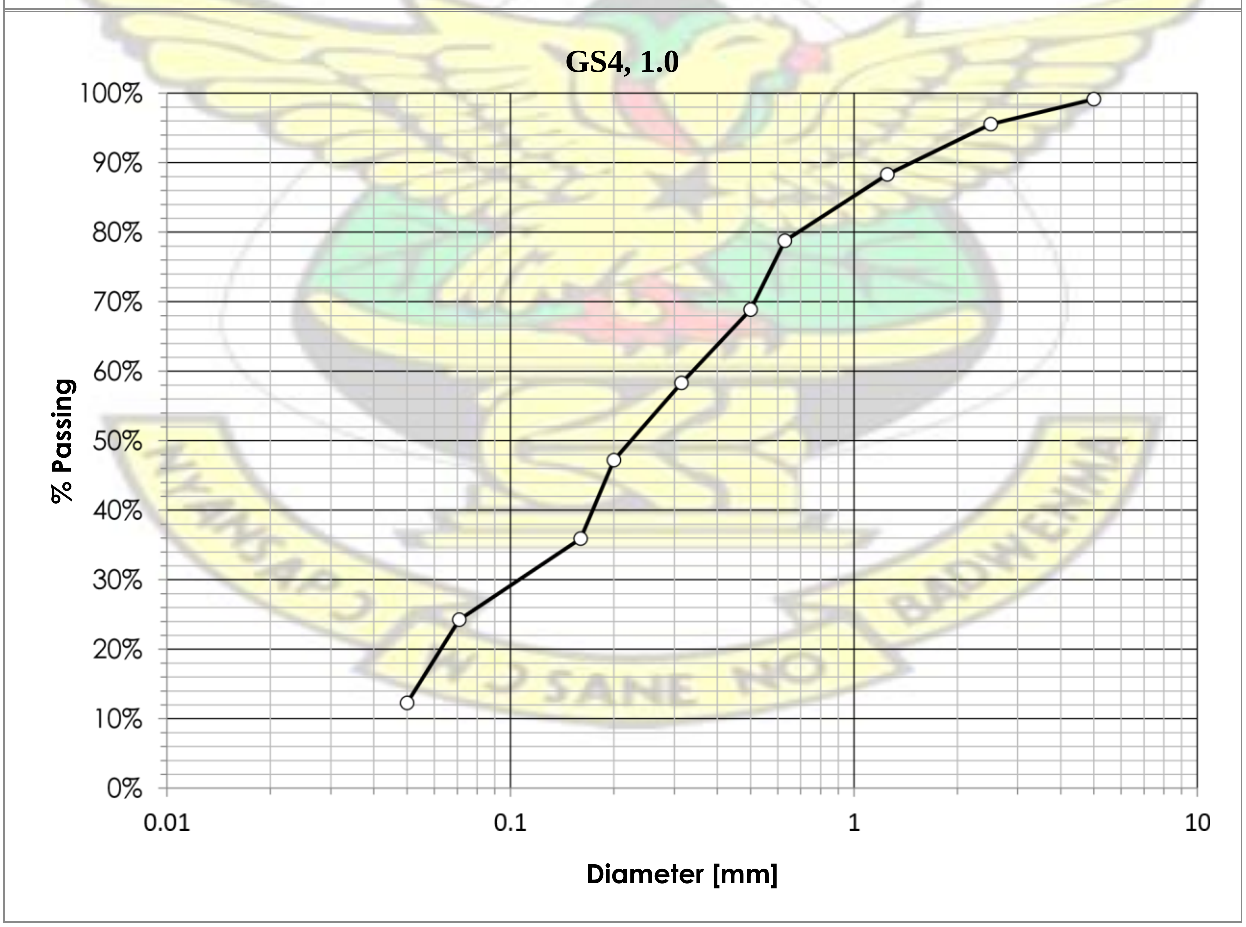

GS3, 0.0
% Passing
Diameter [mm]
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.01
0.1
1
10

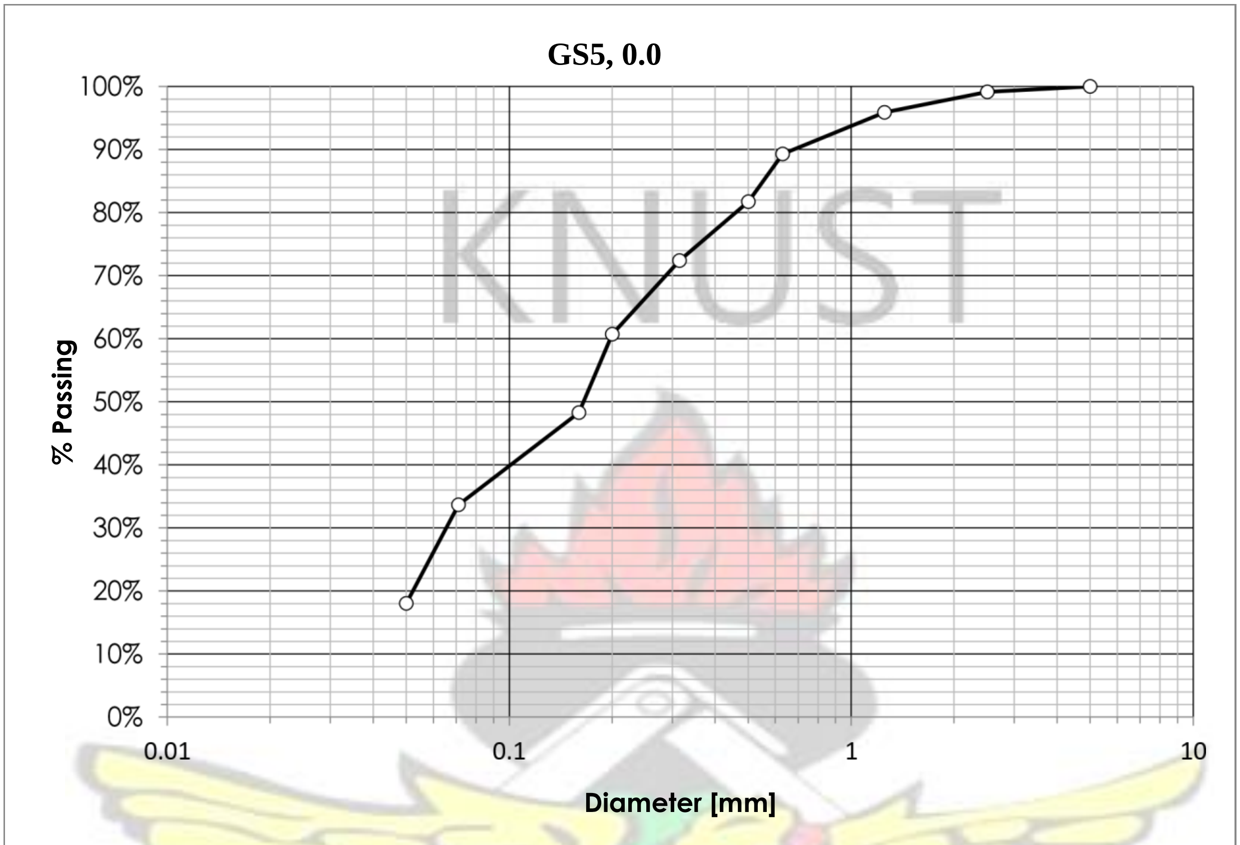

GS3, 0.5
% Passing
Diameter [mm]
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
0.01
0.1
1
10


GS3, 1.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]

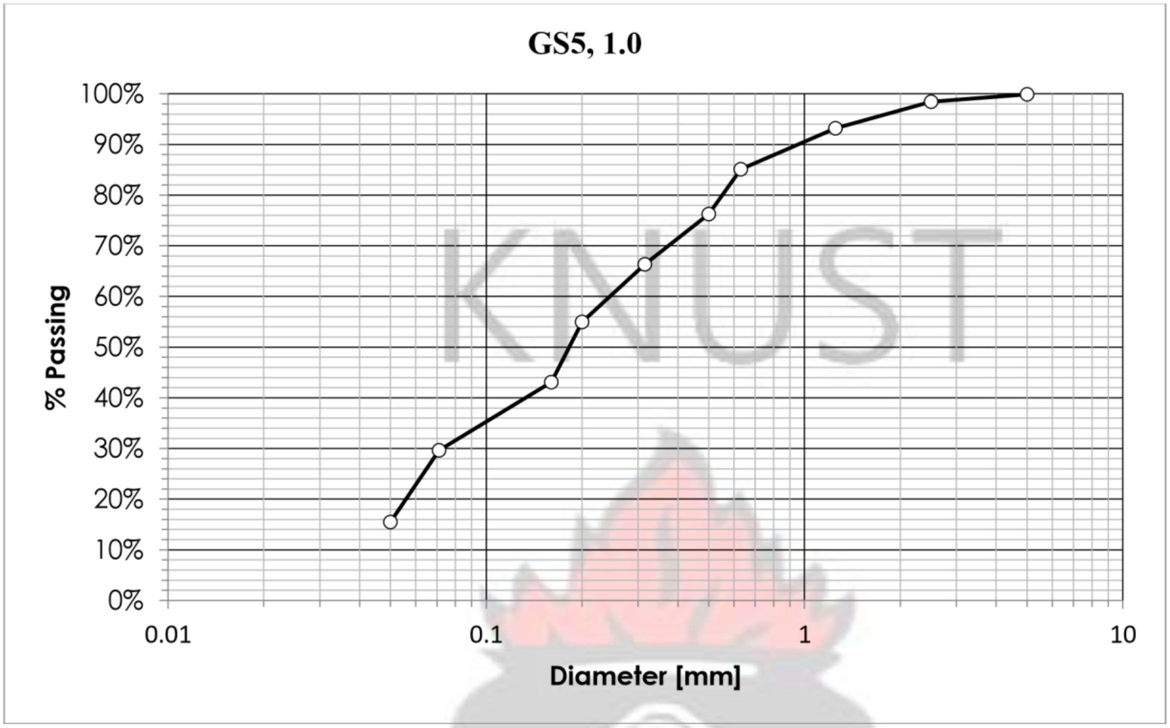

GS4, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]


GS4, 0.5
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]


GS4, 1.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]


GS5, 0.0
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]


GS5, 0.5
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% Passing
0.01
0.1
1
10
Diameter [mm]



Appendix E: List of Plates

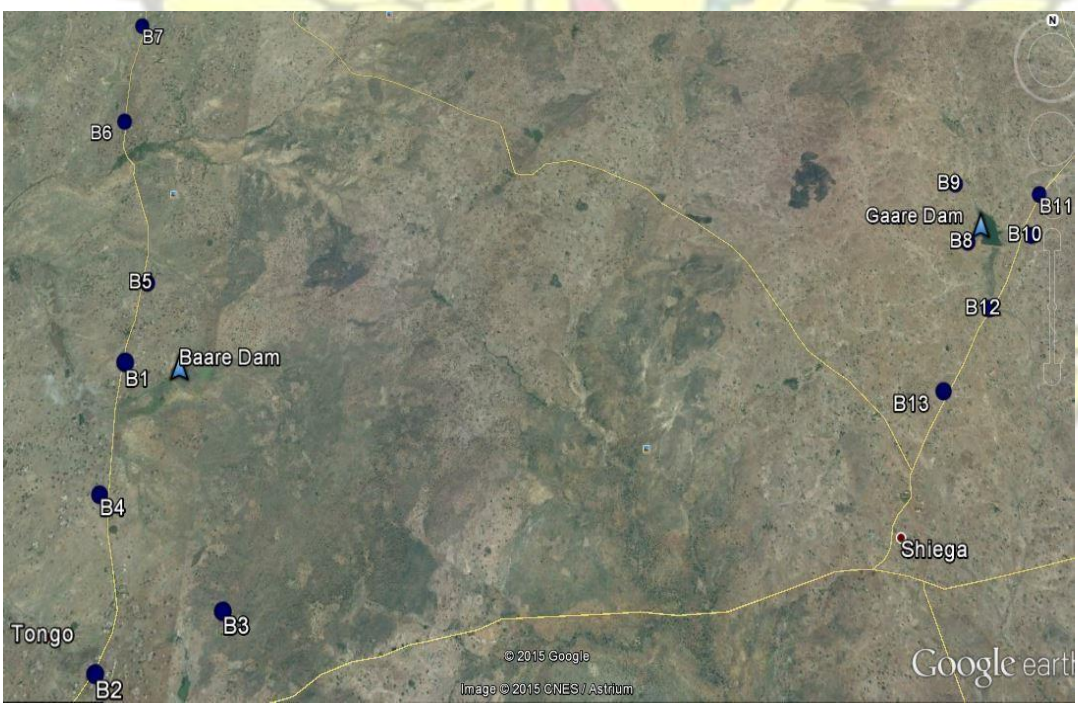


Plate 6.1 Map of study area showing borehole sampling points

Plate 6.2 Map of study area showing hand-dug well sampling points in Baare

Plate 6.3 Map of study area showing hand-dug well sampling points in Gaare

Plate 6.4 A photograph showing one of the boreholes sampled.

Plate 6.5 A photograph showing one of the open hand-dug wells sampled.

Plate 6.6 A photograph showing a closed hand-dug well with a pulley system.