GHANA WATER RESOURCES MANAGEMENT STUDY

INFORMATION BUILDING BLOCK

GEOLOGY and GROUNDWATER

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1. INTRODUCTION

The Volta Basin System consist of five sub basins namely the White Volta Basin, the Black Volta Basin, the Main Volta Basin, Daka Basins and the Oti Basin. These together form approximately 65% of the total Watershed of Ghana.

Due to the extent of the Volta Basin System, the climate, soils and vegetation are largely variable. Rainfall is extremely low in the north and the south and increased gradually to high values in the middle mainly in the Main Volta Basin. Apart from the major rivers which form the basins, most of the streams are ephemeral. It is thus extremely difficult to find portable water in most parts of the Basin Systems during the dry season.

With Economic development and increasing demands for improved water supply and sanitation in the Volta Basin Systems, groundwater through boreholes and hand dug wells have been resorted to. This has resulted in the proliferation of boreholes in the Volta Basin System, particularly in the Black Volta, and White Volta Basins. For example over 2500 boreholes were drilled in the Black and White Volta Basins during the CIDA Projects.

These borehole programmes were carried out without studies into the amount of groundwater recharge, groundwater storage, extent and geometries of aquifers etc. The lack of knowledge on these important parameters couple with recent irregularities in the rainfall probably as a result of climatic change has had adverse effect on the aquifers. Water levels continue falling in some of the wells while others dry up completely during the dry season. To mitigate these adverse effects on groundwater resources development of the Volta River Basin System and provide adequate planning and management of current and future groundwater development projects, it has become necessary to carry out a detailed assessment of groundwater resources based on existing groundwater data.

The earliest groundwater assessment was carried out by Gill in 1964. Inspite of the fact that this assessment was national in scope, it was based on limited data available at the time. Gill (1964) recognizing the limitation of his assessment recommended future groundwater assessment when the data was available. Further groundwater assessment was carried out by Gill (1969), Mallan (1969) and Nathan and Associates (1970).

The first major groundwater assessment based on large data was carried out by Water Resources Research Institute of the C.S.I.R. between 1984 and 1995. This assessment was based on simple statistical analysis of well records on approximately 8,000 boreholes nationwide divided into regions

The present assessment is similar to the earlier one carried out by the Water Resources Research Institute. That is it involves simple statistical analysis of the well records of approximately 6000 boreholes drilled within the Volta Basin System. However this assessment is on Basin Basis instead of Regional Basis. In addition information such as groundwater recharge, groundwater storage and rural water demand, which were not available in the W.R.R.I. report are now provided in the present report.

2.CURRENT INFORMATION

2.1. THE WHITE VOLTA BASIN

2.1.1 Geology

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

2.1.1.1 Birimian Systems

The Birimian System is the oldest rock units in the White Volta Basin. It occurs mainly in the North Eastern and Western parts of the Basin running almost in Southwest - North Easterly direction bounding the Voltaian system in the North - North Western part of the Basin. The Birimian series occurs in two stratigraphic successions namely

i. The Upper Birimian comprising metamorphosed lavas and pyroclastic rocks. This is the dominant Birimian Rock Formation in the Northern and the North Eastern part of the White Volta Basin.

ii. The Lower Birimian consists of phyllites, schists, tuffs and greywackes. This is dominant to the western part of the Basin.

i. The Upper Birimian

The Upper Birimian conformably overlies the lower Birimian. The series consist of great thicknesses of basaltic and andesitic lavas, beds of agglomerate, tuff and tuffaceous sediments. The basic volcanics and pyroclastics have been altered largely to chloritised and epidotised rocks that are loosely grouped together as greenstones (Kesse, 1985).

Where the greenstones have been subjected to metamorphism, they are converted into hornblende schists and amphibolites. In general the folding is intense with dips commonly of the mode of basic intrusions of 30^o - 90^o along the northwest southwest axes.

ii. The Lower Birimian

The lower Birimian series consists of great thicknesses of isoclinally folded, steeply dipping, alternating slates, phyllites, greywackes and argillaceous beds with some tuffs and lavas close to granitic intrusives. The slates and phyllites have been commonly altered to quartz-biotite schists frequently with garnet and staurolitic-rich bands while the impure sandstones have changed to granulite and quartz schists (Kesse, 1985).

2.1.1.2 The Granitoids

The Birimian System is intruded by Granitoids of uncertain age but which are believed to be post-Birimian and pre-Tarkwaian age (Kesse 1985). These Granitoids occur mainly to the northern and western parts of the White Volta Basin.

Three main varieties of Granitoids occur in the White Volta Basin. These are;

a). The Cape Coast/Winneba type (older Granitoids)
b) . The Dixcove type (younger Granitoids)
c). The Bongo Potassic Granitoids

i. The Cape Coast/Winneba Granitoids

The Cape Coast and Winneba Granitoids are often well foliated, magmatic, and potassium-rich. They are usually in the form of muscovite biotite granite and granodiorite, phyroblastic biotic gneiss, aplites and pegmatites. These granitoids are characterised by the presence of many enclaves of schists and gneisses, and are usually associated with the Birimian metasediments (Kesse 1985).

ii. Dixcove Granitoid Complex

The Dixcove Granitoid Complex consist of hornblende granites, granites and granodiorites grading locally into quartz-diorite and hornblende-diorite. This complex is usually sodium rich and forms non-foliated discordant to semi-discordant bodies in the enclosing country rocks which are mostly the Upper Birimian meta-volcanics with numerous enclaves which are found within the granitic complex. The Dixcove Granitoid complex is intruded along deep-seated faults in three distinct phases which follow one another from basic to acidic gabbro-diorite-granites.

iii. The Bongo Granites

The Bongo granites occurs to the top central portion of the White Volta Basin. It is located between longitude 1^0 30' W and 1^0 40' W and latitude 10^0 50' N and 11^0 0' N. They are porphyritic, hornblende-microline plutonic Granites that are locally found in the north-eastern Ghana. They are thought to be younger than the Dixcove Granite (Kesse 1985).

2.1.1.3 The Tarkwaian Systems

Isolated patches of Tarkwaian Rocks occur in the north-eastern part of the White Volta Basin. These Tarkwaian Rocks consist mainly of quartzites, phyllites, grits, conglomerates and schists. The Tarkwaian is thought to rest unconformable on the Birimian, though in some places, the Upper Birimian and the Tarkwaian are interfolded due to the post-Tarkwaian aerogenic activity (Junner, 1935, Junner and others, 1942).

2.1.1.4 The Voltaian Systems

The Voltaian Systems cover a large part of the central, the Eastern and the Southern parts of the White Volta Basin. The Voltaian systems rest unconformable on the Birimian, the Granite and Tarkwaian formations. They are considered to be of late Precambrian to Paleozoic age. It comprises 3000-4000m of horizontal sandstones, shales and mudstone beds.

Three main stratigraphic subdivisions of the Voltaian Systems occur in the White Volta Basin viz:-

i. The Basal Sandstone which is mainly massive quartz sandstone about 75m thick and occurs at the northern and western peripheries of the Voltaian system. It unconformable overlies the Upper Birimian in the north and the Lower Birimian in the west.

ii. The Upper Voltaian which is mainly massive and thin bedded quartzitic and micaceous sandstones. These occur mainly towards the Northern and Western margins of the Voltaian system. Geographically they are mainly located between latitude 10^0 20' N and 10^0 47' N and longitude 0^0 15' W and 0^0 42' W in the North. In the West they are located between longitudes 1^0 11' W and 1^0 47' W and latitude 9^0 5' N and 10^0 5' N. They form approximately 30% of the Voltaian system within the White Volta Basin.

iii. Obosum Beds which are mainly beds of argillaceous sandstones, arkose, siltstones, interbedded mudstone, sandy shale and conglomerates. These form about 55% of the Voltaian system within the White Volta Basin. These occur mainly to the south-south-east and the central parts of the White Volta Basin.

A minor portion of the Oti beds consisting of siliceous sandstone, pebbly grits and arkosic conglomerates occur between Gariwe and Yamalkaraga to the South-Eastern part of the White Volta Basin. Its geographical coordinates are latitudes 9^0 30' N and longitude 0^0 30' W.

2.1.2 Groundwater Conditions

2.1.2.1 Groundwater Occurrence

i. Crystalline Basement Complex Aquifers

Crystalline rocks are essentially impermeable and virtually have no primary porosity. Aquifer development is dependent on the formation of secondary porosity as a result of fissuring or weathering. Consequently most of the groundwater resources within the Northern and the North Eastern part of the White Volta Basin are obtained from the Crystalline Basement Complex, principally in the upper weathered rock or within faults and fractures in certain rock types. The weathering is brought about as a result of water circulating through joints, fractures and quart veins which were earlier developed in these rocks.

Generally the potash rich Muscovite or hornblende bearing granites weather to a mean depth of 30m while the metasediments of the Birimian formation weather to a much greater depth reaching a depth of 73m (Wardrop, 1978) thus giving rise to the development of thicker Aquifers.

Two types of Aquifers thus exist. These are the weathered zone aquifers and the fissured zone aquifers. These aquifers are either phreatic semi-confined or confined depending on the clay and mica content of the upper weathered layer. The weathered zone aquifers develop in:

a).a highly weathered zone where only quartz remains intact.

b).a moderately weathered zone in which the less resistant minerals are partly decomposed.

c).a thin zone of only slightly decomposed rock.

d).the rock underlying zone of more or less fresh rock which is usually broken or fractured.

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

ii.The Voltaian Rocks

Many of the sedimentary rocks of the Voltaian Basin have undergone a slight degree of metamorphism and are well compacted and consolidated. Groundwater occurrence is therefore structurally and textually controlled. That is groundwater occurrence is closely associated with the existence of faults, joints, fractures bedding planes and weathered zones as well as the grain sizes of the beds.

The Upper Voltaian consisting of sandstones, quartzitic and fieldspartic sandstones are fairly hard and well consolidated and therefore inherently impermeable. It is however characterised by well developed and extensive open joints, permeable bedding planes and faults particularly very close to the Birimian contact. These fissure zones give rise to deeper groundwater circulation and thus the occurrence of relatively high yielding aquifers. In the Gambaga highlands in the north and the Konkori highlands in the west good yielding aquifers exist.

The units of the Middle Voltaian are well consolidated and compacted and are therefore essentially impermeable. Groundwater occurrence is dependent on the development of secondary permeabilities as a result of fracturing and jointing and the existence of permeable bedding planes. Groundwater also occurs in significant quantities when these rocks are heavily schistosied. Where shales, silty sands and mudstones occur, groundwater potential is low and only in weathered and fissure zone that groundwater can be expected to occur in appreciable quantity. Where perennial streams flow over land underlain by fissured Obosum and Oti beds, significant recharge occurs giving rise to high yielding aquifers.

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

2.1.3Groundwater Recharge and Discharge

Recharge to the aquifer systems in the White Volta Basin occurs in two forms: direct and indirect recharge.

Direct recharge occurs in the highland areas particularly around the Gambaga and the Konkori highlands as well as within the alluvial deposits in the relatively higher rainfall areas where unconsolidated soil cover and the sandy weathered zone provide the storage and permeability for rain water to percolate through the unsaturated zone to the groundwater table after satisfying the soil moisture deficit. Direct recharge also occur through the fractured or jointed and the weathered rock outcrops of the Birimian and the Basic Intrusive rocks. Rain water percolates through these fractured or jointed or weathered portions of the exposed rock in a colluvial manner.

Indirect recharge principally occurs in the lower rainfall, low relief and low permeability areas particularly within the Voltaian Basin. This happens when runoff from the watershed outside the area or a particular storm event is of sufficient magnitude to cause runoff. The drainage courses or stream which act as conduit for these overland flow are generally weak fissured zones which allow a greater part of the runoff to infiltrate through their beds to the groundwater table. Permanent streams also contribute significant amount of water to the zone of saturation either by infiltration through permeable stream beds, bank storage through alluvial soil or when the stream intersect a fractured, jointed or fault zone.

2.1.3.1Direct Recharge Estimation

Direct Recharge is that portion of the rainfall which reaches the water table directly after runoff, evapotranspiration and soil moisture deficits have been accounted for. Quantification of the concept of direct recharge requires the introduction of the hydrologic budget or water balance equation that describes the hydrologic regime in the watershed. The water balance equation which is used for the estimation of Direct Recharge is given by

$$D = P - R - E \qquad (1)$$

Where P = Precipitation
R = Runoff
E = Evapotranspiration
D = Direct Recharge

This equation is justified in the White Volta Basin since it is underlain by Crystalline Basement Complex and well consolidated and compacted sedimentary rocks with well defined watershed divides. Thus both surface and groundwater inflows are zero. Furthermore since most of the aquifer are formed in hard rocks due to the crystalline nature and the degree of consolidation of the sedimentary formation, groundwater outflow (base flow) forms an insignificant part of the total runoff and therefore can be neglected. Additionally the data available for the computation of direct recharge extends over 30 years, thus the change in groundwater storage within the Basin is essentially zero.

The precipitation and runoff figures used for the computation of direct recharge were the mean runoff and precipitation figures computed over 30 years and quoted in the Land and Water Survey in the Upper and Northern Regions of Ghana Final Report (FAO/UNDP, 1967). The potential evapotranspiration figures were those computed over six years within the same period. The data for three stations notably Navrongo (within the White Volta Basin), Wa and Tamale which are outside but are respectively very close to the West and South East margins of the White Volta Basin are used for computation of the approximate direct recharge. (Table 1)

The runoff coefficient for the White Volta Basin is estimated as 10.8% of the mean annual rainfall (FAO/UNDP, 1967). Thus inserting this value into equation 1 above, the Direct Recharge is given as

$$D = 0.89P - E \qquad (2)$$

If the soil is saturated to field capacity then evapotranspiration takes place at a rate equal to the potential evapotranspiration rate. The soil may be saturated to field capacity only during those months that precipitation exceeds potential evapotranspiration. The months that precipitation exceeds the potential evapotranspiration rates in the White Volta Basin are July, August and September. Thus these are the month with the highest potential for direct recharge. Table 2 shows the computation of the estimated directed recharge using equation (2). Thus the estimated direct Groundwater recharge for the White Volta Basin is 151.1mm/year or 13.3% of the mean annual precipitation. This value may be the minimum direct groundwater recharge since recharge can also take place in a heavy storm even when there is a large soil Mositure Deficit (Rushton and Redshaw, 1979).

2.1.3.2 Indirect Recharge

Indirect recharge occurs mainly through permeable runoff channels and stream beds. On quantitative bases it is regarded as a significant source contributing to aquifer inflow. There is not enough data however to compute indirect recharge.

2.1.3.3 Groundwater Discharge

The Potential Evapotranspiration exceeds the average monthly precipitation for most part of the year. Even those month in which the precipitation exceeds Potential Evapotranspiration. Potential Evapotranspiration forms 66% of the precipitation. This implies that evapotranspiration is the dominant loss factor in the hydrologic cycle of the White Volta Basin. The other mode of natural groundwater loss although minor is base flow during wet periods.

2.1.4Groundwater Flow Distribution

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

2.1.5Aquifer Characteristics

2.1.5.1Piezometric Levels

The discrete nature of aquifers and lack of long term monitoring of water levels have rendered the construction of piezometric maps impossible. However to good approximation static water levels can be used to represent the piezometric levels

2.1.5.2 Static Water Levels

The static water levels generally vary from 0.0m (flowing well) to 34.0m with a mean value of 9.3m. In the Crystalline Basement Complex (Granitoids and Birimian Formations) the Static Water Levels vary from 0.0m to 26.5m with a mean value of 6.9m. The comparison of the mean Static Water Level with the mean depth to aquifer value of 18.2m suggests that most of the aquifers in the Cystalline Basement Complex are either confined or semi confined. This is probably due to the presence of high content of clay and mica in the weathered zone (the regolith).

2.1.5.3 Borehole Yields

Generally the yield of boreholes vary from $0.03m^3$ h^{-1} to $24.0m^3$ h^{-1} with a mean value of $2.1m^3$ 1^{-h} suggesting that most of the aquifers are low yielding. However most of the boreholes data were generated by drilling programmes which emphasized only hand pumped boreholes for rural communities. Thus the boreholes were completed anytime adequate yield to meet rural supply was obtained. Consequently most of the boreholes were only partially penetrating the saturated thickness of the aquifer leading to generally low yielding boreholes.

The yield of boreholes in the Crystalline Basement Complex of the White Volta Basin varies from $0.03m^3$ h^{-1} to $24.0m^3$ h^{-1} with a mean value of $2.1m^3$ h^{-1} while in the Voltaian rocks terrain the yields are within the range 0.6 - $18.0m^3$ h^{-1} with a mean value of $3.8m^3$ h . This implies that borehole yields are generally higher in Voltaian sandstone than the Crystalline Basement Complex although there are isolated boreholes which are high yielding within the Crystalline Basement Complex.

2.1.5.4 Specific Capacity

Specific Capacity is more reliable than airlift yield as a measure of aquifer characteristics since it not affected by uncertainties due to air-water ration or submergence ratio (Hazell et al, 1992). High specific capacities usually indicate a high coefficient of transmissivity and low specific capacities generally indicate low coefficient of transmissivity.

In the White Volta Basin specific capacities vary widely from 0.01 - $21.10m^3$/h/m with a mean value of $0.5m^3$/h/m suggesting generally low transmissivity inspite of the fact that these specific capacities may be affected by partial penetration, well loss or hydrogeologic boundaries.

In the Crystalline Basement rock areas, the specific capacities vary from 0.01 - $21.1m^3$/h/m with an average value of $0.58m^3$/h/m. This implies that to obtain a village water supply of 18 litres per minute, the draw down is expected to be on average less than 2m. The specific capacity in the Voltaian varies from $0.02m^3$/h/m to $1.80m^3$/h/m.

2.1.5.5 Depth to Aquifer

The depth to aquifer generally varies from 3.7m to 51.5m with a mean value of 18.4m. In the area underlain by the Crystalline Basement Complex, the depth to aquifer varies from 3.7m to 51.5m with a mean value of 18.2m while in the area underlain by the Voltaian formation the depth to aquifer varies from 13.0m to 76.0m with a mean value of 27.0m. The mode of depth to acquifer indicate that most of the aquifers in the area underlain by the crystalline Basement Complex are within the 30m of the landsurface.

Similarly the aquifer within the Voltaian Sedimentary areas are within the 35m of the landsurface. The implication of this is that the probability of finding water beyond the depth of 30m in the Crystalline basement Complex and 35m in the Voltaian Sedimentary rock area are very low.

2.1.5.6 Depth of Boreholes

Boreholes are generally shallow within the White Volta Basin. The depth of Boreholes vary from 7.4m to 123.4m with a mean value of 24.7m. In the Crystalline Basement Complex area the borehole depth are within the range 7.4 - 123.4m with a mean of 24.4m while in the area underlain by the Voltaian Formations, the boreholes have depths within the range 27.0 - 91.1m with a mean value of 42.1m. It should be noted however that most of these wells are partially penetrating.

2.1.5.7Relationship between Borehole Depth and Yield

Since the hydrogeology of the White Volta Basin is controlled by secondary porosities the deeper the borehole, the higher the probability that it will intercept a lot of fissures and consequently the higher the yeild. A plot of borehole yeild against borehole depth (Fig. 3) however has shown no discernible picture since some boreholes as shallow as 25m have yields above $10m^3h^{-1}$ while others as deep as 70m have yields less than $3m^3h^{-1}$.

2.1.5.8 Groundwater Storage

In the White Volta Basin most of the aquifers are produced in poorly to moderately decomposed rocks. The mean saturated thickness of the poorly to moderately weathered rock (aquifer horizon) is 13.6m. Assuming the porosity of the aquifer materials (the poorly to moderately decomposed rocks) is 10% (Van Ess, 1984) and the percentage of the poorly to moderately weathered material to unweathered material is 60%. The White Volta Basin has an approximate area of 48000 sq km. Thus the area occupied by poorly to moderately weathered rock is 28800 sq km. The volume of water stored is therefore $3.9 \times 10^{10}m^3$. According to Wardrope and Associates, 1980 the average annual water level fluctuations between (1976-1979) in the Upper East and West Regions (which form part of the White Volta Basin) is 1.7. These groundwater fluctuations could be attributable to groundwater abstractions, base flow, evapotranspiration from the water table and recharge cycles. This could be described as groundwater in the temporary storage which forms 12.5% of the total groundwater storage is equal to $4.9 \times 10^{10}m^3$. This implies that the groundwater in permanent storage is $3.4 \times 10^{10}m^3$. The groundwater in temorary storage is equivalent to replenishable groundwater.

TABLE 1: DATA FOR COMPUTING DIRECT RECHARGE FOR THE WHITE VOLTA BASIN

Wa

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Total**
ET$_o$ (mm)	171.0	171.0	183.0	186.0	179.0	160.0	143.0	130.0	129.0	143.0	153.0	164.0	1902.0
Rainfall (P) (mm)	3.9	9.3	41.8	78.5	131.0	139.5	151.9	202.5	215.0	80.4	6.2	6.2	1076.2

Navrongo

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Total**
ET$_o$ (mm)	144.8	147.3	188.0	180.3	177.8	154.9	134.6	127.0	129.5	154.9	149.9	139.7	
Rainfall (P) (mm)	0.3	5.1	12.7	48.3	109.2	147.3	177.8	266.7	228.6	55.9	5.1	0.3	

ET$_o$ = Potential Evapotranspiration

Tamale

Month	**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**	**Total**
ET$_o$ (mm)	149.9	154.9	185.4	165.1	162.6	132.1	127.0	124.5	116.8	154.9	152.4	147.3	
Rainfall (P) (mm)	0.3	5.1	50.8	81.3	121.9	147.3	149.9	198.1	221.0	99.1	12.7	0.3	

***Mean Runoff (1985 - 1978) is 355.2 (WRRI 1994)**

TABLE 2: ESTIMATION OF DIRECT RECHARGE FOR VARIOUS STATIONS WITHIN THE WHITE VOLTA BASIN

Station	EP for months where P<ETO (mm)	ER for Months where P>ETO, ER = 0.10 EP	ETO for Months where P>ETO	Estimated Recharge
Navrongo	671.1	72.7	391.1	207.3
Tamale	716.3	77.4	500.4	138.5
Wa	569.4	61.5	402	105.9
Mean	652.9	70.5	431.2	150.6

2.2 THE BLACK VOLTA BASIN

2.2.1 Geology

The geology of the Black Volta Basin consists predominantly of granitoids comprising of the Cape Coast and Dixcove granites, the Birimian and Voltaian systems and to a minor extent the Tarkwaian system.

2.2.1.1 The Granites and Basic Intrusives

i. The Cape Coast Granite

The Cape Coast Granite covers about 20% of the Black Volta Basin. It stretches from latitude 9^o N to 11^o N and longitude 2^o 25' W to 4^o 40' W. It consists of well foliated, medium grained potash-rich muscovite-biotite granite, granodiorites, pegmatites, porphyroblastic-biotite gneiss and aplites. It is also characterised by the presence of many enclaves of schists and gneissess.

ii. The Dixcove Granite

The Dixcove granite covers about 15% of the Black volta Basin. Its stretches from latitude 8^oN to 10^o 31' N and longitudes 2^o W to 2^o 50'W. It consists predominantly of soda-rich hornblende biotite granite, granodionites grading locally into quartz-diorite and hornblende-diorite. It forms non-foliated discordant to a semi-discordant bodies in the Upper Birimian metavolcanics rock which it is in contact with. The rocks are variably banded and show various degrees of shear from a faint lineation to well marked foliation. Epidote and tourmaline occur in these granites and their associated quartz veins.

iii. The Granite Undifferentiated

This has underlain approximately 5% of the Black Volta Basin. It occurs mainly between Latitude 10^o 30' N and 11^o N and longitude 2^o 42' W and 2^o 55'W. It consists of rock types comprising Rocks of both Cape Coast and Dixcove Granites.

2.2.1.2 Birimian Systems

i. Upper Birimian

The Upper Birimian overlies the Lower Birimian conformably and it is volcanic in origin. It forms 10% of the rock cover of the Black Volta Basin. The formation consists of great thickness of andesitic and basaltic lavas, pyroclastic rocks, beds of agglomerate, tuff and tuffaceous sediments. The basic volcanics and pyroclastic rocks have been altered largely to chloritised and epidotised rocks that are loosely grouped together as greenstones. Where the greens tones have been subjected to dynomothermal metamorphism, they are converted to hornblende, schists and amphibolites. In general folding is intense with dips commonly of the mode of basic intrusions 30^o - 90^o along the North East - South West axes.

ii. Lower Birimian

The Lower Birimian covers about 20% of the Black Volta Basin. It is mainly pelitic in origin and consists of great thickness of alternating shales, phyllites, greywacke and argillaceous beds with some tuffs and lavas. It shows considerable variation in lithology with dark, grey slaty, and ashy variations.

The phyllites contain pods and lenses of meta-siltstone and greywackes. The sediments have been subjected to high pressures and the greywackes vary from fine to medium grain. Near the contact with the granite batholith metamorphism has produced biotite, staurolite, garnet and kyanite schists. Quarts veins are common in the lower Birimians rocks particularly in the phyllites and slates. The quart veins are usually massive and mostly fissured. The rocks of the lower Birimian particularly the phyllites, greywackes, tuff and lavas are generally foliated, jointed and deeply weathered.

2.2.1.3 Tarkwaian

The Tarkwaian formation covers approximately 2% of the Black Volta Basin. It occurs in a narrow band of 140km in length with a mean width of 0.8km. It trend in the South West -North East direction running from Bepoasi across the Black Volta at Bui. The geographical coordinates of this formation are latitude 7^o 37' N to 8^o 25' N and longitude 1^o 55' W to 2^o 50' W.

The Tarkwaian formation is of the middle continental origin derived from the Birimian and its associated granitic complexes. The formation consists of quartzites, phyllites, grits, conglomerates and schists. Generally it rests unconformable on the Birimian. However in some places, the Upper Birimian and Tarkwaian rocks are interfold due to post-Tarkwaian orogenic activity and the folding is along the axes which is in the North East to South West direction. The Tarkwaian is subjected to low-grade metamorphism. High grade metamorphism is uncommon but where it occurs, it is often associated with intrusive rocks. Common intrusive rocks are thick laccoliths and sills of epidiorite.

2.2.1.4 Voltaian Rocks

The Voltaian system covers approximately 33% of the Black Volta Basin and occurs to the South Eastern part of the Basin stretching from Wenchi-Techiman to Kwadjokrom in the South East. Its geographical coordinates are latitudes 7^o 31' N to 9^o 5' N and longitudes 1^o 5' W to 2^o 10' W.

The Voltaian system is a synclinal structure comprising relatively flat-lying late precambrian to paleozoic sandstones, shales, mudstone, pebbly beds and conglomerates with subordinate limestones attaining a total thickness of 150m. These form outward-facing escarpments around the periphery of the Basin (Kesse, 1985).

Three stratigraphic subdivision of the Voltaian system occur in the Black Volta Basin namely

i. An upper layer of massive and thin bedded quartzitic and micaceous sandstone which occur mainly in the vicinity of Wenchi, Kimtampo, Techiman and Nkoranza.

ii. The Obosum Formation consisting of a bed of argillaceous sandstones, Arkose, siltstone interbedded with mudstone, sandy shale and conglomerates. The Obosum Formation are formed mainly around Mangpa in the north, Chuko River to the East and Bamboi to the West of the Basin.

iii. The Obosum and the Oti formations joined to form the Middle Voltaian system.

The Lower Voltaian Formation occurs to the South Eastern part of the Black Volta Basin where it conformably overlies the Birimian system. It consists of basal sandstone, pebbly grits and grit with ripple marks and galls. Most of the sandstone have greenish tinge when fresh but maintain purple color when weathered.

2.2.2Groundwater Conditions

2.2.2.1 Groundwater Occurrence

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

i. Weathered Zone Aquifers

These constitutes the major aquifer systems within the Black Volta Basin. Chemical weathering normally takes place along fractures and joints and develop an integrated system through which groundwater flows. The movement of groundwater also aids further weathering at depth thus increasing the interconnectivity of fractures. The degree of the weathering normally varies from highly decomposed to slightly weathered rock, mainly granites, granodiorites, phyillites, quartzites and sandstones. The weathered zone generally extends from outcrops to a maximum depth of approximately 60m with a mean depth of 30m. The base of the weathered zone strectching into the fresh bedrock is usually fissured. Groundwater normally accumulates in this transistional zone between the highly to moderately weathered zone and the fresh bedrock. Occasionally however groundwater occurs in the weathered zone itself especially when downward moving rain encounters an impermeable layer within the weathered zone. These perched aquifers which result provide adequate yield for hand dug well during the wet season but may dry during the dry season.

The near surface weathered zone owing to the degree of decomposition and clay mineral formation have very low permeability and yield little water. This is particularly true for deeply weathered (decomposed) schists and the clay-rich metasediments.

ii. Fissured Aquifers

Fissured zones tend to occur underneath thick regolith and in fresh rocks where the regolith acts as the storage facility. Boreholes located in fissured zones are generally high yielding especially when quarts veins are fractured. Fissured aquifers are generally deeper than weathered zone aquifers since fissured aquifer usually occur below the weather zone.

iii. Groundwater Occurence in the Voltaian System

The massive upper sandstones which occur to the south-eastern part of the Basin are characterised by well developed and extensive joint systems. These systems of joints give the sandstones both storage and permeability. Consequently high yielding aquifers exist in this sandstones. The thin bedded quartzitic and micaceous sandstone layers of the upper sandstone are also well jointed and permeable along bedding planes. They therefore have enough secondary porosity and permeability to store and transmit water. Furthermore in the vicinity of the escarpment and the Lower Birimian contact zones, the thin bedded sandstones are severely faultered providing additional permeable zones. Thus significant quantity of groundwater occurs in the massive and thin bedded quartzitic and micaceous upper sandstone. The Upper Voltaian is thus characterised by numerous springs.

The Obosum (Middle Voltaian) is essentially impermeable, groundwater occurs only where and when it is fractured, jointed or where permeable bedding planes exist. Thus groundwater potential in this formation is low.

The basal sandstones are less jointed and more clayey than the Upper sandstone thus the groundwater potential in the basal sandstones (Lower Voltaian System) is lower than that of the Upper sandstone. However groundwater occurs in significant quantities where joint and fractures intercept stream coarses. The joints and fractures act as conduits through which the water is passed to recharge the aquifer.

2.2.2.2 Groundwater Recharge and Discharge

Two types of groundwater recharge occur in the Balck Volta Basin. These are direct recharge and indirect recharge. Direct recharge occurs by the infiltration of rainfall through sandy clay and sandy layers of weathered zones, fractures, open joints and fractures at rock outcrops and through alluvial deposits along river channels and buried valleys. Indirect recharge occurs when runoff from a distant point infiltrate through joints fractures and faults zones into the aquifer. This also occurs when a permanent stream intercept a fissured zone.

i. Estimation of Direct Groundwater Recharge for the Black Volta Basin

The process by which precipitation infiltrate through the soil and reaches the water table (recharge) is not well understood and therefore there is considerable difficulty in estimating the recharge. There are variety of methods of estimating the recharge eg. Recharge estimation for the Black Volta Basin was based on the assumption that the quantity of water that remains after the potential evapotranspiration and direct runoff have been subtracted from precipitation infiltrate through the soil to recharge the aquifer. Consequently the equation used for estimating Direct Recharge is as follows.

$D \quad - \quad P - R - ET_o$ ___________ (1)

where D - Direct Recharge
P - Precipitation
ET_o - Potential Evapotranspiration
R - Runoff

The precipitation data was taken from the 34 years averages for two stations Wa and Wenchi (1930-1964) lack Volta Basin while the Runoff data was the 15 year (195165) average for Lawra, Bamboe, wenchi, Wa, Bole and Bui all located within the Black Volta Basin. If the soil is saturated at field capacity then evapotranspiration will take place at a rate equal to the potential rate. The potential evapo-transpiration for extensive areas is roughly equal to evaporation of open water surface. Thus the evapotranspiration figures used for the computation are the six years estimates of monthly evaporation for Wa and Wenchi from extensive water surfaces according to Penman's Formula (Penman, 1949). The data used for computing Direct Recharge is presented in Table 3. The runoff for the Black Volta Basin is estimated at 8.3% of the rainfall (FAO/UNDP, 1967). Thus equation (1) for the estimation of direct recharge becomes

$$D = 0.917P - ET_o \quad \underline{\hspace{3cm}} \; (2)$$

TABLE 3 CLIMATIC DATA RECHARGE FOR ESTIMATION INTHE BLACK VOLTA BASIN

Station		**Jan.**	**Feb.**	**Mar.**	**Apr.**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Wa	Mean Rainfall (P)	3.9	9.3	41.8	78.5	131.0	139.5	151.9	202.5	215.0	80.4	16.2	6.2
	Mean ET_o	171.0	171.0	183.0	186.0	179	150.0	143.0	130.0	129.0	143.0	153.0	164.0
Wenchi	Mean Rainfall (P)	7.6	45.7	81.3	147.3	177.8	208.2	96.5	71.1	203.2	228.6	81.3	15.2
	Mean ET_o	134.6	137.2	149.9	144.8	139.7	109.2	99.1	99.1	94.0	111.8	119.4	124.5

The soil is probably saturated to field capacity only in those months in which the precipitation values exceeded the potential evapotranspiration vlaues. At Wa stations the months are July, August and September while at Wenchi, the moths are April, May, June, July, September and October.

At Wa the mean rainfall (precipitation) total for the months of July, August and September is 569.4mm while the mean potential evapotranspiration for the same period is 393mm. Substituting these values in equation (2), the direct recharge for the northern part of the Black Volta Basin is approximately 129.1mm or 12% of the mean annual precipitation. Similarly for the Wenchi station, the total mean rainfall for the month of April, May, June, July, September and October is 961.1m while the total mean evapotranspiration value for the same period is 599.5mm. The estimated southern Black Volta basin direct recharge is therefore 281.8mm or 24.3% of the mean annual precipitation. Thus the mean Black Volta Basin direct recharge is estimated as 205.1mm or 17.7% of the basin rainfall.

ii. Indirect Recharge

Indirect recharge occurs mainly through permeable beds along stream channels and drainage path along which runoff flows. It is regarded as contributing significant recharge to the aquifer systems.

iii. Groundwater Discharge

Groundwater is mainly discharged as flow during the wet season when the water table has risen. However the dominant portion of groundwater discharge occurs as evapotranspiration.

2.2.3GROUNDWATER FLOW DISTRIBUTION

The discrete nature of aquifer systems in the Black Volta Basin makes regional groundwater flow a remote possibility. Local groundwater flow is thefore the main flow type. Generally however the groundwater flow distribution mirrors the surface water flow distribution. That is, groundwater flow is from high grounds towards low grounds, valleys and stream channels.

2.2.3.1AQUIFER CHARACTERISTICS

i. Piezometric Levels

The predominance of local flow resulting from the discontinuous nature of aquifers coupled with lack of long-term monitoring of water levels have rendered the construction of piezometric maps extremely difficult. However to a good approximation static water levels can be used to represent the piezometric levels.

ii. Static Water Levels

The static water levels generally vary from 1.8m to 34.4m with a mean of 12.8m. In the Crystalline Basement Complex (Granitoid and Birimian Formations) the static water levels vary from 1.8m to 34.4m with a mean value of 11.2m. A comparison of the mean static water level value of 12.8m and the mean depth to aquifer value of 27.3m suggest taht the aquifers are wither confined or semi-confined. This is probably due to the presence of high content of clay and mica in the regolith.

In the Voltaian formation the mean static level is 14.9 while the mean depth to aquifer is 27.6m. This implies that an average static water level in the Voltaian is higher than average aquifer horizon. Thus most of the aquifers appear to be either confirmed or semi-confirmed. There are however phreatic aquifers.

2.2.3.2 Borehole Yields

Generally the yield of boreholes are highly invariable. They vary from extremely low value of $0.1m^3h^{-1}$ to a high value of $36.0m^3h^{-1}$ with a mean value of $2.2m^3h^{-1}$.
The mean yield of $2.2m^3h^{-1}$ suggest that most of the aquifers may be low yielding.
This is however deceptive since the majority of the boreholes seem to be partially penetrating the saturated thickness of the aquifers. The yield of the boreholes in the Crystalline Basement Complex vary from $0.1m^3h^{-1}$ to $36.0m^3h^{-1}$ with a mean value of $1.5m^3h^{-1}$ while in the Voltaian Sedimentary Basin particularly the Upper Voltaian Sandstones the yields vary from $0.1m^3h^{-1}$ to $14.3m^3h^{-1}$ with a mean of $3.4m^3h^{-1}$. In the Obosum formation areas the yield vary from $0.1m^3h^{-1}$ to $11.9m^3h^{-1}$ with a mean value of $2.2m^3h^{-1}$. This implies that the yield is an average generally highest in the Upper Voltaian Sandstone areas and lowest in the Obosum mudstones and shalesand and the granitoids.

2.2.3.3 Specific Capacity

The specific capacities of wells in the Balck Volta Basin vary from $0.02m^3$/h/m to $5.28m^3$/h/m with a mean value of $0.34m^3$/h/m. The low mean specific capacity value of $0.34m^3$/h/m for the Basin suggests that transmissivities are generally low though the specific capacity may have been affected by partial penetration of the saturated thickness by boreholes, wells loss and possible hydogeologic boundries. Due to the discontinuous nature of aquifers in the Black Volta Basin.

Transmissivities have generally not been computed due to the short duration pumping test whose results are not available. For the few data on transmissivities, transmissivities are in the range 5.8 - $50.9m^3$ day^{-1} with a mean of 32.4^3 day^{-1}.

2.2.3.4 Depth to Aquifer

The depth to aquifer generally vary widely from 4.3m to 82.0m with a mean value of 20.11m. However about 95% of the aquifers occur within the depth of 50m indicating that the probability of getting water below the depth of 50m is very low. A comparison of the mean depth to aquifer with the static water level suggests that most of the aquifers are either confined or semiconfined as the static water is mostly above the aquifer horizon.

2.2.3.5Depth of Boreholes

Boreholes depth vary from 21.5m to 95.7m with a mean value of 28.7m suggeting that an average boreholes are shallow. Most of the boreholes are however only partially penetrating.

2.2.3.6 Aquifer Materials

The aquifer materials are largely composed of slightly to moderately decomposed granites granodiorite, phylites schists, diorite, sandstones and shales. Some of the aquifer also occur in fractures (fissured ones) within the fresh granite, schists and phyllites.

Slightly to moderately decomposed quartz viens also form significant proportions of the aquifer materials.

2.2.3.7 Thickness of the Aquifers

The actual thickness of the aquifers are not known since most of the boreholes are partially penerating. However a rough estimation from the borehole records indicates that the average saturated thickness of the aquifer is 10.3m.

2.2.3.8 Groundwater Storage

In the Black Volta Basin, the aquifer geometries are unknown. However, the mean saturated thickness of the weathered zone which constitute the main aquifers and also the main storage for the fractured aquifers is 10.3m. The Black Volta Basin has an approximate area of 30.582 sq km. The Birimian rocks together with the upper sandstones which form about 66% of the total rock cover of the Black Volta Basin are highly fissured and weathered. Assuming the percentage of the saturated weathered part of the total rock cover is 66, then the area of the fissured or weathered rock cover is 20.184 sqkm. The porosity of the weatherd zone is estimated to be 10% (Van Ess, 1984) consequently the volume of water stored in the saturated zone is $2.1 \times 10^{10} m^3$. According to Wardrope and Associates, 1980 the average annual water level fluctuations between 1976 and 1979 in the Upper East and West Regions is 1.7m. Assuming this figure is true for all the Black Volta Region for which the Upper West Region forms part then the water in temporary storage is $3.4 \times 10^9 m^3$. This volume of water includes all abstraction, base flows evapotranspiration etc. The water in permanent storage is $1.8 \times 10^{10} m^3$. The water in temporary storage is equivalent to the replenishable groundwater.

2.3.THE MAIN VOLTA BASIN

2.3.1 Geology

The geology of the Main Volta Basin is dominated to a large extent by the Voltaian System. Other geological formations found in the Main Volta Basin are the Buem formation, Togo series, Dahomeyan formation and Tertiary to Recent formations.

2.3.1.1 The Voltaian Rocks

The Voltaian system is a synclinal structure consisting of relatively horizontal lying late Precambrian to Paleozoic sandstones, shales and conglomerates that form outward-facing escarpments around the margins of the basin (Kesse, 1985). Lithological classifications by Junner and Hirst (1946), Bates, 1955 Annan-Yorke (1971), Attaton et al, 1980 have subdivided the Voltaian system into the Upper, Middle and Lower Voltaian series.

The Upper Voltaian series are composed of massive quart-sandstones and thin-bedded flaggy sandstones. At some places the overlying layer contains beds of shales and mudstones. Feldspathic clay galls and ripple marks are common in the underlying flaggy sandstones.

The Middle Voltaian series generally rest with slight angular unconformity on the lower Voltaian and in some places fill erosional channels that have cut through the older beds and so rest directly on the older Precambrian rocks.

The Middle Voltaian series are partly composed of argillaceous sandstones, arkose, silt-stone interbedded mudstone and sandy shale and conglomerate called the Obosum beds and partly of siliceous sandstones, pebbly grits and arkosic conglomerates called the Oti beds. Cross-bedding is common in the sandy and pebbly beds of the overlying Obosum beds. Modular structures and yellow weathering are characteristics of the underlying Oti beds.

The Lower Voltaian series is dominated by basal sandstones, pebbly grits with ripple marks and galls. Most of the sandstones have greenish tinge when fresh but maintain purple colour when weathered.

Much (approximately 75%) of the Voltaian cover of the Main Volta Basin is made of the Middle Voltaian and occur mainly to the south-western part of the Main Volta Basin.

2.3.1.2 Buem Formation

The Buem formation lies to the eastern part of the main Volta Basin where it is sandwiched between the Voltaian system to the west and the Togo series to the east.

It is composed of calcareous, argillaceous, sandy and ferruginous shales, sandstones, arkose, greywacke and agglomerates, tuffs and jaspers. The formation is highly folded along north-south lines and the beds generally dip to the east at 10^0 - 90^0 with a mean of about 60^0 - 65^0. In the few places where the beds dip west the dips are usually at high angles. The consistent easterly dip is certainly due to overfolding (Kesse, 1985). Generally the Buem formation is unmetamorphosed, however it is frequently sheared and schistose in fault zone along the Buem - Togo contact.

2.3.1.3 Togo Series

The Togo series lie to the eastern and southern parts of the Main Voltaian Basin. The rocks of these series form the mountain range which trend in northeastern direction from Accra and extend to the Main Volta Basin at Larteh and moves across the Volta River between Kpong and Anum to the Togo.

Originally the Togo series consisted of alternating arenaceous and argillaceous sediment, however except for a few places where the unaltered sediments can be seen, the sediments have been converted into phyllite, schist and quartzites. Quartzites, quartz-schists, sericite-quartz shists, sericite schist and phyllites are the predominant rocks but hornstones, jaspers and hematite, quartz-schists some of which were formed after the deposition of the sediments, also occur in the Togo series.

The series are bounded by two major thrust faults. One at the western contact with the Buem formation, Voltaian system and the Cape Coast/Winneba granitoid complex rocks. The second thrust fault is at the eastern margin where the rock is in contact with the Dahomeyan rocks system.

The beds of the Togo series have originally been subjected to intense directional pressure metamorphism resulting in the axial planes of the folds inclined east south-east at 30^0 - 60^0 (Kesse, 1985). Recumbent folds with dips of less than 30^0 occasionally occur.

2.3.1.4Dahomeyan Formation

The Dahomeyan System occurs at the southern part of the main Volta Basin and is sandwich between the Togo series to the west and northwest and the Recent deposits of the Volta Estuary to the south south-east.

It occurs as four persistent alternating belts of acidic and basic crystalline rocks trending in south south-west to north north-east. It consists of hornblende and biotite gneisses, migmatites, granulites, schists some of which are rich in garnet and marbles. Granites nepheline syenites and dyke of porphery, aplite and dolerite which have intruded into the Dahomeyan System have been intensely folded with the fold axes striking south south-west to north north-east. Dips are generally high and mostly to the east.

2.3.1.5Tertiary Cretaceous Sediments

This occur at the south west part of the Main Volta Basin. These rocks overlie the Dahomeyan basement rocks. They comprise thick series of Upper Cretaceous to Lower Tertiary consolidated and semi-consolidated marine sediments. The marine sediment are also overlain by continental surficial deposits. Stratigraphically, the sediments are composed of sand, clay, marl, fossilferous sandy limestone interbedded marl and limestones, standstone, siltstone, mudstone and shale.

The recent continental surficial deposits consists of semi consolidated limonitic argillaceous sands and gritty sand, basal gravelly beds and gravels. The gravel bed is approximately 2 metres thick and it is generally made of clean white quartz pebbles of about 2.5cm in diameter.

2.3.2Groundwater Conditions

2.3.2.1Groundwater Occurrence

The Cystalline Basement Complex of the Main Volta Basin is composed of a heterogenous mixture of igneous rock, metasediments and metavolcanics. These rocks are inherently impermeable and thus have little or no primary porosity. They can store and transmit water only when they are fissured or weathered. Thus groundwater occurence in the Crystalline Basement Complex is essentially controlled by the development of secondary porosites as a result of fissuring and weathering. Fissuring occurs as a result of tectonic stresses within the rocks and are related to the structural history of the area. On the other hand the weathering is brought as a result of water circulating through joints, fractures, stress zones and quartz veins which have already existed in the rocks.

There are two types of aquifer system. These are the weathered zone aquifers and fissured aquifers. The extent to which these aquifers develop depends on the type of geology. In the Dahomeyan rocks system, fissuring is very low and consequently the degree and extent of weathering low. The weathering depth varies from 0 (at outcrops) to about 45m with a mean of about 10m. Consequently groundwater occurence in the Dahomeyan rocks areas is low and is structurally controlled. Thus it is difficult to obtain adequate groundwater for village supply. However where saturated fractures are encountered, large yields are obtained.

The Togo series and Buem formations are intensively and extensively fractured, jointed, faultered and weathered. Groundwater therefore occurs in relatively higher quantity than in the Dahomeyan formation.

The Voltaian sediments are well compacted and consolidated and essentially impermeable except at a few places. Groundwater occurence is therefore structurally controlled. The Upper sandstones which are extensively fissured and have permeable bedding planes have moderate to high groundwater potential. On the other hand, groundwater occurence in the shale and mudstones of the Obosum bed is generally low.

The tertially and recent deposits in the mouth of the Volta river have enormous porosity and permeability. Thus the groundwater potential of these deposits is high.

2.3.2.2 Groundwater Recharge and Discharge

Recharge to the aquifer systems in the Main Volta BAsin occurs either in direct or indirect form. Direct recharge occurs when rainfall infiltrates through the soil to reach the water table. This occurs mainly at hilly fronts and contact zones between the Togo series and the Dahomeyan formations, the Togo and Buem formations and the Voltaian and the Birimian contact to the West. These contacts are often extensively fractured, open jointed and highly weathered. Direct recharge also occurs when rainfall infiltrates through the sandy clay layers of the discrete weathered zones into the localized aquifers. Direct recharge in the Main Volta Basin occurs also by infiltration through the alluvial deposits along the Banks of rivers and buried valleys and through the sand of the Tertiary and Recent deposits along the banks of the Volta River.

Indirect recharge occurs when runoff from the watershed outside the area or a particular rainstorm event is of sufficient magnitude to cause runoff which infiltrate through open joints, fractures and faults which intercept its path. In the Main Volta Basin, indirect recharge occurs mainly in the areas covered by the Obosum beds of the Voltaian Rock Formations. This is due to the fact that the shales, siltstone and the mudstones of the Obosum beds which cover a large portion of the Main Volta Basin are essentially impermeable. The top soil is mainly sandy, and water infiltrates quickly through the top sandy layer and meets the impermeable beds metres below. The water then moves slowly horizontally as subsurface flow into rivers or valleys. It only infiltrates to reach the aquifer when a fracture or open joints intercepts its horizontal path.

Another source of indirect recharge in the Main Volta Basin is the perennial streams. The streams act as conduits for channelizing overland flow, allowing for greater amounts of recharge to occur where fractures, joints and permable beds intercept stream channels.

i. Direct Recharge Estimation

The estimated direct recharge is computed using data from Tamale and Ho which are within the main Volta Basin (Table 4)

In the Ho area the average monthly precipation exceeds the average potential evapotranspiration for the seven months (May - October). The total average precipitation for these months is 1047.2 mm. The total average potential evapotranspiration for this period is 686.8 mm while the mean runoff is 113.1 mm. Thus the estimated direct recharge is 271.3 mm or 20.4% of the annual precipitation.

In the Tamale area precipitation exceeds evapotranspiration for the period June - September. The total average precipitation for this period is 716.3 mm.

The total average evapotranspiration for the same period is 500.4 mm while the runoff is 77.4 mm. The computed direct recharge is 138.5 mm which is equivalent to 12.7% of the average annual precipitation. The average annual recharge for the Main Volta Basin is thus estimated as 204.9 mm which is equivalent to 17.0% of the mean annual precipitation.

ii. Indirect Recharge

Indirect recharge in the Main Volta Basin forms a major part of groundwater recharge into the aquifer systems. There is however no data to compute the amount of indirect groundwater recharge.

iii. Groundwater Discharge

Groundwater discharge is mainly through evapotranspiration and base flow particularly during the wet season. Some amount of water is also lost through evaporation of the horizontal subsurface flow above the impermeable layers of the Obosum beds

TABLE 4 CLIMATIC DATA RECHARGE ESTIMATION IN THE MAIN VOLTA BASIN

	Month	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Ho	P(Precipitation)	27.7	44.2	105.6	130.9	162.5	210.1	95.6	124.8	208.6	114.7	25.8	69.5
	ET_o (mm)	148.0	154.3	142.9	121.3	107.3	107.0	78.7	79.4	85.1	108.0	138.4	132.7
Tamale	P(Precipitation)	0.3	5.0	50.8	81.3	121.9	147.3	149.9	198.1	221.0	99.1	12.7	0.3
	ET_o (mm)	287.0	269.2	236.2	177.8	124.5	104.1	88.9	83.8	86.4	127.0	205.7	238.8

$ET_{o\,=}$ Potential Evaporation

2.3.2.3 Groundwater Flow Distribution

The discrete nature of saturated permeable zones (aquifer zones) within the Main Volta Basin makes regional or intermediate groundwater flow largely non-existent. Local flow thus predominant in the Main Volta Basin. Generally however the groundwater flow distribution appears to mirror the surface water distribution. Thus groundwater flow is generally from the high grounds towards the valleys.

2.3.2.4 Aquifer Characteristics

i. Piezometric Levels

The discrete nature of aquifers and lack of longterm monitoring of water levels have made it extremely difficult to construct the piezometric map of the Main Volta Basin. However an attempt was made by Minor et al, 1995 to construct the piezometric map of the southern Voltaian Basin. This piezometric map has to be viewed with caution since it is based on over simplified assumptions such as all streams in the Afram Plains are gaining streams and the stream channels represent the water table at any given point. Secondly the piezometric map gives the erroneous impression that the Afram Plains (the southern Voltaian Basin) has a continuous water table and for that matter regional flow exists. However, due to the discrete nature of permeable zones in the Afram Plain and the whole of Voltaian rocks area, regional flow is essentially retarded or non-existent. Nevertheless, it gives an indication that flow is generally from the high grounds (highlands) towards valleys and stream channels and eventually towards the Main Volta.

ii. Static Water Levels

The static water levels generally vary from 0.0m (flowing wells) to 34.4m with a mean value of 8.4m. In the Dahomeyan rocks terrain, the static water level varies from 0.0m to 34.4m with a mean value of 6.1m while in the Togo series and the Buem formation static water levels vary from 0.0m (flowing wells) to 32.4m with a mean value of 8.8m. In the Voltaian System static water levels vary from 0.0m to 31.0m with a mean value of 8.3m.

iii. Borehole Yield

The yields of boreholes in the Main Voltaian Basin are largely variable. They are generally within the range of 0.02 - 36.0m^3h^{-1} with a mean of 5.7m^3h^{-1}. The yield of boreholes taping the Dahomeyan rocks vary from 0.2m^3h^{-1} to 12.0 m^3h^{-1} with a mean value of 2.7m^3h^{-1} while in the Togo series and Buem formation areas, the borehole yield vary from 0.6m^3h^{-1} to 36m^3h^{-1} with a mean value of 5.2m^3h^{-1}. In the Voltaian rock terrain the yield of the boreholes vary from 0.6m^3h^{-1} to 36m^3h^{-1} with a mean value of 7.3m^3h^{-1}. Generally therefore borehole yields are highest in the Voltaian rock terrain and lowest in the areas underlain by the Dahomeyan rocks.

iv. Specific Capacity/Transmissivities

Data on specific capacities are not available for the Main Volta Basin. However a few data exist on the transmissivities on the various rock types within the Main Volta Basin. The data show that transmissivities are generally low and largely variable. In the areas underlain by the Voltaian rocks, transmissivities vary from 1.2m^2 day^{-1} to 71.7m^{2}day^{-1} with a mean value of 14.4m^2 day^{-1}. In the areas underlain by the Buem and the Togo formations, transmissivities vary from 4 m^2 day^{-1} to 50 m^2 day^{-1} while in the Dahomeyan rocks areas transmissivities are in the range 0.1 - 62.5 m^2 day^{-1}. The low transmissivities suggest that well recovery and major groundwater production potential for the aquifers in the Main Volta Basin are low.

v. Depth to Aquifer

Generally the depth to major aquifers are largely variable. It varies from 3.0m to 55m with a mean of 22.7m. In the area underlain by the Voltaian rocks, the depth to aquifers varies within the ranges 4 - 49m with a mean value of 20.2m while the depth to aquifer within the Togo-Buem formations varies from 9m to 55m. In the Dahomeyan rocks terrain the depth to aquifer varies from 8.0m to 48.0m.

A comparison of the static water levels with the depth of aquifer indictes that the static water level are mostly above the aquifer suggesting that despite the existence of phreatic aquifers, most of the aquifers are either confined or semiconfined.

vi. Depth of Boreholes

Generally the depth of boreholes in the Main Volta Basin varies from 21m to 129m with a mean value of 44.5m. In the areas underlain by the Dahomeyan the depth of boreholes vary from 22m to 52m with a mean of 34.6m while in the Togo and Buem formations the depth of the boreholes vary from 22.0m to 100m with a mean value of 42.5m. In the Voltaian formation, the depth of boreholes range from 22.0m to 219.0m with a mean of 53.0m. It should be noted however that most of the boreholes are partially penetrating the aquifers since they were terminated as soon as adequate yield to meet village supply was obtained.

vii. Relationship between the Depth and Yield of Boreholes

Groundwater occurence in the Volta Basin is controlled by secondary porosites (fractures, joints, faults etc). Assuming that the fissure zones (fractures and joints) are randomly distributed with depth, then the greater the depth of the well, the higher the probability that it would intersect a greater number of fissures and therefore the higher the yield would be. Fig. 1 is the plots of the well yield versus depth for the Crystalline Basement Complex. A perusal of the Fig indicates that there is no discernible trend in the relationship between yield and depth. Some boreholes as deep as 61m only yield as low as $0.7m^3h^{-1}$ while some boreholes as shallow as 22m yield as high as between $27m^3h^{-1}$ and $36m^3h^{-1}$. Thus the depth of the boreholes does not appear to have any direct bearing on yield. However boreholes with the high yields (yields higher than $6.0m^3h^{-1}$) have depth within the range 22 - 55m with a mean value of 35.4m. A similar trend was observed for the Voltain Basin in the Afram Plains by Minor et al, 1995.

ix. Groundwater Storage

The total surface area of the Main Volta Basin is $59537Km^2$, assuming the saturated weathered zone forms 50% of the rock mass and the thickness is 13.6m. Let the porosity be 10%, then the groundwater storage is $4.0 * 10^{10}m^3$.

vix. The Replenishable Groundwater

The total surface area is $59537Km^2$. The recharge depth is 204.9mm. Therefore the replenshiable groundwater is $1.2 * 10^{10}m^3$.

Fig. 1 ***[missing]***

2.4THE DAKA BASIN

2.4.1 Geology

The Daka Basin is underlain entirely by the Middle Voltaian System which comprises the Obosum Formation and the Oti Formation. The Oti Formation occurs entirely in the middle of the Daka Basin running north-south and it forms about 40% of the rock cover of the Daka Basin. Stratigraphically the Oti Formation consist of thick beds of siliceous sandstones, pebbly grits and arkosic conglomerates.

The Obosum Formation surrounds the Oti formation and forms 60% of the rock cover of the Daka Basin. Stratigraphically the Obosum formation consists of beds of argillaceous sandstones, arkose, siltstone, interbedded mudstone, sandy shale and conglomerates.

2.4.2Groundwater Conditions

2.4.2.1Groundwater Occurence

The hydrogeology of the Daka Basin is controlled by the development of secondary porosities and permeabilities through jointing, fracturing and weathering. Thus groundwater occur only when the structural elements such as joints, fractures, weathered zones and schistosied zones exist in the rocks. Since these structural elements are few and discontinuous in nature, groundwater occurrence and potential are low.

Generally however, areas underlain by siliceous sandstones and arkosic conglomerates when fractured or weathered to appreciable depth, produce relatively moderate to high yields. The argillaceous sandstones, siltstone, mudstones and shales are practically impermeable unless fractured.

2.4.2.2 Groundwater Recharge and Discharge

Recharge to the aquifer system in the Daka Basin occurs as either in the direct or indirect mode. Direct recharge occurs when rain water infiltrates directly through the top sandy soils through the unsaturated zone to reach the water table. Direct recharge occurs mainly within the sandy areas of the pebby beds and alluvial deposits along stream and river channels and also in buried valleys.

Indirect recharge occurs when runoff from the watershed outside the basin, for instance the Gambaga hills to the north, is of sufficient intensity to reach the Basin or if a particular storm event is of sufficient magnitude to cause runoff. The runoff may intersect a fracture or a cluster of fissures which act as conduits for the runoff to recharge the aquifer with which they are in hydraulic continuity. Since most of the Daka basin is underlain by low permeability Obosum beds, and the relief is fairly low with equally low rainfall, indirect recharge is probably the main mode of recharge into the groundwater system. Another mode of indirect recharge into the groundwater system is the influence of both perennial and epherimeral streams. Streams such as Kuma, Kumoo, Nasiwa, Jeba, Kulunsulu, Yami, Kbongo and Daka River which drain the Daka Basin act as influent streams and channel a lot of water through fracture, joints and permeable channel beds to recharge the groundwater system particularly during the rainy season.

2.4.2.3 Direct Recharge

The estimation of direct recharge in the Daka Basin is based on the assumption that recharge occurs when actual evapotranspiration and direct run off are taken care off by the precipitation. This happens when the soil is saturated to the field capacity.

The soil is likely to be saturated to the field capaicty when precipitation exceeds the evaporatranspiration. Data is taken from two meteorological stations (Salaga and Yendi) which are within the Daka Basin (Table 5). The months in which precipitation exceeds potential evapotranspiration are June, July, August and September. Using data from Salaga, the average total precipitation for the above mentioned months is 693.5 mm while the mean total potential evapotranspiration is 475.5 mm. The runoff is 8.7% of the precipitation (UNDP/FAO, 1967) which is 60.3 mm. Thus the estimated recharge is 157.7 mm. This is equivalent to 13.4 % of the mean annual precipitation. Similarly using data from Yendi, the total mean precipitation for the stated months is 749.3 mm. The total mean evapotranspiration is 491 mm while runoff is 65.2 mm. Thus the annual recharge is estimated to be 193.1 mm or 16.2% of the mean annual precipitation. The annual recharge for the Daka Basin is therefore 175.4 mm which is equivalent to 14.8% of the mean annual Basin precipitation.

2.4.2.4 Indirect Recharge

Indirect recharge occurs mainly through runoff and perennial streams intersecting fissured zones (mainly fractures) or by bed transmission losses along permeable stream channels. On quantitative bases, this mode of groundwater recharge is regarded as very significant. However, due to inavailability of data, it cannot be computed.

2.4.2.5 Groundwater Discharge

Groundwater discharge is mainly through evapotranspiration losses from the water table and evaporation of perched water from sandy soil above the impermeable mudstones and shales. On a minor scale, groundwater is also lost through baseflow particularly during the rainy season.

TABLE 5 CLIMATIC DATA FOR RECHARGE ESTIMATION IN THE DAKA BASIN

	Month	**Jan.**	**Feb.**	**March**	**April**	**May**	**June**	**July**	**Aug.**	**Sept.**	**Oct.**	**Nov.**	**Dec.**
Salaga	Precipitation	5.1	20.3	76.2	91.4	147.3	177.8	137.2	144.8	233.7	127.0	7.6	10.1
	ET_o (mm)	138.0	161.5	184.0	169.5	155.5	127.0	118.0	116.0	114.5	133.0	135.0	138.5
Yendi	Precipitation	0.3	5.1	43.2	96.5	137.2	147.3	154.9	188.0	259.1	132.1	20.3	5.1
	ET_o (mm)	171.0	159.0	178.0	165.0	155.0	132.0	121.0	117.0	121.0	133.0	139.0	148.0

2.4.2.6Groundwater Flow Distribution

The discrete nature of permeable zones (weathered and fissured zones) makes regional flow impossible within the Daka Basin. Groundwater flow is therefore exclusively local flow. Generally however groundwater flow is from high ground towards values and stream channels.

2.4.2.7Aquifer Characteristics

i. Piezometric Levels

The discontinuous nature of permeable beds, lack of regional or even intermediate flow system and longterm monitoring of water levels as well as inavailability of data on the spot height of the well (borehole) heads make the construction of Piezometric map extremely difficult. However, to a good approximation the information on Piezometric levels can be derived from the static water levels.

ii. Static Water Levels

Static water levels varied widely between 0.5m and 28.3m with a mean value of 10.4m. A comparison of the mean static water level and the mean depth of aquifers indicate that the aquifers are either confined or semi-confined. The confinement of aquifers is due to the clayey and shale regolith (Overburden).

iii. Borehole Yields

The yields of the boreholes are largely variable. They vary from as low as $0.5m^3h^{-1}$ to $18m^3h^{-1}$ with a mean value of $4.6m^3h^{-1}$. The relatively higher yields are generally associated with the fissured zones.

iv. Specific Capacity

The Specific Capacity values are generally low. They vary from as low as $0.02m^3$/h/m to $7.5m^3$/h/m with a mean value of $0.93m^3$/h/m. This implies that an average of one metre drawdown is needed to obtain a village supply of 15 litres per minute.

The low mean Specific Capacity is a true reflection of the low transmissivities (permeability) usually encountered in shale, siltstone, mudstone and the well consolidated sandstones aquifers of the Daka Basin.

v. Depth to Aquifer

The depth to aquifer is largely variable. It varies from 8.0m to 66.0m with a mean value of

30.0m. This means that the average depth to expect water within the Daka Basin is 30m. It should be noted however that several of the boreholes tapped water from two or three aquifers in vertical succession.

vi. Depth of Boreholes

The depth of the boreholes vary from 32.0m to 76.5m with a mean of 44.9m. It should noted that most of the boreholes are partially penetrating.

vii Aquifer Materials

The aquifers are composed of weathered sandstones, mudstones, shales and sandstones. Where the yields are relatively high, the aquifer materials are mainly fractured sandstones, mudstones and shales.

viii. Groundwater Storage

The groundwater storage for both the weathered zone and fissured zone aquifered are drawn from the regolith (Acworth, 1987). The mean saturated thickness of the regolith in the Daka Basin is 11.0m. The regolith has a relatively high porosity but low permeability due to the high clay and shale content of the aquifer materials. Assuming that the porosity is 30 percent. The total area of the Daka basin is approximately 8,124 sqkm. The Obosum beds which have underlain about 60% of the Daka Basin are relatively less fissured and weathered. Assuming that the percentage of the weathered part of the Basin is 40. Then the maximum amount of groundwater in storage is 1.07×10^{10} m^3. Assuming again that the groundwater fluctuation is 1.7m in the Daka Basin as Wardrope Assocates 1976 estimated for the Northern and Upper Regions aquifers, then the volume of water in temporary storage is $1.7 \times 10^9 m^3$.

This amount of water is taken up by various kinds of abstraction and baseflow. The volume of water in permanent storage is $9 \times 10^9 m^3$. This volume of water is the reserved groundwater. The volume of water in the temporary storage is equivalent to the replenishable groundwater.

2.5 THE OTI BASIN

2.5.1 Geology

The Oti River Basin is underlain by three main geological formations. These are the Middle Voltaian system, the Buem formation and the Togo series.

2.5.1.1 The Middle Voltaian System

The Middle Voltaian System comprising the Obosum and the Oti beds has underlain about 60% of the basin. It occurs in the north-west and the southern parts of the Oti Basin.

The Obosum beds form about 70% of the Middle Voltaian cover and occur to the north and west of the Oti Basin while the Oti beds forming about 30% of the middle Voltaian cover occur to the south at the vicinity of the confluence of the Oti River with the Volta. The Obosum beds consist of argillaceous sandstones, arkose, siltstone interbedded with mudstone, sandy shale and conglomerates. Cross bedding is common in the sandy and pebbly beds. The Oti beds consist of siliceous sandstones, pebbly grits and arkosic conglomerates. Modular structure and yellow weathering are characteristic of the Oti beds.

2.5.1.2 The Buem Formation

The Buem Formation occurs to the eastern part and underlies approximately 35% of the Oti Basin. It is composed of calcareous, argillaceous, sandy and ferringinous shales, sandstone, arkose, greywacke and agglomerates, tuffs and jaspers. The formation is highly folded along north-south lines and beds generally dip to the east at 10^0 to 90^0 with a mean of about 60^0 - 65^0. In the few places where the beds dip west, the dips are usually at high angles. The consistent easterly dip is certainly due to overfolding (Kesse, 1985). Generally the Buem Formation is unmetamorphosed, however it is frequently sheared and schistose in fault zone along the Buem-Togo contact.

2.5.1.3 The Togo Series

The Togo series underlie only about 5% of the Oti Basin and occur to the east. The rock types of Togo series include phyllite, schists quartzites, quartz-schists, sericite-quartz schist, sericite-schist, jaspers and hematite.

2.5.2Groundwater Conditions

2.5.2.1 Groundwater Occurrence

Secondary porosities control the hydrogeology of the Oti Basin. Groundwater therefore occurs in the Oti Basin only when the rocks are fissured or weathered. Thick weathered zones in the Oti Basin support low but sustainable yield while boreholes located in fissured zones are relatively high yielding. Since fissured zones are few particularly over areas underlain by the Obosum shales and mudstones, it is difficult to obtain adequate water within certain localities (Sibi-Damako area) within the Oti Basin.

2.5.2.2Groundwater Recharge and Discharge

Recharge to the groundwater system within the Oti Basin as in the case of the Daka Basin is by both direct and indirect modes. Direct recharge occurs mainly within the upper reaches of the Basin near the fringes of the Gambaga Highlands which is underlain by the sandstones of the Upper Voltain Formation and also within the vicinity of the confluence of the Oti and the Main Volta.

Indirect recharge occurs mainly over the low relief areas underlain mainly by the low permeability shales and mudstones of the Obosum Beds. Indirect recharge mainly occurs during the rainy season when rivers such as Wawa, Kulaw, Mo and Tankpa intercept a fracture or when runoff outside the watershed interceps a fracture or a fissured zone.

2.5.2.3 Direct Recharge

Due to the closeness of the Oti Basin to the Daka Basin and the two Basins falling into similar ecological zone as well as having similar geology and relief, the recharge mechanism is probably similar. Thus the direct recharge for the Oti Basin is considered to be the same as that for the Daka Basin and is estimated as 175.4 mm or 14.8% of the mean annual precipitation.

2.5.2.4 Groundwater Flow Distribution

The discrete nature of permeable zones (weathered and fissured zones) has given rise to only local flows.

2.5.2.5 Aquifer Characteristics

i. Static Water Levels

The static water levels generally very from 0.0 (flowing wells) to 25.9 m with a mean value of 8.1 m. The mean static water level in comparison with the mean depth to aquifer suggests that an average water stands above the top of the aquifer. This is an indication of the aquifers being either confined or semi-confined.

ii. Borehole Yields

The yield of the boreholes are highly variable. It varies from 0.6 m^3 h^{-1} to 36.0 m^3 h^{-1} with a mean value of 5.2 m^3 h^{-1}. The boreholes situated within the weathered zone produce low but sustainable yields while those situated in fractured zones are relatively high yielding.

iii. Specific Capacity

The specific capacity of the wells vary from 0.06 m^3/h/m to 10.45 m^3/h/m with amean value of 0.97 m^3/m. The low mean Specific Capacity value suggests that transmissivities within the Oti Basin are low. This is expected since the Basin is principally underlain by Shales and Mudstones of the Obosum beds. Weathered Shale or Mudstone produce very fine particles which greatly reduce permeability and thus the transmissivity.

iv. Depth to Aquifer

The depth to aquifer is largely variable. It varies from 6.0 m to 39.0 m with a mean value of 20.6 m. Aquifers in the Voltain formation are generally shallow (average depth of 16.0 m) while in the Buem and the Togo formation the aquifers are deeper (mean depth of 25.0 m). This is probably due to the greater degree and depth of weathering within the Togo and Buem formations.

iv. Depth of Boreholes

The depth of boreholes vary from 25 m to 82 m with a mean value of 32.9 m. There is not much difference between the depth of boreholes located in the Voltaian and those located in the Togo-Buem formations.

v. Aquifer Thickness

The mean saturated thickness of aquifers within the Oti Basin is 10.2 m. Its range is 4.0 - 24.7 m.

vi. Groundwater Storage

The mean saturated thickness of the permeable zone is 10.2 m. Assuming the porosity of most of the rocks within the Oti Basin is 30% (high clay and shales porosity) and the percentage of the permeable to impermeable zones is 40% since the Obosum Beds which forms about 60% of the Oti Basin are poorly weathered and fissured.

The area coverage of the Oti Basin is approximately 17,942 sq km. Therefore the groundwater capacity of the Oti Basin is 2.2×10^{10} m^3. If as in the case of the White Volta sin the groundwater level fluctuation is equal to 1.7 m, then the volume of groundwater in temporary storage is 3.7×10^9 m^3. The groundwater in temporary storage accounts for all abstractions, evaporatranspiration and base flows. The groundwater in permanent storage (reserved groundwater) is 1.8×10^{10} m^3. The groundwater in the temporary storage is equivalent to the replenishable groundwater.

[Tables with data on borehole distribution and groundwater abstraction missing in this scanned copy]

FINDINGS

(1) Except around the Estuary of the Volta River, the hydrogeology of the Volta Basin System is controlled by secondary porosities.

(2) Most of the aquifers are confined or semi-confined. A few aquifers particularly shallow sandstone aquifers are phreatic.

(3) The yield of the boreholes are largely variable. They vary from 0.1 $m^3 h^{-1}$ to 36 $m^3 h^{-1}$. However most of the aquifers are low yielding.

(4) the higher yields are associated with Basal sandstone while the lowest yields are associated with Obosum beds of the Voltaian and the Dahomeyan gneisses.

(5) the boreholes yields are independent of depth as some shallow boreholes are high yielding

and deep boreholes are low yielding.

(6) The minimum recharge for the basins within the Volta System are as follows;

(a) White Volta Basin	151.1mm
(b) Black Volta Basin	205.1mm
(c) Main Volta Basin	204.9mm
(d) Daka Basin	175.4mm
(e) Oti Basin	175.4mm

(7) The replenishable groundwater capacity for the various basins within the Volta system are as follows;

(a) White Volta Basin	6.6 x 10^9 m^3
(b) Black Volta Basin	3.4 x 10^9 m^3
(c) Main Volta Basin	8.2 x 10^9 m^3
(d) Oti Basin	3.7 x 10^9 m^3
(e) Daka Basin	1.7 x 10^9 m^3

3.0 REFERENCES

1. ACWORHT R. I. 1987. The development of crystalline basement aquifers in a tropical environment. Quarterly Journal of Engineering Geology, 20, 265-272.

2. ANNAN-YORKE, R. 1971. Geology of the Voltaian Basin, summary of Current Ideas, J.K.Cudjoe (Ed), Special Bulletin for Land and Mineral Resources, Accra Zap.

3. AFFOTON, P.J. SOUGY AND R. TROMPETTE, 1980. The tecto no-stratigraphic relationship between the Upper Precambrian and Lower Paleozoic Volta Basin and the Pan-African Dahomeyide Orogenic belt (West Africa), American Journal of Science, 280: 224-248.

4. BATES, D.A. 1955. Geological map of Ghana, Ghana Geological Survey, reprinted by the Survey in 1966.

5. FAO\UNDP\SF.31\GHA, 1967. Land and Water Survey in the Upper and Northern Regions, Ghana Final Report Vol II. Survey, Climate and Hydrology.

6. GILL, H.E. 1964. Summary of Occurrences and present use of groundwater in Ghana and recommendations for future studies, Accra. Ministry of Works and Housing, April, 1964.

7. GILL, H.E. 1969. Groundwater Reconnaissance of the Republic of Ghana with description of Geohydrologic provinces, U.S. Geological Survey Water Supply Paper, 1757-k.

8. HEELL, J.R.T., CRATCHLEL, C.R. AND JONES CC.R.C, 1992. The hydrologeology of Crystalline aquifers in Northern Nigeria and Geophysical Techniques used in their exploration. The Hydrogeology of Crystalline Basement Aquifers in Africa .

9. Wright E.P. and Burgess W.G. (ed). Geological Society Special Publication. No. 66

10. JUNNER, N.R. and T. HIRST. 1946. The Geology and hydrogeology of the Volta Basin, Gold Coast Geological Survey Memoir 8, 51PP.

11. JUNNER, N.R. and H. SERVICE, 1936. Geological notes on Volta River District and Togoland under British Mandate. Annual report on the Geological Survey by the Director. 1935-36 p 10-16.

12. KESSE, K.O. 1985. The mineral and rock resources of Ghana. A.A. Balkema Publishers, The Netherlands, 610p.