EVALUATION OF THE HYDROGEOLOGICAL RELATIONSHIP BETWEEN MONITORING AND PRODUCTION BOREHOLES IN THE UPPER WEST REGION, GHANA

BY

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DECLARATION

Apart from the numerous publications and textbooks consulted, and for which the authors have been duly acknowledged, this thesis is the original work undertaken by me under supervision in the Upper West Region as a project work for the award of a Master of Philosophy (M. Phil) degree in Geology at the University of Ghana, Legon. It has never been presented for any degree work in any University.

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ABSTRACT

To evaluate the hydrogeological relationship between monitoring and production boreholes in the Upper West region of Ghana, a total of 192 boreholes were studied. Out of these, 23 are monitoring boreholes and 169 are production boreholes. The types of aquifers being tapped by these boreholes have also been identified to determine the adequacy of the existing network of the monitoring boreholes.

The region is underlain by basement complex rocks. The rocks are composed of granites, granodiorites and granite-gneisses. Metamorphosed volcanics, schists and phyllites of the Birimian formation occur along the western portion of the study area.

Three aquifer types were identified from geologic logs and drillers logs in the Upper West region. These are the weathered rock aquifers, the fractured unweathered rock aquifers and the fractured quartz vein aquifers. These aquifers are inter-related and where they occur in combination with thick overburden, yields are enhanced in such boreholes.

Statistical analysis such as correlation and regression analyses were used to determine the relationship between the borehole properties, while the Theis (1935) Recovery and Cooper-Jacob (1946) methods were used to evaluate the aquifer characteristics.

There is a significant relationship between overburden thickness and yields in the study area. About ninety percent of the boreholes studied have overburden thicknesses exceeding 15 m with yields of not less than 10 l/min. Generally, yields range between 4.5 l/min. and 270 l/min in the 192 boreholes. The mean and standard deviation are 25.4 l/min and 20.3 l/min respectively. Close values of the mean and standard deviation of the borehole yields indicate the heterogeneous nature of aquifers in the area.

An average decline of 4.1 m in static water levels was observed in the region. This was attributed to reduced recharge, low rainfall, high rates of evapotranspiration, increased surface run-off and excessive withdrawal of water from the boreholes.

Transmissivity values computed using the Cooper-Jacob(1946) method ranges from 1.2 m^2/day to 108.2 m^2/day in 47 boreholes. The mean and standard deviation values are 35.2 m^2/day and 30.1 m^2/day respectively. The closeness of these values, again explains the wide variations and extremity in transmissivity values of basement rock aquifers in the Upper-West region. The Theis(1935) Recovery method was used to compute the transmissivity values of six boreholes. The values range from 19.5 to 213.4 m^2/day, while those calculated using the Cooper-Jacob (1946) solution technique from the same boreholes range between 24.5 and 183.4 m^2/day.

It was noted that more accurate transmissivity values were obtained from the Theis (1935) Recovery method than obtained from the Cooper-Jacob (1946) method.

Step-drawdown results used to calculate the borehole efficiencies of five boreholes after one hour of pumping indicate that none of the boreholes analysed have inefficiencies exceeding 75% in the study area.

Finally, the studies indicate that there exists virtually little or no hydrogeological relationship between ninety percent of the monitoring boreholes and the production boreholes; hence the 23 monitoring boreholes established across the region are not adequately monitoring the groundwater levels of the area. They are also not representative of the production boreholes in the study area.

DEDICATION

To the Omnipotent, Neema and Stella, I Dedicate This Work.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Groundwater serves as an engine of growth in many areas of the world where surface water resources are inadequate or unreliable. While incomes and productivity have risen, in some cases water tables have fallen.

Conscious management of the resource is therefore necessary to forestall adverse effects on the economy and the environment including land subsidence, depletion of the resource and deterioration of the water quality.

In an attempt to improve the quality of life of the people and also to combat the incidence of water-borne and water-related diseases in the Upper West and Upper East regions, the Ghana Water and Sewerage Corporation (GWSC) in collaboration with the Canadian International Development Agency (CIDA) have from 1973 to date drilled 2,600 boreholes to expand the water supplies for the two regions. Prior to this project, other drilling activities by some agencies had taken place in these regions.

Among the 2,600 boreholes drilled, 1,018 are located in the Upper West region. In addition to these, the Catholic Diocese of Wa also sponsored the drilling of a further 350 wells to augment the supplies of water in the region.

A network of 54 observation wells was established across the two regions. Among these, 23 of the observation boreholes are found in the Upper-West region and supposed to be monitoring the groundwater resources of the region. However, it is doubtful whether the data from these observation wells adequately represent the hydrogeological situation in the Upper-West region.

Considering the wide distribution of boreholes and the heterogeneous nature of aquifers in the region, it is necessary that appropriate measures are taken to monitor the behaviour of aquifers in this peculiar situation.

As a result, this research undertaken for the Upper Regions Community Water Project (COWAP) was considered under the Action Research Fund and the National Strategic Investment Programme (SIP) to study the 23 observation boreholes in order to assess whether they are really representative of the production boreholes and to identify the type of aquifers these wells are tapping.

1.2 HISTORY OF WATER DEVELOPMENT

Before groundwater became a major source of water supply in the study area for both urban and rural populations, hand-dug wells, dug-outs, intermittent streams, rain water harvesting and ponds served as the main water sources for the rural dwellers. However, prior to the 1973 project in the Upper West region, a few drilled boreholes existed in the towns.

Most of the water sources do not last the dry season due to excessive evaporation resulting from high temperatures and low humidity. Hence, the people depend on the temporary dug-outs along stream beds for water. These sources are invariably heavily contaminated and are causes of the spread of water-borne diseases such as cholera, guinea worm and bilharzia among the people.

Consequently, the use of groundwater has become necessary since 1973 when the Ghana Water and Sewerage Corporation and the Canadian International Development Agency helped to curb the problems of water shortages in the region.

Also, in recent years, the Catholic Diocese of Wa, Water Aid, Danish International Development Agency (DANIDA) and other non-governmental organisations have provided clean potable water to most of the rural populations for domestic use.

The rural communities are supplied with water from wells fitted with hand pumps whereas urban communities with schools, hospitals and towns obtain water from wells fitted with fuel pumps.

The Upper Regions Community Water Project is therefore involved in creating new water sources for the people and examining the hydrogeological aspects of pump replacement as well as land use and environmental impact on water resources to further develop the groundwater resource base of the region.

1.3 LITERATURE REVIEW

Crystalline basement terrains in tropical and sub-tropical regions are now in the process of very extensive development as a readily available alternative source of water supply for most rural populations.

Gustafson and Krasny (1994) discussed that the importance of hard rock aquifers for hydrogeological and water management issues differs from place to place and depends mainly upon the overall availability of water and water demand. This is evident in many countries where surface water is unreliable as a major source of water supply

Studies conducted on basement aquifers by Reboucas and Cavalcante, 1982; Chilton and Smith-Carington, 1984 indicate that the presence of a relatively thick saturated regolith is of critical significance in terms of groundwater storage.

Banoeng-Yakubo (1989) noted that the occurrence of groundwater in crystalline basement rocks of the Upper Regions depends to a large extent on the thickness of saturated regolith and the aquifer depth. He further noted that topographic highs are areas where recharge to the aquifers take place and topographic lows are areas of natural discharge.

Wright et al (1985) reported that high sustained yields are to be expected where boreholes penetrate a significant thickness of saturated permeable overburden and into fractured bedrock with both sections screened. They also observed that fractured bedrock tend to have high transmissivity but low storativity contrasting with the clayey overburden of low to moderate transmissivity but high storativity. These aquifer characteristics depend mainly on the extent of fracturing and weathering occurring in the rocks.

However, aquifers in the crystalline basement of the Upper Regions are characterised by low transmissivities and reported to have variable hydraulic characteristics over short distances CIDA/GWSC (1980).

The average yield to be obtained from a group of wells can be estimated where sufficient data on existing wells are available. Heath (1976) reported that since the yield of a groundwater system depends on the areal extent of the aquifers comprising the system and the hydrologic nature of their boundaries, the most practical way to determine the extent of such aquifers is to observe the regional continuity of water levels or to collect data at widely-spaced observation wells to ensure uninterrupted hydraulic continuity.

Groundwater assessment in the crystalline terrains of Ghana conducted by Gills (1969) estimated that about ninety percent of boreholes drilled in crystalline basement rocks up to a depth of about 34 m (110ft) will have yields adequate for hand pump installation if the boreholes penetrate the entire zone of partially decomposed rock down to the level of relatively fresh rock

Feasibility studies to investigate the existing water supplies of Wa in the Upper West region indicated that the causes of the drop in water levels was due to the mining of the groundwater reserves where abstraction exceeds recharge, and the life of the borehole is consequently likely to be limited (Humphrey and Sons, 1970). They further discussed that the period over which this abstraction rate could be sustained is a function of the transmissibility, the storage coefficient, the depth of the aquifer and the amount of natural recharge.

In the final hydrogeological report for the drilling programme in the Upper Regions, CIDA/GWSC (1980), it was stated that in choosing observation wells in the regions, particular consideration was given to wells with high yields and low drawdown. The static water levels in these wells were only taken after the wells recovered after pumping, provided the effect of pumping immediately prior to obtaining the static water level was minimized.

The amount of water available to recharge in basement aquifers depends mainly on the annual total rainfall. However, Bannerman and Ayibotele (1984), and Parry et al (1987) estimated an average recharge between two and three percent of the annual rainfall in the Upper regions of Ghana.

The need for the continuous monitoring of groundwater systems throughout Ghana so as to generate data for management and planning purposes can be achieved through density determination using information on geology and climate as suggested by the Water Resources Research Institute (1990).

UNEP/WHO (1987) proposed that the monitoring system of wells need to be strengthened. Observation wells must be representative and the variables must have the same values as the production wells. Furthermore, accessibility is an important consideration for the monitoring crew, particularly in regions exposed to severe climatic conditions.

In order to establish regional trends with which to manage aquifers in the crystalline rocks of the Upper regions, Bannerman and Ayibotele (1984) suggested that due to the heterogeneous and localized nature of these aquifers, the most efficient way to monitor production boreholes is to use the production boreholes themselves, in that a number of boreholes in the area is selected and taken as a sample of many isolated aquifers thought to be in the region.

They also stated that there has been no significant decline of water levels in the two regions over a twenty-year period since the average water level change over this period is considerably smaller than the seasonal fluctuation of water levels.

Daniel (1990) reports that the only way to ensure the most efficient operation of a well is to closely monitor water levels and pumping rates. Water levels in the pumped well are measured routinely. Data from a monitoring programme are used to track aquifer performance. Knowledge of this is vital for an optimum utilization of the groundwater resources.

Stallman (1971) also discussed that the accurate location of observation wells with reference to the position of production wells is especially important in a heterogeneous or anisotropic aquifer. This is necessary so that the data obtained can be effectively used to portray the aquifer characteristics.

According to Akiwumi (1994) the significance of a groundwater monitoring network in any country cannot be left unmentioned. In many developing countries, the cost of establishing this network is expensive due to limited resources. The lack of logistical support for data collection teams makes continuous monitoring difficult, hence data is often unreliable.

Groundwater resources need to be rationally managed to prevent the deterioration of groundwater quality and the side effects on the environment. Xiao (1994) discussed that a primary groundwater monitoring network should be implemented to support the groundwater management policy at a national or regional scale so that information collected from this network may provide the basis for groundwater resource planning, management and hydrogeological studies.

Groundwater studies conducted by Mallari (1959) in the Upper regions of Ghana show that there is a general low nitrate concentration in the region with a mean value of 1.5 mg/litre. Only one sample with nitrate concentration higher than 9 mg/litres, but lower than 10 mg/litres was encountered. Pelig-Ba et al (1985) recorded nitrate levels as high as 127 mg/litre in some boreholes in the Upper West region. These isolated high values may probably be the result of local pollution.

1.4 OBJECTIVES OF STUDY

The primary objective of this study is to evaluate the hydrogeological relationship between monitoring boreholes and production boreholes in the Upper West region.

Other objectives include the following:

a) To identify the types of aquifers that the monitoring and production boreholes are tapping in the region and

b) Based on the findings of the primary objective, a general review of the monitoring wells network structures would be put in place.

The study would therefore contribute to the understanding of the groundwater potential and occurrence in the region as well as establish hydrogeological conditions required for the location of monitoring wells in crystalline basement terrains, and hence present a status for the future trends in all aspects of groundwater resources, utilization and development.

1.5 METHODOLOGY

The methodology adopted to achieve the purpose of this study comprised mainly Data Collection, Data Analysis and Interpretation.

1.5.1 DATA COLLECTION

This involved the following

a) The review and study of existing literature on groundwater in crystalline basement rocks, the collection of borehole logs on the 23 monitoring boreholes and 169 chosen production boreholes.

This information was obtained from the COWAP/GWSC Office in the study area.

b) Field studies, including the measurement of the static/dynamic water levels of the monitoring and sampled production boreholes that are distributed in all the five districts of the study area with a well sounder (Water Level Indicator-SOLINST P2/M3/80M).

c) The Global Positioning System (GPS GARMIN 75) instrument was used to locate the position and elevation above sea level of the production and monitoring boreholes.

d) Relate the location and elevation of the 23 monitoring boreholes and 169 sampled production boreholes to the geology and hydrogeological conditions of the area

1.5.2 DATA ANALYSIS AND INTERPRETATION

a) Data analysis involved the detailed studies of the existing geological reports, hydrogeological reports, maps and borehole logs of the study area with the view to categorizing the observation and production boreholes to identify the type of aquifers they monitor.

b) From the analysis, the percentage of the observation boreholes that tap the main aquifer types was determined; the same was done for the sampled production boreholes.

c) An evaluation of the hydraulic characteristics of the boreholes from the available logs and data was performed

d) From the study of the available and currently measured static water level data on boreholes, the trend in static water levels over the years was established.

e) The established results and percentages indicate whether the main aquifer types are adequately monitored by the existing network of observation boreholes.

f) Similarly, the correlation and regression analyses helped to establish whether there exists any similarity in the borehole properties in the different rock types in the region irrespective of their spatial and locational differences.

g) Based on the findings, maps and graphs relating the various aquifer and borehole parameters were prepared.

1 6 SOURCES OF DATA

Twenty three observation boreholes and a sample of one hundred and sixty-nine production boreholes were chosen from the main data base of about 1,018 boreholes in all the districts of the Upper-West Region from the COWAP office. Particular consideration was given to high-yielding wells, though data from some low-yielding wells were included. In addition, data from some redeveloped boreholes were obtained from the Technical team at the COWAP office in Wa.

Data obtained for analysis were derived from the pre-project boreholes drilled between 1954 and 1974, and boreholes completed by CIDA/GWSC between 1975 and 1979. Some of these boreholes are mechanized, whereas others are fitted with hand pumps.

Data for evaluation of aquifer properties of some production boreholes in the Wa North and South well fields were obtained when pumping test was performed by the Kumasi Drilling Unit team of the Ghana Water and Sewerage Corporation in the region during the study period

Information on some boreholes selected for the study was obtained from data provided by the Catholic Diocese of Wa and the Water Resources Research Institute, Accra. This information included borehole records and hydrogeological reports.

The Meteorological Services Department of the Upper West Region made data available on the annual rainfall totals in millimetres covering a period of twenty seven years. Other information obtained from the department included the mean monthly temperatures, the mean daily minimum and maximum temperatures in degrees Celsius and the monthly relative humidity data in percentages.

CHAPTER TWO

PHYSICAL SETTING OF THE STUDY AREA

2.1 LOCATION AND AREAL EXTENT

The Upper West region lies within latitudes 9°40'N - 11° 00'N and longitudes 1°30'W - 2°55'W. It is one of the ten administrative regions of Ghana.

The region is divided into five districts namely Wa - which is the regional capital, Nadowli, Jirapa-Lambussie, Lawra and Tumu districts (Figure 1). The region covers an area of 18,476 km². It is bounded in the east by the Upper East region, and to the south by the Northern Region. It is also bounded by the Republic of Burkina Faso to the north and west.

2.2 RELIEF

The study area is characterized by a flat and gently undulating topography. The relief ranges from 50 m to 300 m. However, elevations as high as 400 m are quite common. Flatlands are prevalent, whilst low and gentle hills form the main relief features. The undulating terrains have patches of rolling plains scattered throughout the area. Hills often form ridges stretching over tens of kilometers (ridgy topography). These ridges show a close relation to the geology of the area stretching along the strike of most rock masses.

The generally subdued topography coupled with the low rainfall has led to the development of poor drainage systems and poorly-defined valleys over extensive areas. However, where large tributaries of the Black Volta river occur, well-defined valleys are found.

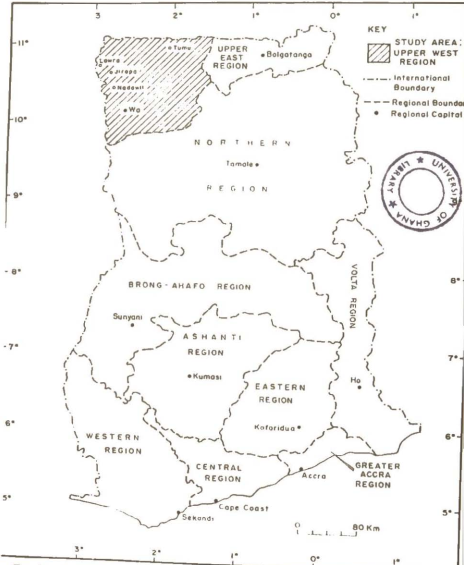


Fig. 1 A MAP OF GHANA SHOWING LOCATION OF THE STUDY AREA: UPPER WEST REGION

2.3 CLIMATE

The region falls within the Guinea Climatic zone and is mainly influenced by two air masses; the North-East Trade Winds and the South-West Monsoons. This climate is tropical in nature and characterised by two main seasons - the wet and dry seasons.

The two air masses, that is: the North-easterlies and the South-westerlies, which converge at the Inter Tropical Boundary (ITB) are controlled by two subtropical high pressure belts (Tandoh, 1985).

The south-west monsoon that blows over the region contains a great deal of water vapour which it collects during its long journey across the sea. Its influence is experienced during the wet season. This season is rainy and starts from April to September. The months of April, May, June and July have rains of short durations with high intensities. Rains are often preceded by thunderstorms and lightning. The mean monthly rainfall in May is about 115 mm. However, the peak rainy period occurs from August to September, where there are more rainy days than dry days. Rains are continuous with low intensities and relatively cool days.

Mean monthly rainfall as high as 900mm is experienced during the rainy periods in the region. Pobedash (1965) mentioned in his survey that rainfall in the region is in the form of tropical rainstorms and about thirty five to forty percent of rain is recorded during the peak rainy season and annual precipitation averages about 1200mm.

The North-east trade winds blow from the heart of the Sahara-Arabian desert and it is associated with dry, cool winds known as the Harmattan. This period normally occurs in the months of December, January, and February. Humidities are low and there are no rains and night dew

These, coupled with a permanent inflow of hot, dry wind from the Sahara results in high evaporation and transpiration rates which eventually have deadly effects on some plants in the area.

The harmattan season in the region is characterized by high day temperatures and low temperatures at night. There is little condensation in the dry atmosphere thereby resulting in a general absence of rain clouds. However, occasional thunderstorms are experienced in the afternoons or evenings. This period normally occurs in the months of October, February and March.

Temperatures are relatively high ranging from a maximum daily temperature of about 40° Celsius in March to a minimum of 15° C in January. The monthly mean daily temperatures vary from 20° C in August to 34°C in March. Generally the average annual temperature is about 30°C.

Relative humidity in May to September reaches fifty to seventy percent (50-70%) in the wet season and drops to about 15% during the rest of the year. The mean annual relative humidity ranges from thirty seven to forty six percent (37-46%).

2.4 EVAPOTRANSPIRATION

Evaporation and transpiration constitute major components of the hydrologic cycle. These two processes, when they occur together is termed Evapotranspiration. It is the combined effect of evaporation from the surface and groundwater as well as the transpiration of plants, where water is lost into the atmosphere. This depends largely on the extent to which water is available at the surface.

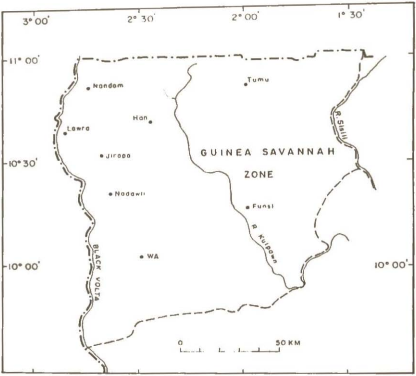
Owing to the high temperatures and heat experienced in the Upper West region, potential evapotranspiration is very high. Estimates made by UNDP/FAO (1967) indicate that on the basis of rainfall and runoff data, the actual evapotranspiration averages around 890 mm and falls to 635 mm in dry years. Banoeng-Yakubo (1989) reported that the rate of evapotranspiration is accelerated through the combined effect of variable rainfall, temperature, humidity and sunshine duration conditions

2.5 SOILS AND VEGETATION

The Upper West region is categorized under the Guinea Savannah Woodland type of vegetation (Figure 2). Short trees occurring singly or in clumps with light, medium or denser grass covering the ground between them is prevalent in the area.

Patchy growths of woodland with moderate grass cover are occasionally found. Different species of trees such as Shea-butter, Baobab and Acacia trees are very common. Stream channels are also dominated by denser trees and grass cover, whilst marshy lands occur in some places.

The principal soils which cover the study area are the groundwater lateritic soils and savannah ochrosols. The lateritic soils are present at generally shallow depths below the soil surface and more or less of a cemented layer of iron pan through which rain water does not easily penetrate. The texture is coarse, sandy-loam if developed over granites.



Source: After W. L. Wardrop and Associates (1980).

FIG. 2 UPPER WEST REGION - VEGETATION ZONES

The savannah ochrosols are well-drained, porous, loamy soils if developed over granites and Birimian rocks. They are mildly acidic (Dickson and Benneh, 1988) Generally the soil cover in the area is not thick; and the most fertile soils are usually found in the valleys of rivers, streams and at the foot of hill slopes.

2.6 SURFACE WATER RESOURCES AND DRAINAGE

Surface water, mainly dams, streams and the Black Volta river serve as alternatives to the groundwater resources to meet the increasing water demands of the people in the region during the rainy season. However, most of the surface water is ephemeral and dry up in the dry season. Only small pools of standing water remain. These pools and dams are easily contaminated through agricultural and other human activities.

The only perennial river in the region is the Black Volta. It flows roughly from the north to the south. Its catchment area is very extensive and a large proportion of water is drained from its tributaries such as the Kamba, Pale and San. The Kulpawn and Sissili rivers drain into the White Volta.

The poorly-defined valley floors and depressions near the villages are considered as streams. Such depressions make it difficult for any surface impoundment to be undertaken since the catchment area is too small and discharges from them are relatively inadequate for the increasing population especially during the dry seasons.

The overall surface drainage system in the region is dispersed but patterned in a dense and dendritic manner, increasing in density from the north towards the south. However, the rectangular drainage pattern is also common and occurs mainly at areas where the rocks are jointed. Streams like the Aruba, Kule, Vetare, Pale, Bele, Molebule and Nowenereme drain into the Black Volta and practically dominate the entire drainage network of the Upper West region.

TABLE 1: LOCATION AND CATCHMENT AREAS OF SOME STREAMS IN THE REGION (HUMPHREY AND SONS, 1970).

STREAMS	LOCATION	CATCHMENT AREA (square kilometres)
Molebule	Sing	42.1
Bele	Charia	147.4
Pale	a) Pissi	181.7
	b) Kpongu	213.4

2.7 POPULATION AND SETTLEMENT

In 1984, the Upper West region had a population of 439,161 people in an area of 18,476 km square and the population density was 17 persons per square kilometre. Bannerman (1990) projected that the expected growth by the year 2000 would increase by 2.91% and the region could have a population of 690,000 people. He further projected the population to five yearly intervals in the region as shown below.

TABLE 2: PROJECTED POPULATION AT FIVE YEARLY INTERVALS IN THE REGION

1984	1990	1995	2000
439,161	521,637	602,083	692,938

As it is characteristic of Northern Ghana, about 75% of the population in the region is rural, though urban migration has been on the increase in recent years. A little over 50% of the people in the Upper West region live in the Wa and Nadowli districts which constitute the highest concentration of urban population, followed by the Lawra, Jirapa/Lambussie and Tumu districts respectively. A significant number of people live in towns like Nandom, Jirapa, Hamile, Kaleo, Tangasia and Dorimon. This trend of rural-urban population concentrations is not expected to change much by the end of the year 2000.

The population of the area is concentrated in small settlements usually located at market centres and along the valleys of rivers. Rural settlements are mostly nucleated. The Tumu district has the lowest population density. This belt is generally called the "Tumu gap" mainly due to the difficult physical environment which accounts for the large uninhabited strip of land.

2.8 PEOPLE AND OCCUPATION

The Dagaaba and Sissalas are the main ethnic groups in the region whilst the Wallas live within settlement units in and around Wa, the regional capital. The Dagaaba tribe is the dominant tribe and they occupy most of the land area mainly in the Nadowli, Jirapa/Lambussie and Lawra districts. The Sissalas are mainly found in the Tumu district and parts of the Jirapa/Lambussie district, however these ethnic groups are inter-related.

The districts are linked mostly by third class roads. The major road networks providing communication with the rest of the country are the north-eastern road linking Tumu, Navrongo and Bolgatanga from Wa to the Southern part of Ghana and the other runs due South from Wa and connects the area with the central parts of Ghana. A densely developed network of footpaths linking villages and settlements are prominent. In the rainy season, some of the major motor roads and third class roads are sometimes not motorable due to floods.

A large percentage of the population is engaged chiefly in agriculture as a source of livelihood. Farming and animal husbandry is common in the area. Crops such as yams, maize, millet, sorghum, groundnuts, cotton and rice are cultivated. Cattle, sheep, goats, and poultry are the animals reared for both commercial purposes and domestic consumption. Cattle, yams and shea butter are supplied from the area to other parts of the country. Other people living in towns engage in handicrafts, weaving, leather tanning, pito brewing and petty trading. Fishing is also common among people living along the Black Volta river.

2.9 NATURAL RESOURCES

Occurrences of both primary and alluvial gold have been detected at Lawra and Duori in the study area. Junner (1935) traced some auriferous quartz veins in the locality of Duori.

Gold is also common in alluvium along the Black Volta down the vicinity of Birifu.

Though the economic value of the ore found so far may not be promising, it will be of practical interest for investors to undertake detailed prospecting in the area. Manganese and graphite ore reserves are found at Kambale and on the Wa-Dorimon road respectively.

Granitoids occur in unlimited quantities in the area and are used for roads and other construction purposes. The establishment of a quarry in the area particularly along the Wa-Loggo and Wa-Bullinga-Ducie roads for the extraction of quarry stones would be economically viable.

Other mineral resources in the study area are chromium and iron ore located in the Tumu district (Kesse, 1985). Concerns have been expressed in recent years for the Government of Ghana to begin exploiting the iron ore reserves in the study area at Pudo.

CHAPTER THREE

GEOLOGICAL SETTING AND HYDROGEOLOGY

3.1 GENERAL GEOLOGY

The region is generally underlain by crystalline basement rocks which form one of the main geohydrologic provinces of Ghana (Figure 3). The rocks are mainly composed of granites, granodiorites and granite-gneisses. There are metamorphosed volcanics, schists and phyllites of the Birimian formation along the western portion of the study area.

The crystalline basement of the African continent is formed by major suites of the Precambrian rocks. The predominant lithological types are granitic-gneisses and lower grade metamorphic rocks derived from volcanic and sedimentary deposits. Amongst the latter, greenstone belts are especially prominent in some areas. Large areas of more recent anorogenic intrusive rocks associated with major rifting are included.

In his survey, Roudakov (1965) noted that the volcanic and volcanogenic rocks include greywackes, fine tuffaceous sediments and cherts rich in manganiferous sediments. These lithologies form a north-south belt of supracrustal rocks which extend from the south-west of Wa to Ouagadougou in Burkina Faso. Plutonic rocks are the most abundant type in the area and are composed of granitoid rocks some of which are considered to be intrusives.

Roudakov (1965) carried out a regional mapping in the area and explained that the fine grained tuffogene sediments probably represents reworked and primary ash deposits which occur to the east to Babile-Lambussie area. At the north-central part in the Babile-Lawra area are mafic volcanic rocks typical of greenstone belts.

3.1.1 THE BIRIMIAN SYSTEM

Junner (1935) divided the Birimian system in Ghana into two series. The Lower and Upper Birimian series. Traditionally, Upper Birimian rocks were considered to overlie the Lower Birimian rocks conformably. However, in a recent reinterpretation of the stratigraphy, Leube et al., (1990) recognised the two assemblages as coeval with the sedimentary/volcaniclastic units representing the distal facies, or basins between a sequence of evenly-spaced volcanic belts.

Typical lithologies of the Lower Birimian include schists, phyllites, greywackes, crystalline schists, tuffaceous shale and chemical (Mn-rich) sediments that are largely confined to the basin margins. These rocks are believed to have been derived from the Liberian-type of rocks as found in the nucleus of the West African Craton (Bessoles, 1977). Lower Birimian rocks are confined to the west of the study area.

Upper Birimian rocks include an assemblage of tholeiitic basalts with some interflow sediments. The Upper Birimian is volcanic in origin and is composed of pyroclastics, lavas, sheared conglomerates 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). The Tarkwaian rest unconformably on the Birimian. According to Junner (1935) the Upper Birimian and the Tarkwaian are inter-folded due to post-Tarkwaian orogenic activity. Tarkwaian

3.1.2 GRANITES AND BASIC INTRUSIVES

Intrusive rocks occupy about seventy percent of the area studied and are represented by the Cape Coast Granite Complex, Dixcove Granite Complex and Undifferentiated granites which intrude and metamorphose the Birimian rocks. These rocks are of Early Proterozoic age. They form a large part of the West African craton and crop out extensively in the Upper West region.

Cape Coast Granite Complex, denoted by (G1) occur throughout the eastern half of the area and constitute part of the large pluton that outcrops in the northeast and south-east of the region. Smaller massives are found in the west and southwest of the area surrounded by Lower Birimian rocks.

Rocks of this complex, consist primarily of granites, biotite and muscovite granite, granodiorite, pegmatites and aplite with biotite-schist pendants. The pluton is conformal and harmonic to the structure of the country rocks. Migmatites and gneisses are also found among the complex.

On the basis of studies carried out on the magmatic rocks of the Granite Complexes found in the project area and in adjoining localities, Pobedash (1965) proposed that the Cape Coast Granite Complex was emplaced in four phases whereas the Dixcove Granite Complex was emplaced in three phases. Each complex is recognised for its trend of increase in acidity of rocks from the older to the younger phases.

The Dixcove type which is usually called (G2) is composed of sodic hornblende-granite, granodiorite, diorite, porphyry, aplite and pegmatite, biotite-gneiss and porphyritic biotite. This complex forms non-foliated, discordant to semi-discordant bodies in the enclosing country rocks which are generally Upper Birimian metavolcanics with numerous enclaves found within the granite complex.

Dixcove granitoids are less widespread than Cape Coast granitoids. Typical massive outcrops of the Dixcove Granite Complex is located to the southwest of Tangasia and the extreme northwest of the Yaga. In the central and southern parts of the area, smaller stocks were found in Lambussie, north-west and east of Lawra, Babile and Birifu.

The G2 granitoids are less metamorphosed than G1 granites which are associated with gold mineralization. The G2 type forms small intrusive bodies within the volcanic belts (Roudakov, 1965). Where faults were detected, the granitoids had suffered cataclasm, mylonitization and sericitization.

Undifferentiated granites occur around Lawra, Nandom and Birufu. Apart from the granitoids and intrusive rocks, small stocks of basic rocks in some portions of the area were observed. They include groups of gabbros, dolerites, norites and serpentinites.

3.2 STRUCTURAL GEOLOGY

The Lower Proterozoic rocks in Ghana have generally been affected by two deformation events. During the first event, the Birimian System was deformed and intruded by granitoids. Subsequently, it was uplifted and eroded with the Tarkwaian which accumlated in a series of grabens and was located within the volcanic belts. The second deformation event involved folding, (Moon and Mason, 1967; Ledru et al., 1988; and Leube et al., 1990) and gravity tectonic processes which affected both the Birimian and Tarkwaian rocks. Metamorphic rocks of the Birimian series together with the granitoids which intrude into the Birimian are the most common rocks in the study area.

The main regional geological and structural features in the area are the Dorimon synclinorium and the Sawla-Wa anticlinorium. The Dorimon synclinorium appears to be a large synclinal structure with a fairly gentle western limb and a steep eastern limb. It plunges in a north-south direction towards the Babile-Duori and Hamile-Bapala area (Roudakov, 1965).

This synclinorium is composed essentially of Lower Birimian rocks and consists of a combination of simple folds and extremely complex minor ones with amplitudes measuring several meters; a system generally typical of localities of Archean and early Proterozoic folding (Pobedash, 1965).

Fold structures have in general the same orientation as the synclinorium and are en echelon arranged. The extent of fissuring and fracturing in the rocks of the area can be linked to the presence and development of these structures. Drag folds are common in phyllites and phyllite-like schists.

The Tangasia and the Dorimon faults are major faults which occur in the area. The strike of the Tangasia fault turn south-westward beyond Kpahu and Tangasia. The middle section of the fault is characterized by mylonites and cataclasites which have developed within metamorphic rocks. To the east of the fault, the mylonites are replaced by granite rocks, while the phyllonites are replaced by schists in the west.

The fault traverses rocks of the Lower Birimian and granitoids of the Cape Coast Complex in the north. The South western end cuts across Dixcove granitoid massives whilst the middle section runs through the Upper Birimian. Pobedash (1965), judging from the nature of rock displacement suggested it must be a large dip- and strike-slip fault, with a younger age than all known pre-quaternary rocks in the area.

The Dorimon fault strikes south-westwards from Tappo to Dorimon. Other less extensive faults were encountered near Yaga. These fault zones occur within metamorphic schists. They traverse rocks of the Birimian series and granitoids of the Dixcove complex.

Field observations of fractures and joints were noticed on the granites in the vicinity of Kamba. They are oriented in a northwesterly direction. Veins in the area generally show a northwest or southeast trend. The contact of the veins with the country rocks are uneven and indicate zones of shearing.

Pegmatites are the most widespread rocks in the group of veined formations of the Cape Coast granite complex. They are pink or pale grey in colour and show coarse-grained pegmatitic texture. Aplites are fine-grained and brightly coloured rocks. They are closely associated with the pegmatite veins.

Quartz veins are very numerous in metamorphosed Birimian rocks, where they are in contact with the Cape Coast granitoid complex. In the Birimian rocks, they are a few centimetres to hundred meters thick and range from meters to several hundred meters in extent

In some portions near Lawra, thin parallel traversing quartz veins were observed. In few instances, quartz stocks were detected. In the vicinity of Jirapa and Duori, the quartz veins are numerous and associated with locally crushed zones. They are prevalent also within the stretch of Birimian rocks from Doweni to Nandom Normally, the quartz is milky-white or bluish grey in colour being occasionally spotted and streaky.

Dykes are a few meters to several meters in thickness and more than 300 m in extent. They are often found in portions of rocks of granitoid complexes as well as in Birimian rocks. Diorites, diabase porphyries and diabases are often located in metamorphic rocks of the Birimian series close to the contacts with the Dixcove granitoid complex. They also form dykes and strike north-east and north-west. They always cut across the enclosing country rocks.

3.3 HYDROGEOLOGICAL CONDITIONS

3.3.1 MODE OF GROUNDWATER OCCURRENCE

Generally, crystalline basement rocks have little intergranular porosity. The few pores that are present are small and not interconnected; consequently the crystalline rocks have little primary permeability. However, considerable secondary permeability have been developed by fracturing and weathering. Most of the water in crystalline rocks is stored and transmitted through the weathered zone near the land surface and in fractures in deeper, less weathered zones.

Groundwater accumulation in areas underlain by crystalline rocks depends on the availability of the thick regolith or the presence of a network of fractures. The nature and extent of fracturing also influence the rate and pattern of weathering as well as the amount of overburden thickness Malomo (1987).

Basement aquifers occur within the regolith and the fractured bedrock. The mode of occurrence of groundwater in the study area is controlled by the extent and effect of rock decomposition, the presence of quartz, pegmatite and aplite veins within the decomposed rock and the presence of fracturing and shearing.

In most cases, the extent and depth of weathering is determined by the degree of fracturing, veining and jointing.

The geological setting of the project area is fairly complex and as a result, groundwater availability varies considerably even on a very local scale. Therefore, where the regolith has adequate thickness (12 m-30 m), and the weathering profile has developed more fully in the formation that are sheared and fractured, sufficient supplies of water are obtained.

Kaehler and Hsieh (1993) describe fractured rock aquifers primarily on the basis of weathering into three zones, namely: the regolith, where the rock has been altered substantially into a layer of loose, broken weathered rock materials near the surface. Below the regolith is a layer of fractured and partially weathered rock that is referred to as the transition zone and below the transition zone is the fresh unweathered bedrock which may not be fractured.

Studies from lithological profiles in the area indicate that the degree of weathering in the rocks depends on their permeability. Evaluation and studies of the drillers logs carried out reveal that most of the water bearing horizons in the area occur in the moderately decomposed zones with few fractured zones. Banoeng-Yakubo (1989) also identified the moderately to poorly decomposed zones as the producing zones in studies in the Upper region.

However, the water bearing zones do not generally follow the same sequence in all the boreholes drilled. Sequences of the lithological profiles are likely to differ due to the fairly complex nature of groundwater occurrence in basement rocks of the Upper West region.

Although the vertical extent of each lithology cannot be defined precisely, the distinctions are useful for hydrogeologic characterization. The regolith is derived primarily from in-situ weathering of bedrock and to a lesser extent from deposition of alluvium by streams and rivers. Fractures originally in the parent rock may persist in the regolith. Permeability and porosity are usually provided by the presence of intergranular pore space and as well developed by fracturing and weathering.

Producing wells in the Upper West region were completed mainly in the moderately to poorly decomposed zones. Where numerous fractures, joints, quartz veins and pegmatites occur in the rocks of the study area, thick decomposed zones exist and weathering is enhanced along fissured zones. The decomposed zones create openings between the mineral grains along which the water may circulate. The fractures, joints and veins aid in water transmission.

In the region, water occurs at the moderately to poorly decomposed zone. This depends greatly on the petrographic composition and mineralogy of the rocks. Micaceous and feldspathic schists alter to clays and permeability is reduced. However, relatively high yields are obtained from quartz-schists in the moderately decomposed zones.

In the phyllites, groundwater occurs in fissured rocks and high-yielding aquifers are obtained when they are completed in fractured quartz veins. CIDA/GWSC (1976) reports that there is no well-defined transition from the decomposed rock to the fresh bedrock in the phyllites, because the fresh rock is often soft. The decomposed zones are usually thick and vary from 6 m - 36 m.

The decomposed products of greenstones are generally fine grained, rich in mica, chlorite and hornblende. The thickness of the decomposed zones does not usually exceed 47 m. Again, the water bearing capacity of the greenstones is enhanced by shattered quartz veins, joints and fractures.

UNESCO (1979,1985a,b) reported that the hard rock lithologies have variable yields depending on the rock type. Granites tend to be relatively good aquifers with a typical median yield of 16 l/min. Gneisses tend to yield similar quantities or somewhat less with schists and phyllites. About seventy five percent of the successful wells were completed in granitic terrains in the study area.

Reboucas and Cavalcante (1987) report that terrains composed of granite-gneiss or other high grade metamorphic rocks generally contain more springs and are more favourable for developing groundwater supplies than terrains composed of schists and slates. There is no spring in the area of study probably because of the poor hydrogeological conditions existing in the area.

More groundwater occurs in coarse-grained granites and granodiorites than in fine-grained mica and hornblende rich granodiorites and granites (CIDA/GWSC, 1980). Banoeng-Yakubo (1989) also made the same observation in studies in the basement complex rocks of the Upper regions of Ghana. The most prolific zones in the granites are common where pegmatites, aplites and fractured quartz veins occur.

The decomposed zones in these rocks are not up to 40 m. However, where granitic gneisses occur, the decomposition profile is not uniform because more resistant poorly decomposed layers are often deposited with less resistant moderately decomposed layers.

Yields are however enhanced in fractured quartz veins and pegmatitic zones. Also, quartz dykes intruding into schists and granites develop joints during cooling. These joints are able to store groundwater and have therefore proven to be a valuable source of groundwater supply in the study area especially under unfavourable geological conditions.

It is imperative in groundwater investigations to identify and evaluate the geologic zones that are important to groundwater occurrence. Studies in the region have identified three types of aquifers. They are the fractured quartz vein aquifers, the fractured rock and the weathered zone aquifers. These aquifers may be inter-related and hence produce significant amounts of water.

3.3.2 CHARACTERISTICS OF THE AQUIFERS

The most striking hydrogeological feature of aquifers in crystalline rocks are the overwhelming variability of their properties. They are heterogeneous and limited in areal extent.

The hydraulic conductivity normally varies within the same rock unit and often within short distances. Recent studies by Gustafson and Krasny (1994) explained that groundwater transmission is by the fractures and joints that form the conductive openings through the basically impervious basement rocks. Zones of increased degree of fracturing or crushed rocks may acts as conductors through the rock.

Wright (1992) reported that basement aquifers occur within the regolith and the fractured bedrock.

Their occurrence and characteristics are distinctive and is largely a consequence of the interaction of weathering processes. He further stated that basement aquifers are essentially phreatic in character, but respond to localised abstraction in semi-confined fashion if the static water level occurs in a low permeability horizon such as a clay regolith.

Aquifers in the study area are variable in extent and range from areas of deep weathering to jointed and fractured zones. They are usually characterised by low transmissivities varying from 7.5 to 30 m^2/day and low storativities ranging from $3x10^{-4}$ to $8x10^{-3}$ (CIDA/GWSC, 1980). Banoeng-Yakubo (1989) obtained a storage coefficient value of $2.87X10^{-3}$ in a production borehole (401G 2) at Danko in Wa.

Aquifers form isolated groundwater basins in the region and the long-term storage capacity is determined by the areal extent of the aquifers, the permeability of the aquifers and the saturated thickness of the aquifers.

Regolith aquifers occur more extensively where a relatively thick and permeable saturated weathered zone exists. The saturated thickness of the regolith is a controlling factor on the transmissivity, aquifer storage and also determines the available drawdown to the most productive aquifer horizon.

Chilton and Foster (1992) reported that saturated thickness in excess of 10 m need to be available for the regolith alone to act as a useful aquifer in the context of a village water supply. This agrees with the saturated thicknesses of regolith in the study area which do not exceed 20 m in most situations. McFarlane (1992) also discussed that such conditions are generally fulfilled in the more humid regions with shallow groundwater table especially on the African erosion surface where the deepest uniform weathering has occurred.

Generally, aquifers in the region are characterized by limited areal extent, low transmissibilities and low storage capacities which result invariably in comparatively low yields. The thickness and character of aquifers in crystalline basement rocks vary within short distances depending particularly on the petrographic composition of the rocks, their tectonic deformation, the type of weathering and geomorphological conditions

3.3.3 GROUNDWATER RECHARGE

Recharge to groundwater forms the most effective and reliable means of subsurface water replenishment in the study area. Rainfall is the dominant source of recharge to the aquifers in the region. However rainfall in the study area is seasonal and intensified by periodic droughts.

Adverse land use practices such as poor farming methods, pasture over-grazing and deforestation through firewood exploitation, bush burning and charcoal burning tend to aggravate desertification and expose the soil to the scorching sun. These adverse effects bring about serious environmental consequences such as soil erosion, local climatic changes especially high evapotranspiration as well as instability in the hydrological regime and the destruction of water bodies.

In the study area, the highly decomposed material which overlies the aquifer varies from silty sand and laterites to almost pure clay. Hence infiltration is usually substantial through the silty sand in considerably large areas. Whereas in zones of high clay content, very little downward percolation can take place and the main recharge is along more permeable zones and fractured quartz veins. Normally infiltration is reduced by soil crusting

Soil moisture storage is also reduced by the erosion of finer grained material resulting in the hindrance of downward percolation of water. Groundwater resources of basement rocks strongly depend on recharge to the groundwater system and climatic conditions. Climatic factors control precipitation, temperature distribution and character of rock weathering in the long-term perspective.

Generally, recharge to the aquifer systems in the Upper West region is small and limited but significant because of the barrier normally formed by the overlying clayey decomposed zones and evaporation. The basement rocks do not have high groundwater storage. Retention possibilities are limited and groundwater is rapidly depleted. However, the presence of pegmatites, shear and contact zones, fractured quartz veins and the extent and effect of deeper rock weathering, aid a lot in augmenting the groundwater availability in the region

CIDA/GWSC (1978) reported that the quantity of groundwater replenishment in the region depends not only on the total precipitation in a given year, but also upon soil moisture conditions before a storm and the manner in which the rains occur. Recharge to the aquifer begins to take place only when the moisture deficit in the soil has been met.

Estimates of direct recharge are likely to be more reliable than those of indirect recharge. Lerner et al (1990) are of the opinion that since recharge tends to be correlated with rainfall, short periods of heavy rainfall within the year are more important in producing recharge than many years of average rainfall.

As far as the hydrology of the African basement is concerned the climatic variables of rainfall and potential evaporation are the most significant factors in determining run-off and groundwater recharge (Farquharson and Bullock, 1992).

The study area is characterised by a cyclical annual weather condition with a single rainfall period from April to October and a mean annual rainfall between 900 mm and 1150 mm. This is followed by a prolonged dry season. The potential evapotranspiration is very high. Pelig-Ba et al (1988) estimated an annual potential evapotranspiration value of 1726 mm for Wa. Relative humidity is high in the rainy season and low in the dry season.

The studies of Banoeng-Yakubo (1989) in the basement complex rocks of the Upper region of Ghana estimated the average annual groundwater recharge to the Lawra drainage basin to be 138 mm. He explained that this amount of recharge is expected to augment the groundwater base of the study area.

Parry et al (1987) discussed that an average recharge rate estimated between two and three percent of the annual rainfall obtained from the limited information on urban borehole fields in the area. Water level fluctuations in a network of observation wells are dependent on the timing and intensity of rains and the local hydrogeological setting prevailing in the area.

Where the mean annual rainfall is less than 400 mm, recharge from direct infiltration is likely to be small or negligible (Edmunds et al. 1988). Therefore groundwater resources are only likely to develop in association with runoff either in alluvium or underlying basement rocks.

Annual recharge of groundwater in the study area is significant but of local origin and not supplied by any distant source. Akiti (1976) discussed that groundwater in parts of the Upper Region are of recent age and characterized by an active groundwater circulation.

Theis (1937) pointed out that unless and until withdrawals of groundwater are balanced by an increase in recharge or a reduction in natural discharge, water will be removed from storage and water levels will decline. In the Upper West region, the abstraction rate of water from boreholes exceeds the recharge. This accounts for the regional decline of water levels in the region.

3.3.4 GROUNDWATER FLOW SYSTEM

The overall pattern of groundwater flow in basement terrains is controlled primarily by the regional topography and geology. Fundamental to any groundwater study is an adequate understanding of the geological conditions prevailing in the area. The pattern and rate of groundwater movement within an area is governed not only by topography, but by the rock structures as well. Particularly the fault and fold pattern and its influence on rock fracturing.

The study area is underlain by hard rocks consisting primarily of granitic and Birimian metamorphic rocks. The granitic rocks comprise granites, granodiorites and granite-gneisses. The Birimian rocks in the area are schists, phyllites, greenstones and sheared conglomerates. Generally, these rocks have virtually little or no permeability, except in places where they are weathered and/or fractured.

The Birimian rocks in the region have been highly folded and often sheared and/or faulted Quartz veining is common in the schists and phyllites. They are usually deeply weathered and more noticeable in valleys and flat terrains where intensive fracturing and shearing has occurred than on hillsides.

In the crystalline basement aquifers, groundwater flow occurs largely through discontinuities. The nature and orientation of these discontinuities aid in the occurrence and movement of groundwater, the permeability of the rocks and the storage capacity of the aquifers. Generally, discontinuities and shatter or breccia zones associated with faults form irregular and tortuous flow channels which may be filled with permeable or impermeable materials. In some rocks they may be locally enlarged by solution to form discrete flow paths

Freeze and Cherry (1979) noted that groundwater flow occurs from the highlands towards valleys The groundwater flow system in the region consists mainly of recharge on local topographic highs and discharge in topographic lows.

CHAPTER FOUR

ANALYSIS OF DATA

4.1 AVAILABLE DATA

Information obtained at the time of construction of boreholes was extracted from the archives held by Community Water Project (COWAP) offices in Wa. Others were obtained from field studies during the study period. The information included; construction details, static and dynamic water levels, lithologies, yields and topographic locations

In total, records from one hundred and ninety two boreholes were analyzed for the study over the entire region. Among these were twenty three observation boreholes and one hundred and sixty nine production boreholes.

Borehole records were analyzed and estimates of borehole depths, depths to top of aquifer, overburden thicknesses, borehole yields, and aquifer thicknesses were obtained However, six boreholes do not have records pertaining to boreholes depths and overburden thicknesses Information was also obtained on static water levels from one hundred and seven boreholes during pump installations. One hundred and five boreholes also had static water level measurements taken during the field studies.

Available data shows that there had been one hour pumping tests data for forty-seven boreholes at the time of construction, and twenty-four hours pumping tests were conducted on six other boreholes in the Wa well fields during the study. The Global Positioning System was used to measure the locations and elevations of observation and production boreholes during the study.

4.2 LIMITATIONS OF AVAILABLE DATA

In an attempt to provide clean potable water in the Upper regions of Ghana, the Canadian International Development Agency (CIDA) in conjunction with the Ghana Water and Sewerage Corporation (GWSC) drilled 1,018 boreholes in the Upper West region in order to eradicate water-borne diseases.

Notably, boreholes with low to moderate yields were pump tested for only one hour. In such situations, well efficiencies and sustained yields become unpredictable and the responses of the aquifer are usually limited to only areas that are influenced by the cone of depression for that period only.

Due to poor storage conditions and old age of the data, some writings on the borehole logs had faded and were illegible, giving rise to poor quality data. The possibility of drillers making common errors in the measurements and estimation of borehole parameters cannot be ruled out. This rendered the data unreliable in some cases.

Step-drawdown and constant discharge tests were carried out in the Wa well fields with the Kumasi drilling team of the Ghana Water and Sewerage Corporation during the study. The constant discharge tests lasted twenty four hours with six hours recovery. The step drawdown tests were carried out for one hour per step for three steps. However, due to variations in well discharges as the pump adjusts itself to changing head, early time data are not accurate. Therefore, to achieve better results for the step tests, the pumping period for each step must be longer.

Constraints such as logistics and inaccessibility to some of the communities due to the early rains made it difficult for field studies to be undertaken in some parts of the region.

However, field work was extended to all the twenty three observation boreholes found in the five districts of the region.

In any case, none of the observation boreholes was pump tested to update borehole conditions during the course of study. The inability of the Global Positioning System (GPS, GARMIN 75) to function was a drawback to obtaining accurate locations of the boreholes.

4.3 METHODS OF DATA ANALYSIS

The most common form of well testing is by pumping water from a well and studying the response of the water level within the well and the adjacent parts of the aquifer.

Theis (1940), pointed out that the response of an aquifer to withdrawals from wells depends on the rate of expansion of the cone of depression caused by the withdrawal of water. This further depends on the transmissivity and storage coefficient of the aquifer, the distance to areas in which water discharges naturally from the aquifer and finally on the distance to recharge areas.

Under natural conditions, over a sufficiently long period of time prior to the start of withdrawals, the discharge from every groundwater system equals the recharge to it.

Theis (1935) utilized an analogy to heat flow theory to arrive at an analytical solution. This analytical solution takes into account the related parameters of time and aquifer storage. His solution, in terms of drawdown is

$$s = \frac{Q}{4\pi T}\int_{u}^{\infty} \frac{e^{-u}}{u}\,du \quad (4.1)$$

where s = drawdown (m)

$$U = \frac{r^2 S}{4Tt} \quad (4.2)$$

r = distance to observation point (m)

Q = constant pumping rate (m^3/day)

T = transmissivity (m^2/day)

S = storage coefficient (dimensionless)

t = time since pumping started (days).

The value of the integral equation is given by an infinite mathematical series that Theis expressed as W(u) known as the "Well function" of u, and the equation simplifies to,

$$s = \frac{Q}{4\pi T} W(u) \quad (4.3)$$

Equation (4.1) is known as the Theis Non-Equilibrium equation. This equation generally permits the determination of the constants S and T by conducting pumping test for the wells, or if the constants are known, the drawdown can be computed for a given well discharge.

The derivation of Theis formula is based on the following assumptions (Johnson, 1972).

1) The water-bearing formation is uniform in character and permeable in both horizontal and vertical directions.
2) The formation has uniform thickness.
3) The formation has infinite areal extent. It is confined, isotropic, homogeneous, and is fully saturated.
4) The formation receives no recharge from any source.
5) The pumped well penetrates and receives water from the full thickness of the water-bearing formation.

These assumptions are rarely met in practice. For the solution of any groundwater problem, idealisation of the aquifer and boundary conditions of the flow system is necessary. However, all formulas for the analysis of pumping test data are based on certain assumptions and generalization. Erroneous results of the computation of hydraulic characteristics of an aquifer are sometimes ascribed to incorrectness of the formula applied, whereas the actual cause of error is that, the field conditions do not satisfy the assumptions on which the formula is based.

There are two types of pumping tests, the constant discharge and the step drawdown tests.

The constant discharge test involves the use of a control valve to maintain the discharge rate throughout the pumping period to a stipulated range which must be less than plus or minus five percent of the chosen rate. The step drawdown test involves pumping a well at an initially low rate for a period of time. The discharge rate is then increased through a successive series of steps. Graphical methods attributed to Theis (1935) and Cooper-Jacob (1946) have been used to analyze pump test data for this study.

4.3.1 COOPER-JACOB METHOD OF SOLUTION

Cooper and Jacob (1946) suggested a simplification of the Theis equation which dispenses of the need for type curves by utilizing a semi-logarithmic plot for those field data where u < 0.01. Beyond, the first log cycle of time usually gives a straight-line relationship

The drawdown, s is expressed by

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \ln u + u - \frac{u^2}{2.2!} + \frac{u^3}{3.3!} - \cdots\right) \quad (4.4)$$

This expression is convergent. For small values of r and large values of t, u is small, so that the series terms in equation (4.4) become negligible after the first two terms.

$$s = \frac{Q}{4\pi T}(-0.5772 - \ln u) \quad (4.5)$$

Substituting for u in equation (4.5), using equation (4.1)

$$s = \frac{Q}{4\pi T}\left(-0.5772 - \ln\frac{r^2S}{4Tt}\right) \quad (4.6)$$

$$s = \frac{Q}{4\pi T}\left(\ln\frac{4Tt}{r^2S} - 0.5772\right) \quad (4.7)$$

This reduces to

$$s = \frac{2.30Q}{4\pi T}\log\frac{2.25Tt}{r^2S} \quad (4.8)$$

A plot of drawdown, s, versus the logarithm of t forms a straight line (Figure 4). The straight line is projected to intercept the time axis at s = 0 and t = t_0. Equation (4.8) then becomes

$$0 = \frac{2.30Q}{4\pi T}\log\frac{2.25Tt_0}{r^2S} \quad (4.9)$$

It follows then that

$$\frac{2.25Tt_0}{r^2S} = 1 \quad (4.10)$$

$$S = \frac{2.25Tt_0}{r^2} \quad (4.11)$$

If $t/t_0 = 10$, then $\log t/t_0 = 1$

hence, s can be expressed by the drawdown per log cycle of time Δs, therefore

$$T = \frac{2.30Q}{4\pi\ \Delta s} \quad (4.12)$$

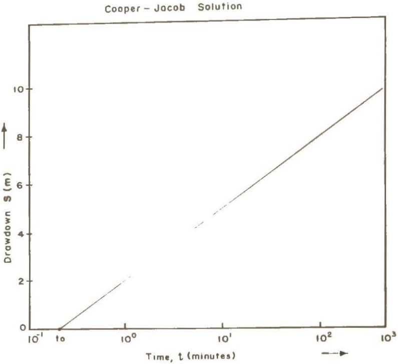


Fig. 4 : Time – drawdown curve for constant – discharge tests showing Cooper – Jacob's method.

In the Cooper-Jacob method of solution, the same assumptions as for the Theis method should be satisfied; also the value of u is small ($u < 0.01$), i.e, r is small and t is large. The condition that u is small will be satisfied in confined aquifers for moderate distances from the pumped well within an hour or less, but for unconfined conditions it may take twelve or more hours of pumping. The Cooper-Jacob method is used to detect anomalies in the aquifer such as aquifer dewatering and responses to aquifer during pumping.

4.3.2 THEIS RECOVERY METHOD

After pumping has been shut down the water level will stop dropping and instead rise again to its original position, this is the "recovery" of the well. The recovery of the well should behave as a mirror-image of the pattern of drawdown regardless of the type of aquifer conditions and thus can be used as a check on those aquifer properties determined from the drawdown data.

The rise of the water level is measured as the residual drawdown (s^1) that is the difference between the original water level prior to pumping and the actual water level measured at a certain moment (t') since pumping stopped (Figure 5).

Where the preceding pumping has been of reasonably long duration, the residual drawdown method is more appropriate. In this case, it is essential to know the duration of pumping (t) prior to cessation as well as the depth to water at successive time intervals after pumping has ceased.

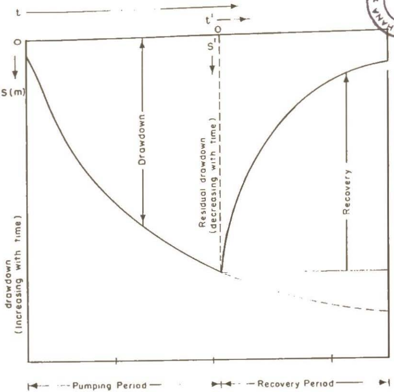


Fig. 5 : Schematic time – drawdown / residual drawdown curves in a well. (after Kruseman and de Ridder, 1970).

The data obtained during recovery permit the calculation of the transmissivity, thus giving a check on the results of the analysis of the data obtained during the pumping period. Moreover, the recovery method has the advantage that the rate of recharge, Q is constant and equal to the rate of discharge Q, during pumping. This means that drawdown variations resulting from slight differences in the rate of discharge during pumping do not occur during recovery. Theis recovery method can be used to calculate the hydraulic properties of an aquifer if the assumptions and conditions of the Cooper-Jacob method are satisfied.

The residual drawdown, during the recovery period, according to Theis (1935) is given by

$$\Delta s' = \frac{Q}{4\pi T}\{W(u$$ [illegible]

For small u,

$$\Delta$$ [illegible]

The slope of a straight line from a semi-logarithmic paper, with the time abscissa representing a ratio of t/t^1 drawn through the point over a log cycle of t/t^1. Δs^1 is given by

$$\Delta s' = \frac{2.30Q}{4\pi T} \quad (4.13)$$

$$T = \frac{2.30Q}{4\pi \Delta s'} \quad (4.14)$$

The value of S (storativity) cannot be obtained from this method. In the study, these two methods of solution were used in determining the hydraulic properties.

4.3.3 SPECIFIC CAPACITY

Specific capacity is the term used to describe the yield per unit drawdown. It is also expressed graphically in the form of the yield-drawdown curves.

Specific capacity = Q/s

Where Q = the yield or pumping rate (m^3/day)

s = drawdown (m)

Specific capacity has units of m^2/day. Any specific capacity value should be expressed relative to a common time base. Thus (Q_t/s) would mean the prevailing abstraction rate divided by the total drawdown after pumping for one day, and could be different from that determined after a duration of pumping for one hour or one week

The specific capacity of a well decreases with time for a given rate of discharge, Q. Since drawdown increases with time, the specific capacity of a well is independent of the discharge rate as long as there are no well losses.

The efficiency of a well is the ratio of the actual specific capacity to the theoretical specific capacity of the well. Factors influencing the actual specific capacity include the hydraulic properties of the aquifer (coefficients of transmissivity and storage), geologic boundaries of the aquifer, the partial or total penetration of the aquifer, the effective open area of the well screen or perforated casing, duration of pumping and pumping rate.

Rorabaugh (1953) recognized that well construction and development are important and affects the predictions of total drawdown and consequent estimates of well efficiency. According to Bierschenk (1963) the efficiency of a well is governed largely by the magnitude of well loss and thus falls off rapidly as discharge is increased. The efficiency of a well in an aquifer having a high transmissivity is affected by well loss to a greater degree than the efficiency of a well in an aquifer having a low transmissivity, and it is least affected by partial penetration of aquifers having a large transmissivity.

4.3.4 STEP-DRAWDOWN PUMPING TEST METHODS

Step drawdown tests involve pumping a well at an initially low rate for a period of time. The discharge rate is then increased through a successive series of steps. Three steps are at least required for the analysis of step-drawdown test. The drawdown and the corresponding measurements of time are recorded for each step.

The efficiency of a well can be expressed quantitatively by identifying and determining the separate components of the total drawdown $S_w = S_a + S_b$. Where S_a is that part of the drawdown due to formation loss and S_b represents that part due to well losses.

The formation loss component arises from the resistance of the water-bearing formation and is proportional to the discharge. It is also termed as the aquifer loss, which is the inevitable loss of head due to laminar flow of water through the aquifer. Well loss represents a function of turbulent flow within the well and adjacent parts of the aquifer. Well losses can be minimized by adequate and proper well design. In this study, Jacobs graphical solution method was adopted for the analysis of step-drawdown results.

4.3.5 JACOB'S GRAPHICAL METHOD

Jacob (1947) derived the equation

$S_w = BQ + CQ^n$. Equation (4.15)

where B (m^{2} day) and C (m^{5} day^2.) are aquifer and well loss constants respectively.

Q = the discharge rate. (m day)

n = a variable exponent.

On the assumptions that for turbulent flow, losses are related approximately to the square of the discharge. Jacob suggested a value of n = 2. This enables simplification of equation (4.15) by dividing through Q so that

$S_w/Q = B + CQ$ Equation (4.16)

The parameters B and C can be determined from a graphical method by plotting S_w/Q against Q. C is determined from the slope of the line of best fit through the data points and B is calculated from the intercept on the S_w/Q axis (Figure 6).

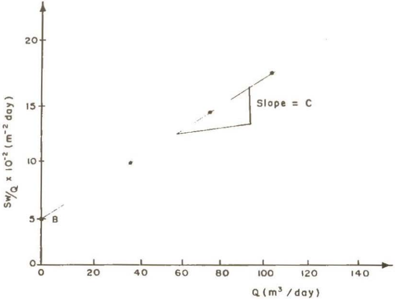


Fig 6: Determination of B and C using Jacob's method.

4.4 ANALYSES PERFORMED IN THE PRESENT STUDY

Statistical and pumping-test analyses were the analyses performed in the present study. The lithological logs aided in the determination of the lithologies in the boreholes, overburden thicknesses, depths to top of aquifer, aquifer thicknesses and borehole depths. Fractured and veined zones were all deduced from these logs for the observation and production boreholes. A summary of borehole and aquifer characteristics is shown in Table 30.

4.4.1 PUMPING TEST ANALYSIS

Two types of pumping test were used for the analysis: Constant rate test and step drawdown analysis. In the constant rate pumping test, graphs of drawdown on the normal scale against time on the logarithmic scale were plotted to determine the transmissivity using Cooper-Jacob (1946) method. The data points on the semi-log paper lie in most cases on a straight line for each graph plotted. Deviations from a straight line plot are used to delineate boundary conditions and other inhomogeneities in the aquifer.

The Cooper-Jacob (1946) method was used to analyse data from one hour and twenty four pumping test data. The twenty four hours pumping test was performed in parts of the Wa well fields on six boreholes, during the study with the G.W.S.C drilling unit from Kumasi. No data was available on 24 hours pump test from the existing borehole logs for the project. However, one hour pump tests were conducted for most of the boreholes during pump installation.

Transmissivities were computed using equation 4.12. No storage coefficient parameter was calculated. Specific capacities were determined from the constant rate pumping test data for one hour and twenty four hours in the boreholes studied.

Residual drawdown curves were drawn from the recovery data. The residual drawdown, s^1 was plotted on the arithmetic scale while the ratio of t/t^1 was plotted on a logarithmic scale. The transmissivities were then calculated using Equation 4.14 The recovery method was applied to only six boreholes in the Wa well fields

All the borehole and aquifer parameters, as well as the time-drawdown and residual plots were converted to the SI units from the imperial units. Only five of the wells in the Wa well field were tested by step-drawdown pumping.

The test was performed by pumping the wells at various discharges by increasing the discharge rate in a step-wise fashion. The pumping rates were carefully regulated and water levels measured accurately. One shortcoming encountered was that the pumping rate was either increased or decreased on an irregular basis so that the estimated maximum yield of the well at the end of the test was not exact.

Time was plotted on the logarithmic scale while the drawdown was plotted on the arithmetic scale. The three steps were plotted on the same graph paper, with the origin of time for all steps taken as the beginning of the test. Values of s/Q were determined for each step. Using an arithmetic graph sheet, values of s/Q were then plotted against Q. The formation constant is calculated from the intercept of the line with the s/Q axis and the well loss constant is determined from the slope of the line of fit through the data point (Jacob, 1947).

4.4.2 STATISTICAL ANALYSIS

This part of the analysis was aimed at relating each of the collected and recorded data of borehole and aquifer properties, and hence summarizing the information that has been amassed. Relevant information as well as patterns are fairly easy to detect when data are treated statistically. Table 3 shows the summary of borehole characteristics studied.

Borehole properties were presented in the form of percentages, averages, frequency distributions and histograms. Properties such as borehole depths, overburden thicknesses, aquifer thicknesses, aquifer depths, yields and static water levels have been presented in tables and figures for easy visualization.

In terms of percentages, information is provided about the frequency of each property of the borehole. It therefore gives a good indication of the relative preponderance of each property in the sample. The mean of the borehole properties has been estimated. Its main limitation is that it is vulnerable to extreme values, in that it may be unduly affected by very high or very low values which can respectively increase or decrease its magnitude. The standard deviation was also used as a method to summarize the dispersion properties. In essence, the standard deviation calculates the average amount of deviation from the mean. It permits the direct comparison of degrees of dispersion for comparable samples and measure.

Correlations and regressions were also used to provide easy-to-interpret indications of the relative strength of the relationships between borehole properties. Correlation entails the provision of a yardstick whereby the intensity or strength of a relationship can be determined.

Pearson's product moment of correlation coefficient was adopted. It is often referred to as Pearson's r. In this measure of correlation, the nature of the relationship between two variables is either a pattern which implies a negative relationship, meaning that as one variable increases the other decreases or a positive relationship which means higher values of one variable are associated with higher values of the other.

However, if no correlation is discernible then there is virtually no relationship between two variables. Pearson's coefficient of correlation (r) varies between -1 and + 1. The closer r is to 1, whether positive or negative, the stronger the relationship between the two variables.

Regression analysis was also performed as a means of expressing relationships among pairs of variables. Each regression coefficient (B), estimates the amount of change that occurs in the dependent variable. Moreover, the regression coefficient expresses the amount of change in the dependent variable with the effect of all other independent variables during drilling operations.

Correlation and regression analyses were performed for the borehole properties. Geologic influences on some borehole properties were established from these analyses. This enables the significant relationships existing among these properties to be obtained and also results in a better understanding of the occurrence of groundwater in the study area.

TABLE 3 SUMMARY OF BOREHOLE CHARACTERISTICS

BOREHOLE PROPERTY	NUMBER OF WELLS	MINIMUM	MAXIMUM	MEAN	STANDARD DEVIATION
BOREHOLE DEPTH (m)	186	12.0	90.0	31.2	10.8
OVERBURDEN THICKNESS (m)	186	9.0	60.0	26.2	10.2
AQUIFER THICKNESS (m)	192	3.0	18.0	7.3	2.7
AQUIFER DEPTH (m)	192	5.5	55.0	22.1	9.0
STATIC WATER LEVEL (m)	107	0.8	21.3	8.6	4.2
YIELD (l/min)	192	4.5	270.0	25.4	20.3

CHAPTER FIVE

PRESENTATION AND DISCUSSION OF RESULTS

5.1 BOREHOLE DEPTHS

Borehole depths computed for 186 boreholes range appreciably between 12.0m and 90.0 m, and this depends entirely on the combination of local hydrogeological conditions such as favourable lithology, the presence of structural features and the extent of weathering. An average of 31.2 m and a standard deviation of 10.8 m was obtained from the 186 boreholes.

About 80% of the boreholes in the study area have depths between 20 and 50 m. Analysis indicates that few boreholes were drilled deep enough to verify the full potential of the borehole sites selected. This is illustrated in Figure 7 where few of the wells reached depths greater than 60 m.

Average borehole depths are comparable in 64 granitic rocks and 54 boreholes drilled through greenstones (Table 4). Thirty-four percent of the boreholes were intercepted in granites, 29% in greenstones, whiles 16% were completed through phyllites and 21% drilled in schists. The deepest borehole was from a production borehole drilled through greenstone. This borehole at Saan with number 399E 2 has a final depth of 90 m and is located on a flatland, whereas a depth of 43 m recorded from an observation borehole, was the deepest borehole at Yagtuuri with number 437E 1 from phyllite.

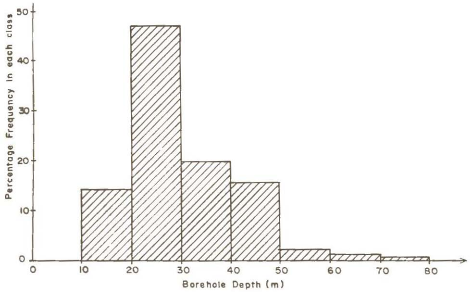


FIG. 7 HISTOGRAM OF BOREHOLE DEPTHS

TABLE 4

SUMMARY OF BOREHOLES DEPTHS ACCORDING TO GEOLOGY

GEOLOGY	NUMBER OF WELLS	MINIMUM BOREHOLE DEPTH (M)	MAXIMUM BOREHOLE DEPTH (M)	MEAN (m)	STANDARD DEVIATION (m)
GRANITES	64	12.0	42.0	26.4	6.4
GREENSTONES	54	12.0	90.0	28.8	12.2
PHYLLITES	39	24.0	64.0	41.4	10.3
SCHISTS	29	23.0	65.0	34.6	8.7
TOTAL WELLS	186	12.0	90.0	30.3	8.1

TABLE 5

SUMMARY OF BOREHOLE DEPTHS ACCORDING TO TOPOGRAPHY

TOPOGRAPHY	NUMBER OF WELLS	BOREHOLE DEPTHS (m)			STANDARD DEVIATION
		MINIMUM	MAXIMUM	MEAN	
FLATLAND	129	12.0	90.0	30.8	11.4
HILLSIDE	33	16.0	64.0	33.9	10.4
VALLEY	24	18.0	43.0	29.2	7.1
TOTAL WELLS	186	12.0	90.0	31.6	8.8

Despite the topographic locations and hydrogeological conditions prevailing, the chances of obtaining moderate to high yields are enhanced by increasing the depth of the borehole to a much greater extent, since some localised fractures containing water could be found at deeper depths. It was noted that 72% of the boreholes were drilled in flatlands, 17% on hillsides and 11% in valleys. Flatlands and valleys have comparable average borehole depths (Table 5). Flatlands and valleys are considered as favourable areas for deeper rock decomposition and are likely to coincide with fractured zones. However, it was observed that drilling was stopped when water from the moderately decomposed zone was sufficient for hand pump installation.

5.2 <u>OVERBURDEN THICKNESS</u>

The overburden thickness is the depth to fresh bedrock. A total of 186 boreholes were analysed for overburden thicknesses. The minimum overburden thickness is 9.0 m and the maximum is 60.0 m. The mean and standard deviation of the 186 boreholes are 26.2 m and 10.2 m respectively. The nature and distribution of overburden thicknesses is presented in (Figure 8).

In order to obtain adequate yield, it has been found that a minimum regolith thickness of approximately 10 m is required. This is in agreement with a survey conducted by Omorinbola (1981) over Nigerian basement rocks.

Nearly all the boreholes have overburden thicknesses exceeding 13 m. Banoeng-Yakubo (1989) reported an average of 29 m for overburden thickness in the basement rocks of the Upper Regions of Ghana that include the study area. Sites with thicker overburden were priorities in drilling for water in the study area, since the focus of the drilling programme was based mainly on tapping water from the regolith.

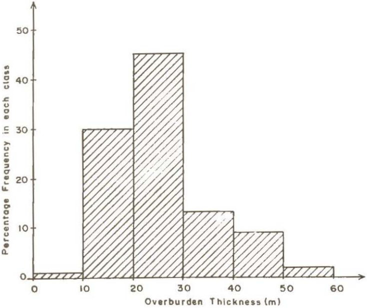


FIG. 8 HISTOGRAM OF OVERBURDEN THICKNESSES

Average overburden thicknesses are comparable in granites and greenstones (Table 6). However the thickest overburden of 60 m was obtained from phyllites in Guorpuo and Birifu with borehole number 399C 10 and 437H 16 respectively, both of which are production boreholes. Thirty boreholes drilled through phyllites have an average overburden thickness of 29.9 m, while an average of 30.5 m was obtained from thirty-eight boreholes completed in schist rocks.

The relative depth and degree of weathering in a rock depends to some extent on the intensity of fracturing and the grain size of the minerals in the rock. Chilton and Foster (1993) explained the importance of the regolith thickness on the success rate of drilling. The regolith thickness provides the dominant elements of aquifer storage and determines the available drawdown to the most productive aquifer horizon.

Overburden thicknesses encountered in flatlands were higher compared to those found in valleys and on hillsides. An average of 20.6 m overburden thickness was obtained from 32 boreholes drilled on hillsides, while comparable averages of 25.6 m and 25.1 m were obtained from 138 boreholes drilled in flatlands and 22 boreholes drilled in valleys respectively (Table 7).

Boreholes drilled in flatlands and valleys have thicker saturated regoliths and hence represent zones of deeper weathering. In most cases, weathering is less deep in less resistant rocks on hill tops, while in valleys and flatlands, weathering is intensive and deeper

TABLE 6 SUMMARY OF OVERBURDEN THICKNESSES ACCORDING TO GEOLOGY

GEOLOGY	NUMBER OF WELLS	OVERBURDEN THICKNESS (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Granites	64	9.0	37.5	21.1	5.9
Greenstones	54	12.0	47.0	23.3	8.5
Phyllites	30	18.0	60.0	37.4	10.9
Schists	38	16.0	47.0	29.9	8.6
Total Wells	186	9.0	60.0	30.5	7.8

TABLE 7 SUMMARY OF OVERBURDEN THICKNESSES ACCORDING TO TOPOGRAPHY

TOPOGRAPHY	NO. OF WELLS	OVERBURDEN THICKNESS (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Flatland	132	9.0	60.0	25.6	10.2
Hillside	32	15.2	46.0	20.6	10.7
Valley	22	11.6	43.0	25.1	7.8
Total Wells	186	9.0	60.0	23.3	8.6

5.3 AQUIFER THICKNESS

Aquifer thicknesses vary between 3.0 m and 18.0 m in the 192 boreholes. The mean is 7.3 m and the standard deviation is 2.7 m. About 87% of aquifers in the study area have thicknesses less than 10 m. A distribution of these results is presented in Figure 9.

Aquifers encountered in phyllites and greenstones are thicker than those found in granites and schists. Average aquifer thicknesses in the phyllites and greenstones are 8.3 m and 7.2 m respectively. Average aquifer thicknesses are however, comparable in greenstones and schists (Table 8).

Aquifers are generally discontinuous and vary from a few meters to tens of meters thick. Thick aquifers are found in the phyllites due to the presence of fractured quartz veins in the moderately decomposed zones of these rocks.

Aquifers in greenstones are also thick probably because of the developed joint systems which constitute prospective high-yielding aquifers. In the granites and schists, where quartz and pegmatitic veins intrude the rocks, well-developed fractures and joints that carry appreciable amounts of groundwater occur. Rocks in which these structures occur decompose more readily and promote the development of thicker aquifers than those which do not contain these structures.

Average aquifer thicknesses are comparable in flatlands and on hillsides. The thickest aquifer of 18 m was obtained from a production borehole found in a flatland at Tanchara in the Lawra district with borehole number 43711 7

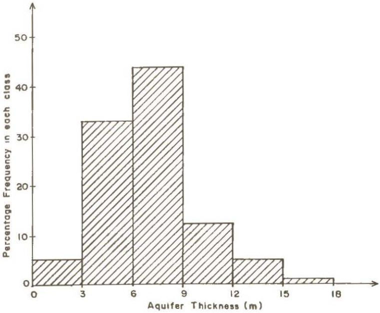


FIG. 9 HISTOGRAM OF AQUIFER THICKNESSES

TABLE 8 SUMMARY OF AQUIFER THICKNESSES ACCORDING TO GEOLOGY

GEOLOGY	NO OF WELLS	AQUIFER THICKNESSES (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Granites	66	3.0	12.3	6.9	2.3
Greenstones	56	3.4	17.0	7.2	2.9
Phyllites	30	5.9	18.0	8.3	3.1
Schists	40	3.0	15.0	7.1	2.6
Total Wells	192	3.0	18.0	7.4	2.5

Valleys and flatlands are known to be associated with fractures and zones of deeper decomposition. However, 23 boreholes drilled in valleys have a minimum aquifer thickness of 3.0 m and a maximum thickness of 12 m (Table 9). It has been noticed that more boreholes were drilled in flatlands than in valleys in the study area. This is because, most of the valleys are liable to flooding.

5.4 AQUIFER DEPTH

Aquifer depth is the depth to top of the productive water bearing zone. Approximately 50% of the aquifers have depths of less than 20 m. Figure 10 illustrates the nature and distribution of aquifer depths in 192 boreholes.

Aquifer depths range considerably from 5.5 m to 55.0 m and average 22.1 m with a standard deviation of 9.0 m. The least aquifer depth of 5.5 m was obtained in a production borehole located on a flatland underlain by granite. This shallow aquifer is due to the presence of a thin and poorly-developed weathered zone. However water was not encountered at such shallow depths in any of the observation boreholes.

Average aquifer depths of 18.2 m and 18.9 m are comparable in granites and greenstones respectively. However, the phyllites and schists have the same maximum aquifer depths of 55 m in the study area. The depth to top of the productive water bearing zone in borehole number 437E 33 at Lawra was the highest due to the presence of pegmatites, quartz veins and fracture openings associated with the underlying weathered schist. The presence of these geological structures provide avenues for deep weathering, thicker aquifer depths and increased yields when they are found within the weathered zone and underlying bedrock. The summary of aquifer depths according to geology is shown in (Table 10).

TABLE 9 SUMMARY OF AQUIFER THICKNESSES ACCORDING TO TOPOGRAPHY

TOPOGRAPHY	NO. OF WELLS	AQUIFER THICKNESSES (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Flatland	138	3.0	18.0	7.4	2.9
Hillside	31	3.0	12.3	7.1	2.3
Valley	23	3.0	12.0	6.6	2.2
Total wells	192	3.0	18.0	7.0	2.6

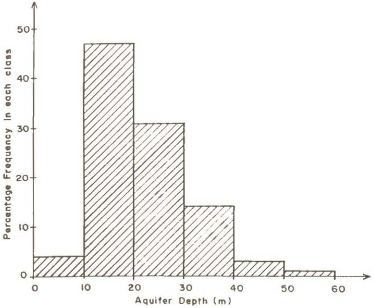


FIG. 10 HISTOGRAM OF AQUIFER DEPTHS

TABLE 10 SUMMARY OF AQUIFER DEPTHS ACCORDING TO GEOLOGY

GEOLOGY	NO. OF WELLS	AQUIFER DEPTHS (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Granites	66	5.5	33.0	18.2	5.6
Greenstones	56	6.0	41.0	18.9	7.6
Phyllites	30	15.0	55.0	31.5	9.8
Schists	40	14.0	55.0	25.9	7.8
Total Wells	192	5.5	55.0	24.6	6.9

Generally, aquifers are encountered at shallow depths in valleys and flatlands than on hillsides. Average aquifer depths are comparable in flatlands and valleys with values of 21.4 m and 21.2 m respectively (Table 11).

5.5 BOREHOLE YIELDS

Borehole yield analysis shows that variations in yield within the study area are large. The tendency for most yields to be low is very great with only a limited number of high yields.

Estimated yields obtained from the drillers log generally fall between 4.5 l/min. and 270 l/min. in 192 boreholes. The mean and standard deviation is 25.4 l/min. and 20.3 l/min. respectively. The values of the mean and standard deviation are close because of the extreme variations in the yields as a result of the heterogeneous nature of aquifers in the area.

Approximately eighty-five percent of boreholes yield 30 l/min. or less of water. Figure 11 illustrates the distribution of borehole yields in the study area. The distribution is heavily skewed to the left due to majority of the boreholes exhibiting low yields with values less than 30 l/min.

Average yields in granites and greenstones are comparable. The mean yield for sixty-six boreholes in granites is 22.8 l/min and the average yield for fifty-six greenstone rocks is 23.5 l/min (Table 12). The highest yields of 135 l/min. in the granites and 148.5 l/min. in the greenstones obtained from boreholes 438G 03 in Jirapa-Yipala and 437E 13 in Lawra are monitoring boreholes in the region.

TABLE 11 SUMMARY OF AQUIFER DEPTHS ACCORDING TO TOPOGRAPHY

TOPOGRAPHY	NO. OF WELLS	AQUIFER DEPTHS (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Flatland	137	5.5	55.0	21.4	8.8
Hillside	32	6.0	55.0	25.7	10.6
Valley	23	11.0	35.0	21.2	5.6
Total Wells	192	5.5	55.0	22.8	7.6

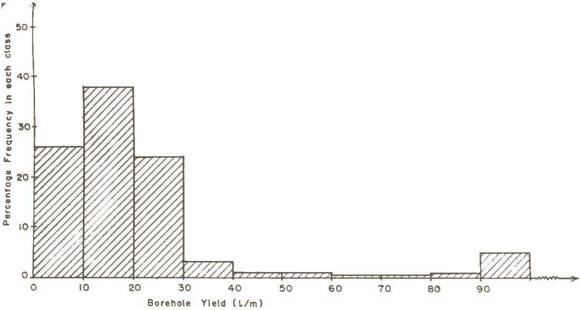


FIG. 11 HISTOGRAM OF BOREHOLE YIELDS

The yield from these boreholes are high possibly because of the numerous fractured quartz veins and crushed zones located within the decomposed zones of the profile. These structures offer areas of high permeability with relatively high storage capacities in the water bearing zones.

In some cases, moderate to high yields are associated with granites because they are more jointed and have weathered products which are sandy and more permeable. Enough yields are also obtained when dykes cut across the granites, and joints are created by contraction during cooling. A typical example is at Pulima in the Tumu district with borehole number 444F 2 (monitoring borehole) which has a yield of 103.5 l/min. In contrast, the low yielding wells are open to only a few fractures that intersect the weathered zone.

The mean yield of 22 boreholes located in valleys is 17.4 l/min. and the average yield obtained for 138 boreholes sited in flatlands is 28.1 l/min. An average yield of 20.2 l/min. was obtained for 32 boreholes located on hillsides (Table 13).

In the study area, residents rely mainly on groundwater for their water supplies. During the project in the 1970's, boreholes were usually required close to the communities which in some cases severely constrained the choice of sites for drilling. Most of these sites close to the communities were not quite promising but had to be completed, hence the low yields.

About 70% of the area studied is underlain by granites. These rocks are generally considered to be poor aquifers except when they are associated with thick, deep weathered zones resulting from fractures and joints, quartz and pegmatite vein intrusions as well as fractures and joints in the fresh rocks. The presence of these structures usually increase the yields of boreholes significantly.

Boreholes drilled through granites have the least average yield, while boreholes drilled through schists gave the highest average yield of 33.3 l/min. Granites, greenstones, phyllites and schists in the study area have produced less water from their decomposed zones. However, where these rocks are fractured or intruded by quartz and pegmatitic veins, relatively high yields are obtained. This explains the highest average yields obtained from boreholes completed in schists.

Topographic influences on borehole yields are very significant. In the study area, boreholes located in flatlands and valleys commonly yield more water than boreholes sited on hilly upland areas or on hillsides. However, a monitoring borehole 358C 03 which is artesian (flowing well) was obtained on a hillside at Gurungu. It is situated near the foot of a relatively steep slope with swarms of quartz and pegmatite veins in the decomposed zone as indicated in the drillers' log. This underlying weathered rock can form a substantial groundwater reservoir and may be receiving some water from fractures in the bedrock, thereby enhancing the yield in the aquifer.

The high yielding wells are open to numerous fractures that are found within the weathered zones below the water bearing zone in flatlands and valleys. However, most of these boreholes can no longer provide enough water for the growing population in the region as demand increases put pressure on the groundwater resources of the area.

Parry et al (1987) reported that the boreholes are yielding less water and are not able to provide a continuous supply of water. He further discussed that the boreholes can no longer sustain the discharge capacity of the pumps used during the project.

TABLE 12 SUMMARY OF BOREHOLE YIELDS ACCORDING TO GEOLOGY

GEOLOGY	NO.OF WELLS	YIELDS (l/min)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Granites	66	4.5	135.0	22.8	20.3
Greenstones	56	4.5	148.5	23.5	21.5
Phyllites	30	4.5	270.0	26.1	19.6
Schists	40	4.5	270.0	33.3	30.4
Total Wells	192	4.5	270.0	27.4	22.8

TABLE 13 SUMMARY OF BOREHOLE YIELDS ACCORDING TO TOPOGRAPHY

TOPOGRAPHY	NO. OF WELLS	YIELD (l/min)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Flatland	138	4.5	270.0	28.1	24.8
Hillside	32	4.5	90.0	20.2	16.0
Valley	22	4.5	37.0	17.4	8.8
Total Wells	192	4.5	208.2	18.8	12.4

In any case, most of these boreholes are being redeveloped and rehabilitated to a large extent. New Village Level Operation and Maintenance (VLOM) pumps such as the Afridev and Nira pumps are also being installed to replace the old Moyno and Monarch pumps.

5.6 STATIC WATER LEVELS

Static water levels measured during pump installations in 107 boreholes vary from 0.8 m to 21.3 m below ground level with an average of 8.6 m and a standard deviation of 4.2 m.

About 82% of the boreholes have static water levels not exceeding 10 m (Figure 12). The effect of geology on static water levels is shown in (Table 14). Boreholes drilled in granite have the least average static water levels. Those drilled in greenstones and phyllites have comparable average static water levels.

Comparable average static water levels were noticed from 70 boreholes drilled in flatlands and 12 boreholes drilled in valleys. The averages are 8.8 m and 8.7 m respectively as shown in Table 15.

Evidence to support the regional decline of water levels in the study area can be shown from the comparison of static water levels measured during the study from 105 boreholes and the static water levels obtained from the same boreholes at the time of construction. Table 16 gives an average of 8.6 m for the original static water levels recorded at the time of construction and an average of 10.9 m from the static water levels measured during this study. In addition, an average decline of static water levels in 76 boreholes was 4.1 m and an average rise of static water levels in 29 boreholes was 2.5 m.

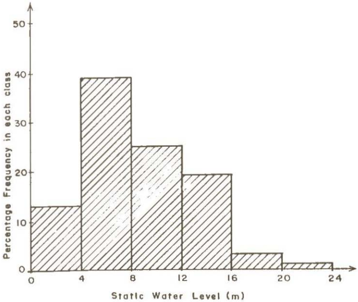


FIG. 12 HISTOGRAM OF STATIC WATER LEVELS

TABLE 14 SUMMARY OF STATIC WATER LEVELS ACCORDING TO GEOLOGY

GEOLOGY	NO. OF WELLS	STATIC WATER LEVEL (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Granites	51	0.9	17.4	7.9	3.7
Greenstones	26	0.8	14.3	8.7	3.8
Phyllites	14	1.3	15.6	8.5	4.1
Schists	16	3.1	21.3	10.9	5.3
Total Wells	107	0.8	21.3	8.4	4.2

TABLE 15 SUMMARY OF STATIC WATER LEVELS ACCORDING TO TOPOGRAPHY

TOPOGRAPHY	NO OF WELLS	STATIC WATER LEVELS (m)			STANDARD DEVIATION (m)
		MINIMUM	MAXIMUM	MEAN	
Flatland	70	0.8	17.4	8.8	4.4
Hillside	25	1.2	21.3	7.8	4.1
Valley	12	2.7	7.0	8.7	5.1
Total Wells	107	0.8	21.3	7.9	4.6

TABLE 16: STATIC WATER LEVELS RECORDED DURING STUDY

BOREHOLE NUMBER	ORIGINAL SWL(m)	YEAR	CURRENT SWL(m)	YEAR	STATIC WATER LEVEL DIFFERENCE (m)
438I 2	7.0	1975	7.8	1995	-0.8
437E 1	3.4	1975	8.3	1995	-4.9
437F 1	7.0	1975	11.8	1995	-4.8
437H 9	5.2	1975	6.9	1995	-1.7
444F 2	5.8	1957	5.6	1995	+0.2
403D 1	12.2	1975	16.5	1995	-4.3
403A 1	12.5	1975	9.2	1995	+3.3
358C 3	1.2	1975	0.6 (FLOWING)	1995	+0.6
401G 6	8.8	1977	20.5	1995	-11.7
403A 3	16.2	1977	16.6	1995	-0.4
398D 3	8.2	1977	13.4	1995	-5.1
398D 4	16.2	1977	13.7	1995	+2.5
398D 5	9.8	1977	11.9	1995	-2.1
398D 8	11.9	1978	12.6	1995	-0.7
398G 6	12.5	1977	8.4	1995	+4.1
398G 7	20.1	1978	22.1	1995	-2.0
398H 7	10.1	1977	7.6	1995	+2.5
398I 1	3.4	1974	13.7	1995	-10.3
398I 4	7.6	1975	4.7	1995	+2.9
398I 5	2.7	1975	2.3	1995	+0.4
398I 6	5.5	1975	4.0	1995	+1.5
398I 13	12.5	1976	7.3	1995	+5.2
398C 1	0.9	1975	8.3	1995	-7.4
398C 2	10.1	1975	8.5	1995	+1.7
399C 10	4.3	1978	20.8	1995	-6.8
401G 2	6.1	1974	15.4	1995	-9.3
401G 3	10.1	1974	10.8	1995	-0.7

(-) IMPLIES THAT STATIC WATER LEVEL HAS DECLINED
(+) IMPLIES THAT STATIC WATER LEVEL HAS RISEN

BOREHOLE NUMBER	ORIGINAL SWL (m)	YEAR	CURRENT SWL (m)	YEAR	STATIC WATER LEVEL DIFFERENCE (m)
401G 4	6.7	1975	11.5	1995	-4.8
401G 9	10.4	1975	13.0	1995	-2.6
401G 16	4.3	1977	7.2	1995	-2.9
401H 2	5.5	1975	3.4	1995	+2.1
401H 3	18.9	1975	6.6	1995	+12.3
401H 7	11.6	1977	13.8	1995	-2.2
401H 8	6.4	1977	15.4	1995	-9.0
399C 3	8.2	1978	11.9	1995	-3.7
399C 4	8.9	1977	28.2	1995	-19.3
399C 6	16.5	1977	17.3	1995	-0.8
399C 9	5.8	1978	7.5	1995	-1.7
438D 10	3.7	1977	4.9	1995	-1.2
438D 12	1.8	1977	5.3	1995	-3.5
438D 13	4.9	1977	7.9	1995	-3.0
438D 15	11.3	1977	21.2	1995	-9.9
438D 19	17.4	1978	16.5	1995	+0.9
438E 5	10.7	1976	7.3	1995	+3.4
438G 18	13.4	1977	10.6	1995	+2.8
438G 24	8.5	1978	6.2	1995	+2.3
438I 1	7.9	1975	7.3	1995	+0.6
437E 6	8.6	1975	7.6	1995	+1.0
437E 10	4.3	1972	7.8	1995	-3.5
437E 11	6.4	1975	14.6	1995	-8.2
437E 16	7.3	1975	7.2	1995	+0.1
437E 17	4.3	1975	12.6	1995	-8.3
437E 32	13.7	1978	17.0	1995	-3.3
437F 6	6.4	1975	11.7	1995	-5.3
437F 9	8.2	1974	20.6	1995	-12.4
437F 14	2.4	1977	14.0	1995	-11.6
437F 17	7.6	1978	8.1	1995	-0.5

TABLE 10 (continued)

BOREHOLE NUMBER	ORIGINAL SWL (m)	YEAR	CURRENT SWL (m)	YEAR	STATIC WATER LEVEL DIFFERENCE (m)
437F 18	8.8	1978	14.1	1995	-5.3
437F 20	12.2	1978	17.0	1995	4.8
437F 21	7.9	1978	10.4	1995	-2.5
437F 25	30.8	1978	34.5	1995	-3.7
437H 3	2.7	1975	6.9	1995	-4.2
437H 5	1.2	1975	8.4	1995	-7.2
437H 7	7.0	1975	13.8	1995	-6.8
437H 11	4.3	1976	5.2	1995	-0.9
437H 14	8.8	1978	9.5	1995	-0.7
437H 15	4.9	1978	6.1	1995	-1.2
437H 16	6.1	1978	7.3	1995	-1.2
438A 1	4.1	1978	3.7	1995	+0.9
439F 17	9.2	1955	18.9	1995	-9.7
438D 4	9.5	1975	8.2	1995	+1.3
439F 20	8.5	1978	10.6	1995	-2.1
447D 5	7.0	1976	6.1	1995	+0.9
444F 5	5.8	1976	6.1	1995	-0.3
398C 12	15.6	1977	20.0	1995	-4.4
398C 13	10.4	1978	11.6	1995	-1.2
398C 14	14.6	1978	13.7	1995	+0.9
398E 2	9.2	1977	9.4	1995	-0.2
399F 2	7.1	1976	8.8	1995	-1.7
399F 3	3.4	1976	4.5	1995	-1.1
399F 6	2.1	1977	6.9	1995	-4.8
399F 8	3.4	1978	4.6	1995	1.2
399I 1	6.4	1976	9.0	1995	-2.6
399I 4	11.3	1978	18.5	1995	-7.2
399I 5	11.6	1978	21.4	1995	-9.8
400C 3	5.2	1975	5.1	1995	+0.1
400D 12	12.2	1978	13.2	1995	-1.0
400E 2	5.8	1976	8.7	1995	-2.9

TABLE 16 (continued)

BOREHOLE NUMBER	ORIGINAL SWL (m)	YEAR	CURRENT SWL (m)	YEAR	STATIC WATER LEVEL DIFFERENCE (m)
400E 5	21.3	1977	12.0	1995	+9.3
400F 2	6.1	1975	7.0	1995	-0.9
400F 8	3.1	1977	5.6	1995	-2.5
400F 10	5.5	1978	6.2	1995	-0.7
400G 1	9.5	1975	19.0	1995	-9.5
400G 3	12.2	1977	12.7	1995	-0.5
400G 5	15.9	1978	21.7	1995	-5.8
400H 1	12.5	1976	6.9	1995	+5.6
400H 11	3.1	1978	10.8	1995	-7.7
401A 3	9.5	1975	8.5	1995	+1.0
401A 5	9.8	1975	13.2	1995	-3.4
401A 6	6.7	1975	6.6	1995	+0.1
401A 8	9.5	1955	10.1	1995	-0.6
437H 18	3.7	1978	11.0	1995	-7.3
437H 19	4.9	1978	5.7	1995	-0.8
437H 20	3.1	1978	3.5	1995	-0.4
438A 4	7.3	1978	8.1	1995	-0.8
403A 3	16.2	1977	16.6	1995	-0.4
398D 3	8.2	1977	13.4	1995	-5.1
398D 4	16.2	1977	13.7	1995	+2.5
398D 5	9.8	1977	11.9	1995	-2.1
398D 8	11.9	1978	12.6	1995	-0.7
398G 6	12.5	1977	8.4	1995	+4.1
398G 7	20.1	1978	22.1	1995	-2.0
398H 7	10.1	1977	7.6	1995	+2.5
398I 1	3.4	1974	13.7	1995	-10.3
398I 4	7.6	1975	4.7	1995	+2.9
398I 5	2.7	1975	2.3	1995	+0.4
398I 6	5.5	1975	4.0	1995	+1.5
398I 13	12.5	1976	7.3	1995	+5.2
398C 1	0.9	1975	8.3	1995	-7.4

Over a 20-year period, about 72% of the boreholes in the region have declined in their water levels considerably, whilst 28% have risen in static water levels. The only flowing artesian well seen during the study was found at Gurungu in the Wa district.

Bannerman (1990) reported that the area is a water-deficit region and normally experiences a dry season of six months duration. Sometimes, this period is exceeded and leads to the drying up of many water bodies. Moreover, it was observed during the study that in low rainfall months, the inhabitants depend mainly on the boreholes for their water supply which in most cases cannot provide enough water for the population. This is evidenced in the reduced yield of some of the boreholes in the Upper West region which can be related to a significant decline in water levels. Possible causes of the decline can be attributed to reduced recharge, low rainfall, increased surface run-off and excessive withdrawal of water from the boreholes.

Data obtained and analysed serve to show the cyclic fluctuations in groundwater levels and its dependence on the rainfall regime. Continuous measurements of static water levels in five monitoring boreholes from August 1993 to August 1994 for one year indicates that the cycle of rise of groundwater levels in the rainy seasons and decline in the dry seasons continues, independent of responses to local pumping.

The hydrograph of monitoring borehole number 398C 1 (Figure 13) shows a steady decline in water levels in dry months and the rise of water levels in rainy months.

Large water level fluctuations are also caused by nearby groundwater pumping and to some extent caused by borehole clogging thus leading to turbulent flow processes which as a consequence reduce the efficiency of the boreholes.

The seasonal trend was caused mainly by greater withdrawal of groundwater during the drier months. The average static water level obtained within the year for this borehole is 8.1 m below ground level.

Figures 14,15,16 and 17 show hydrographs of monitoring boreholes 401A 7, 401G 6, 400D 4 and 403D 1 respectively which also indicate fluctuations related to seasonal changes in pumpage. Average static water levels recorded below ground level in each borehole is 4.2 m, 9.7 m, 26.0 m and 19.8 m respectively. The water level fluctuations in boreholes 401G 6 and 403D 1 which obtain water from the moderately decomposed zones in granites is higher than that found in boreholes 401A 7 and 400D 4 which were screened in Birimian schists. Generally,the sharp changes in the water levels of these boreholes can be attributed to the infiltrating capacity of the soil during rainfall, the soil moisture deficit and the permeability of the rocks. However, the water level trends are similar with a gradual rise in water levels during the rainy season and a steady decline of water levels in the dry season.

These observations explain clearly that factors which are likely to influence groundwater levels in the region are related to the hydrology of the area especially evapotranspiration and the rate of recharge. Recharge depends on the rainfall intensity, distribution, the amount of run-off and the nature of the soil surface. In general, rainfall is low in the area and its annual distribution is very poor.

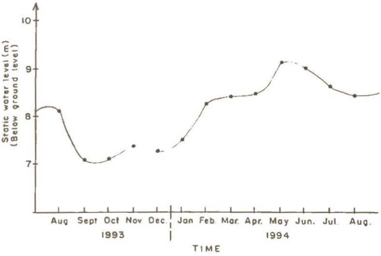


FIG. 13 WATER LEVEL HYDROGRAPH FOR BOREHOLE NUMBER 398 C 01 – KALEO

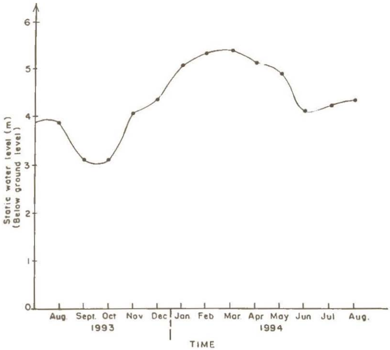


FIG. 14 WATER LEVEL HYDROGRAPH FOR OBSERVATION BOREHOLE NUMBER 401 A-7 - JANG

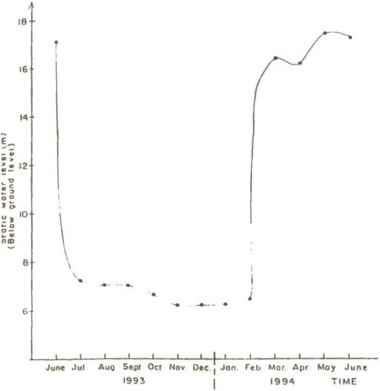


FIG. 15 WATER LEVEL HYDROGRAPH FOR BOREHOLE NUMBER 401 G 06 – WA SOUTH WELL FIELDS

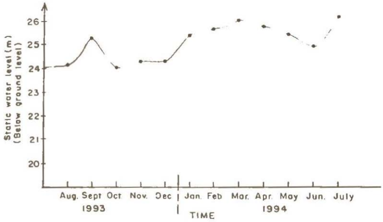


FIG.16 WATER LEVEL HYDROGRAPH FOR BOREHOLE NUMBER 400 D 04 – IZIIRI

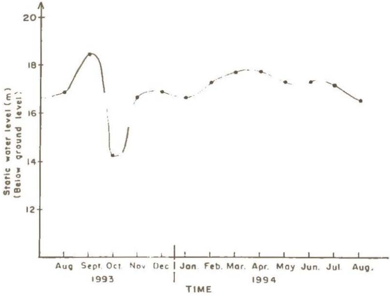


FIG. 17 WATER LEVEL HYDROGRAPH FOR BOREHOLE NUMBER 403 D1 - FIAN

Seasonal changes in the water levels can also be related to seasonal changes in the use of water by vegetation and the rate of soil moisture evaporation.

Figure 18 illustrates the relations of temperature with rainfall for four consecutive years in the region. High temperatures are usually associated with dry periods when there is virtually little or no rainfall, whereas low temperatures are experienced in rainy periods During the rainless months, temperatures are very high.

Paulachock (1991) discussed that water level fluctuations are caused by variations in recharge, water use and evapotranspiration. The adverse effects of relatively low or falling groundwater levels lead to desertification which in all probability will eventually include a reduction in recharge. Gombar and Kent (1987) reported that the rates of recharge and recharge volumes can be calculated by long term measurements of water levels in boreholes

A further indication of water level declines in the region can be observed from Figure 19 which shows the static water levels recorded from nine monitoring boreholes at the time of construction and that of static water levels recorded at time of study in the same boreholes at some communities. Except in Gurungu, where the borehole is flowing, there is an appreciable decline in the static water levels of most boreholes

Moreover, environmental degradation has serious consequences on the vegetation and when it rains, there is just little infiltration into the soil. In addition, the sun's intensity is high and bakes the soil surface and prevents the easy infiltration of water into the soil and also hinders subsequent percolation into the groundwater circulation system which contributes to base flow

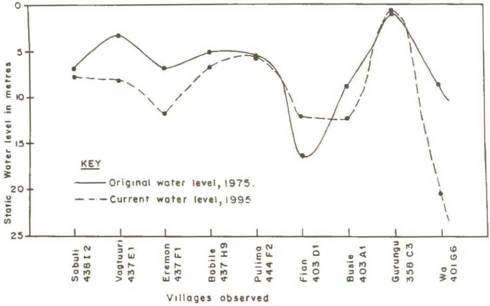


FIG. 19 WATER LEVEL HYDROGRAPH OF OBSERVATION BOREHOLES

5.7 RELATION BETWEEN BOREHOLE PROPERTIES

The present study indicates that there exists some relationships between well properties in the boreholes. Table 17 compares well yield with other borehole properties such as overburden thickness, borehole depth, aquifer depth, aquifer thickness and static water levels.

Across the study area, it is clear that there is a significant relationship between overburden thicknesses and yields. About ninety percent of the boreholes have overburden thicknesses exceeding 15 m with yields of not less than 10 l/min. It is noted that overburden thicknesses in the boreholes encountered in granites and greenstones have comparable mean thicknesses of 21.1 m and 23.3 m respectively. Boreholes drilled in flatlands are usually associated with thicker overburden.

The correlation coefficient between aquifer depths and borehole depths is 0.66. This indicates a fair relationship of aquifer depths with borehole depths. This is because deeper boreholes were drilled when water bearing zones were not intercepted at shallower depths. Moreover, deeper wells were drilled where water was obtained from such deep depths.

The static water levels and yields in boreholes correlate significantly in the study area. The higher the yield of a well, the shallower the static water level. This is because, factors that cause increased yield such as the lithology of the area, the topographical setting and the structural geology of the area, also causes static water levels to rise in a well.

TABLE 17 **RESULTS OF PEARSON'S CORRELATION COEFFICIENT IN BOREHOLE PROPERTIES**

BOREHOLE PROPERTIES CORRELATED	COEFFICIENT OF CORRELATION
a. Overburden thickness and yield	0.68
b. Borehole Depth and Yield	0.14
c. Aquifer Depth and Borehole Depth	0.66
d. Yield and Aquifer Depth	0.16
e. Aquifer Depth and Aquifer Thickness	0.12
f. Overburden Thickness and Aquifer Depth	0.78
g. Overburden Thickness and Borehole Depth	0.43
h. Yield and Static Water Level	0.55

There is no direct relationship between well yields and borehole depths. However, in some cases, variations in well yields are attributed to increases in borehole depth. Whatever the hydrogeologic conditions and topographic locations, the chances of obtaining moderate yields are enhanced by increasing the depth to a much greater extent than expected.

Data obtained from boreholes were also subjected to regression analysis. From Table 18, a multiple regression on yield with overburden thickness and aquifer depth gave a value of 0.33 and 0.35. From these results, it is obvious that the overburden thickness and aquifer depth have marked effect on borehole yields. The yield obtained from a well depends on the fracturing and weathering characteristics of the rock type. Further analysis indicated an increase in yield by 0.15 l/min for every unit rise in static water level.

Tables 19 and 20 show the influence of aquifer depth, aquifer thickness, overburden thickness and static water levels on the yields obtained from granites and greenstone rock aquifers respectively. It is evident that yields are increased respectively by 0.55 l/min., 0.62 l/min., 0.63 l/min. and 0.71 l/min. with a unit increase in aquifer depth, static water level, overburden thickness and aquifer thickness in the granites. In the greenstones, the yield increases by 2.19 l/min. by a unit increase in aquifer thickness. Thicker aquifers usually yield more water. This is so because of the numerous fractures and quartz veins present in these rocks that result in deeper weathering.

TABLE 18 MULTIPLE REGRESSION RESULTS FOR YIELDS IN THE BOREHOLES STUDIED

DEPENDENT VARIABLE IS THE YIELD

VARIABLE	REGRESSION COEFFICIENT
a. Aquifer Depth	0.35
b. Aquifer Thickness	0.11
c. Overburden Thickness	0.33
d. Static Water Level	0.15
e. Borehole Depth	0.34

TABLE 19: REGRESSION ANALYSIS FOR BOREHOLES IN GRANITES

DEPENDENT VARIABLE: YIELD

VARIABLE	REGRESSION COEFFICIENT
a. Aquifer Depth	0.55
b. Static Water Level	0.62
c. Overburden Thickness	0.63
d. Aquifer Thickness	0.71

TABLE 20: REGRESSION ANALYSIS FOR BOREHOLES IN GREENSTONES

DEPENDENT VARIABLE: YIELD

VARIABLE	REGRESSION COEFICCIENT
a. Aquifer Depth	0.75
b. Static Water Level	0.76
c. Overburden Thickness	0.57
d. Aquifer Thickness	2.19

TABLE 21: REGRESSION ANALYSIS FOR BOREHOLES IN PHYLLITES

DEPENDENT VARIABLE: YIELD

VARIABLE	REGRESSION COEFFICIENT
a. Aquifer Depth	9.37
b. Overburden Thickness	2.50
c Aquifer Thickness	4.88

TABLE 22: REGRESSION ANALYSIS FOR BOREHOLES IN SCHISTS

DEPENDENT VARIABLE: YIELD

VARIABLE	REGRESSION COEFFICIENT
a. Aquifer Depth	1.50
b. Aquifer Thickness	7.44

Table 21 shows that a unit increase in aquifer depth, aquifer thickness and overburden thickness increases the yield in boreholes drilled through phyllites by 9.37 l/min., 4.88 l/min and 2.51 l/min. The same conditions occur in the schists, where a unit increase in aquifer depth and aquifer thickness gives an increase in yield by 1.5 l/min. and 7.4 l/min. respectively (Table 22).

Norgbe (1994) discussed that the high increase in yield is possible in the schists because, though the micaceous and feldspathic schists decompose to clays and permeability is reduced appreciably, the schists having marked schistosities coupled with the presence of quartz veins and fractures give rise to porous weathering products which aids in groundwater storage. Relatively high yields have been obtained from the moderately decomposed zones in quartz-rich schists.

Areas in Nandom, Lawra, Kalsara and Kuo obtain significant supplies of water from schists. The phyllites, give rise to an argillaceous soil upon weathering and actually exercise strong control on groundwater movement by reason of their lack of jointing. However, if the rock is strewn with fractured quartz veins then relatively moderate to high yields are obtained from phyllites.

5.8 AQUIFER PROPERTIES

5.8.1 DISCUSSION OF CONSTANT-DISCHARGE TEST RESULTS

Time drawdown plots derived from pumping tests are necessary in the prediction of future water level changes that reflect long-term effects of conditions at the aquifer boundaries.

There was not enough data available for the determination of aquifer parameters.

However, values computed for transmissivity using Cooper-Jacob(1946) solution technique range from 1.2 to 108.2 m^2/day in 47 boreholes (Table 23). The average transmissivity value is 35.2 m^2/day and the standard deviation is 30.1 m^2/day.

The closeness of the standard deviation value to the average value indicates the wide variations and extremity in transmissivity values of the basement rock aquifers in the Upper-West region. Banoeng-Yakubo (1989) obtained transmissivity values ranging from 1.1 to 98.3 m^2/day in the basement complex rocks of the Upper regions of Ghana and an average of 22.2 m^2/day for 52 wells. These values were computed using the Cooper-Jacob (1946) method.

It is worth mentioning that transmissivities computed for the study were obtained from pump tests conducted for only one hour. According to Giernaert (1989), several aquifer parameters determined from short term pump tests do not represent actual values. To some extent, this is due to the generally localised and discontinuous nature of aquifers in crystalline basement rocks.

The transmissivity values obtained from 23 granitic rock aquifers range from 2.6 to 108.2 m^2/day. The average and standard deviation values are 33.2 and 27.0 m^2/day respectively. Four aquifers in the greenstones were evaluated for transmissivity values. The values vary between 8.1 and 107.3 m^2/day. An average of 48.0 m^2/day and a standard deviation of 45.5 m^2/day were obtained.

Transmissivity values for 12 phyllitic rock aquifers range from 1.2 to 90.3 m^2/day. An average and standard deviation of 37.4 m^2/day and 31.5 m^2/day were obtained respectively. For eight schist aquifers, the transmissivity values range between 7.2 and 99.6 m^2/day. The average is 33.6 m^2/day and the standard deviation is 31.2 m^2/day.

TABLE 23: SUMMARY OF AQUIFER CHARACTERISTICS

REHOLE UMBER	LOCATION	DURATION (HOURS)	SPECIFIC CAPACITY (m²/day)	TRANSMISSIVITY (m²/day)		GEOLOGY
				JACOB	RECOVERY TEST	
438C 3	Tuopare	1	12.7	23.2	-	Granite
437H 9	Babile	1	7.0	12.8	-	Granite
403D 1	Fian	1	5.4	13.2	-	Granite
444F 7	Sibelle	1	17.8	108.2	-	Granite
437F 1	Eremon	1	9.3	16.9	-	Granite
403A 1	Busie	1	9.3	17.4	-	Granite
438D 1	Dowine	1	26.2	48.8	-	Phyllite
400F 5	Duong	1	8.3	15.3	-	Schist
399I 5	Kuo	1	7.5	14.0	-	Schist
437H 15	Kumasal	1	10.2	18.8	-	Granite
398I 14	Nakori	24	15.7	28.9	32.5	Greenstone
37H 17	Babile	1	2.9	5.3	-	Granite
37H 18	Birifu	1	7.5	13.9	-	Phyllite
399F 2	Saan	1	30.8	56.5	-	Granite
38D 13	Boo	1	3.9	7.2	-	Schist
37E 18	Amburi	1	14.5	26.8	-	Phyllite
398I 17	Wa	24	13.3	24.5	56.2	Granite
438E 5	Dia	1	32.6	59.4	-	Greenstone
44F 6	Sorbelle	1	24.4	44.5	-	Granite
38B 7	Kpari	1	16.3	31.1	-	Granite
37H 16	Birifu	1	43.5	83.3	-	Granite
38E 1	Janoure	1	2.9	5.4	-	Phyllite
7H 11	Birifu	1	96.5	90.3	-	Phyllite
37E 2	Yagtuuri	1	10.7	19.6	-	Phyllite
37E 3	Kikaila	1	6.2	11.7	-	Phyllite
7F 14	Duori-Dia	1	1.4	2.6	-	Granite
98I 15	Wa	24	2.0	36.6	62.1	Granite
99F 8	Yaro	1	51.9	91.5	-	Granite
99I 3	Busie	1	55.9	99.6	-	Schist
99I 1	Sampina	1	32.2	57.9	-	Granite

LE 23 (continued

BOREHOLE NUMBER	LOCATION	DURATION (HOURS)	SPECIFIC CAPACITY (m³/day)	TRANSMISSIVITY (m²/day)		GEOLOGY
				JACOB	RECOVERY TEST	
400G 5	Kuuri	1	9.9	18.6	-	Phyllite
398I 13	Wa (catholic seminar)	24	54.3	100.5	19.5	Granite
399I 2	Sampina	1	15.6	28.4	-	Granite
400F 4	Duong	1	10.0	18.7	-	Granite
400E 1	Kalsara	1	8.5	15.3		Granite
399C 3	Tuolo	1	0.7	1.2		Granite
401G 4	Wa (urban)	24	115.8	183.4	213.4	Greenstone
437F 11	Duori	1	55.9	57.5	-	Phyllite
437H 7	Tanchara-ko	1	4.7	58.0	-	Schist
438G 19	Jirapa Sec. Sch.	1	13.0	23.2	-	Granite
401G 19	Wa Lamanyiri	24	41.6	77.1	90.1	Granite
438D 15	Saabayiri	1	4.0	7.4	-	Granite
399I 7	Bire	1	16.3	30.7	-	Granite
438G 17	Nibari	1	17.8	46.2	-	Granite
437E 20	Lawra	1	37.6	70.7	-	Granite
441B 2	Nandawala	1	30.0	108.2	-	Granite
400E 6	Damba	1	9.2	16.6	-	Granite
437F 3	Kondipie	1	8.3	15.3	-	Schist
438G 14	Zakpayiri	1	4.3	8.1	-	Greenstone
437E 9	Tuori	1	19.6	36.3	-	Schist
401G 1	Sing (Wa)	1	6.8	8.3	-	Granite
438G 3	Jirapa-Yipala	1	101.9	107.3	-	Greenstone
398C 1	Kaleo	1	10.8	17.2	-	Greenstone

Chilton and Foster (1993) discussed that low values of transmissivity are likely to exhibit significant variations in yield and responses to abstraction. This is characteristic of the yields and transmissivities obtained from aquifers in the study area. However, transmissivities are generally higher in the granitic rock aquifers than in the schist rocks even though they have comparable average transmissivity values.

The small number of aquifers encountered in the greenstones makes it unrepresentative for any meaningful discussion though the highest average transmissivity value obtained in the study was in the greenstone aquifers. The same observation was made by Banoeng-Yakubo (1989) from his studies in the calculation of transmissivity values from greenstone rock aquifers in the Upper regions of Ghana.

Using the Theis Recovery method, the transmissivity values for six boreholes range from 19.5 to 213.4 m^2/day. The average value was 82.3 m^2/day. Those calculated from the same boreholes using the Cooper-Jacob (1946) solution technique gave a range between 24.5 and 183.4 m^2/day with an average value of 75.2 m^2/day.

Transmissivity values from the recovery data are higher than those obtained from the Cooper-Jacob (1946) solution technique. This is because, during the recovery period, water levels are measured without any interference from pump adjustments to changing head during the constant-discharge rate test. Therefore more accurate results are obtained from recovery data.

5.8.2 SPECIFIC CAPACITIES

Driscoll (1989) defines specific capacity of a well as the rate of discharge per unit drawdown. Specific capacity varies with the duration of discharge. Essentially, the time at which the specific capacity of a well is obtained is very necessary.

Other factors which influence the specific capacity of a well include the hydraulic characteristics of the aquifer, the partial or total penetration and the effective open area of the screen (Bierschenk, 1963).

The specific capacities of six boreholes tested for 24 hours during the study in the Wa well fields were computed over the test period. A minimum specific capacity of 2.0 m^2/day and a maximum value of 115.8 m^2/day was obtained for the six boreholes. The average specific capacity value is 40.5 m^2/day and the standard deviation is 41.7 m^2/day. Again, this exhibits the wide measure of dispersion in specific capacity values in the study area.

Forty-seven boreholes tested for one hour have specific capacities ranging from 0.7 to 101.9 m^2/day with an average and standard deviation value of 22.3 and 24.9 m^2/day respectively. The amount of deviation from the mean is high, which explains the heterogeneous and localised nature of aquifer in the region.

Granitic rock aquifers encountered in 23 boreholes tested for one hour and have specific capacity values ranging between 1.4 and 52.0 m^2/day. The average is 16.3 m^2/day. In schists, the average specific capacity is 21.6 m^2/day with values varying from 3.9 to 55.9 m^2/day for eight aquifers. The standard deviation is 21.7 m^2/day.

The specific capacities of wells tested for one hour range from 0.7 m^2/day to 96.5 m^2/day in twelve phyllitic aquifers. The mean value is 21.7 m^2/day. Greenstones have specific capacity values varying between 4.3 and 101.9 m^2/day with an average of 37.4 m^2/day in four boreholes tested for one hour.

The range and standard deviation values of specific capacities obtained in the various rock aquifers deviate greatly from their mean with common wide disparities. This may be due to the fact that, aquifers in the study area are variable in extent, thickness, composition and hydraulic characteristics. The variable lithologies and degrees of fracturing intersected by the boreholes also account for these differences in specific capacity values.

Chilton and Smith-Carington (1984) agree that these specific capacities are enough to sustain rural water supplies. Sixty percent of the boreholes tested for one hour have specific capacities of over 5.0 m^2/day, a minimum value required to achieve a village water supply of 10 l/min.

Hazell et al (1992) reported that in the crystalline basement rocks of Kano state in Northern Nigeria, the mean specific capacities of undifferentiated granites in weathered and fractured aquifers is 14.9 m^2/day and 16.9 m^2/day respectively. The average specific capacities obtained from the weathered aquifers in granites is 17.6 m^2/day in the study area and that obtained from fractured aquifers is 15.8 m^2/day. As drawdown increases, there is a marked decrease in the specific capacity. Driscoll (1989) explains that this decrease depends on the geologic origin of the aquifer.

From Table 23, high specific capacity values are usually associated with high transmissivities. From earlier discussions, the average specific capacity values in phyllites and schist rock aquifers are comparable. However, according to Ajayi (1987), the productivity of wells can only be compared if a pumping period is chosen and the yield of these wells are compared at a specified level of drawdown. Therefore, in real terms, it is improper to compare the average specific capacity values that have been obtained

5.8.3 DISCUSSION OF STEP-DRAWDOWN RESULTS

Step-drawdown tests were performed for five boreholes in the Wa well fields. The analysis was done using the Jacob (1947) graphical solution method.

A case study is one of the Wa (Urban) South-west boreholes in the well field. This borehole, 3981 15 was drilled in a flatland and screened through granite. The final depth of the borehole is 58 m. The overburden thickness is 32 m and the depth to top of the aquifer is 41 m. It has a static water level of 9.02 m and the dynamic water level after 24 hours of pumping is 32.18 m.

A step-drawdown test consisting of 3 steps with each step lasting for one hour was conducted by the Kumasi Drilling Unit of the Ghana Water and Sewerage Corporation (GWSC) during the study. The test was performed at discharge rates of 130 m^3/day, 156 m^3/day and 176 m^3/day. The origin of time for all steps is taken as the beginning of the test.

The formation and well loss constants, B and C were calculated from equation (4.16) as shown in Figure 20. The calculated drawdown obtained from the values of B and C are illustrated in Tables 24a and 24b. The formation loss constant, B, is 0.096 m^{-2} day. The formation loss component of the total drawdown is 16.89 m. Further, the well loss constant C is 0.0004 m^{-5} day^{2}. The well loss component of the total drawdown is 12.39 m calculated for the same borehole. The computed total drawdown is therefore 29.28 m. The maximum discharge at which the step-test was performed for this borehole is 176 m^3/day. The actual drawdown after 24 hours of pumping is 22.98 m and the discharge rate for the constant rate test is 160 m^3/day.

The efficiency of this borehole after one hour was calculated from the ratio of the formation loss component, BQ to the total drawdown, S_w (Jacob, 1947). The efficiency of borehole number 3981 15 after one hour of pumping is 58%. This implies that the well loss component, CQ^2 of the total drawdown has introduced inefficiencies to the borehole performance by 42%. Banoeng-Yakubo (1989) indicated in his studies that such inefficiencies introduced by the well loss components hinder groundwater abstractions and significantly reduce the yield of the boreholes.

Corrective measures such as the redevelopment and rehabilitation of the boreholes should be implemented to remove these inefficiencies. Most of the boreholes should be pump-tested for a longer duration to determine the aquifer parameters and how sustainable determined yields are when projected over long periods of pumping.

Results of the step-drawdown analysis shown in Table 25 were used in the calculation of borehole efficiencies after one hour of pumping. The result indicated that none of the boreholes analysed had inefficiencies exceeding 75%.

5.9 AQUIFER TYPES IN OBSERVATION AND PRODUCTION BOREHOLES

Groundwater occurs mainly within the overburden and in fractures within the bedrock. Three types of aquifers have been identified from the drillers' logs in the Upper West Region. These are the weathered rock aquifers which are fracture-related, the fractured unweathered rock aquifers and the fractured quartz-vein aquifers.

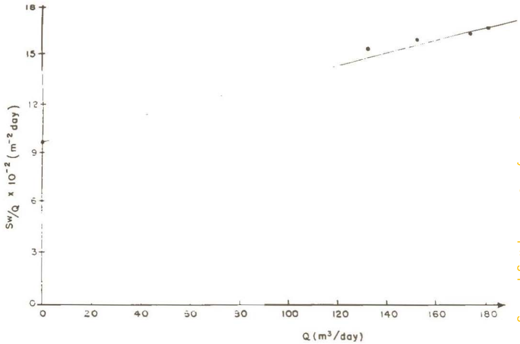


FIG. 20 : Plot of $^{Sw}/_{Q}$ versus Q for Well Number 398 I 15

TABLE 24 a:

CALCULATED DRAWDOWN FOR STEP-DRAWDOWN PUMPING

TEST AT WA (BOREHOLE NUMBER 3981 - 15)

USING RESULTS FROM PLOT OF FIGURE 20

STEP	Q (m^3/day)	S (m)	S/Q x 10^{-2} (m^2/day)	Q/S (m^2/day)
1	130	12.50	9.60	10.4
2	156	4.56	2 90	34 2
3	176	4.49	2 50	39.2

B = 9.6 x 10^{-2} (m^2/day) = 0.096 (m^2/day)

C = 4 x 10^{-4} (m^5/day^2) = 0 0004 (m^5/day^2)

TABLE 24 b:

STEP	Q (m^3/day)	BQ (m) B = 0.0004 m^{6} day^{1}	CQ2 (m^{-2}) C = 0.0004 m^{4} day^{2})	SW=BQ + CQ^2 (m)
1	130	12 48	6.76	19.34
2	156	14.97	9.73	24.70
3	176	16.89	12 39	29.28

TABLE 25:

Summary of Formation and Well Loss Components
of Total Drawdowns Using Jacob's (1947) Method

Borehole Number	Number Of Steps	QMAX (m^3/Day)	Sw at end of test (m)	B (m^{-2} Day)	C (m^{-5} Days^2)	$Sw = BQ + CQ^2$		
						Sw (m)	BQ (m)	CQ^2=m
398I 13	4	209	9.79	0.0475	0.0002	18.67	9.93	8.74
398I 1	3	189.1	5.97	0.0800	0.0017	2.12	1.51	0.61
401G 4	4	196	4.79	0.0066	0.0019	2.02	1.29	0.73
398I 15	3	176	22.77	0.0960	0.0004	29.28	16.89	12.39
401G 19	3	189	10.49	0.0285	0.0103	9.07	5.39	3.68

Aquifers in the weathered zone are well developed as is commonly the case in almost seventy-five percent of the rocks in the study area. Virtually, all the infiltrating water moves through the weathered zone before it can percolate into the deep fracture systems in the fresh unweathered rock. Thus, groundwater is stored transiently in the weathered zone.

This groundwater generally forms a continuum with that stored in the deeper fracture system of the bedrock. In some cases, the fractures are interspersed within the weathered zone

During the project in the mid-seventies, the borehole drilling programme was basically focused on obtaining yields required for borehole completion from the weathered zone. This policy, therefore, affected how deep the drilling should be carried out, hence explaining why most boreholes in the study area were completed in the moderately decomposed zones

Aquifers were also encountered in rocks where fractured quartz veins traversed the rocks. These aquifers are normally observed to be very productive. Yields are enhanced when many fractured quartz veins cross cut the rocks. The fractures superimpose secondary porosity on the rocks and increase their porosities and permeabilities

Among the twenty-three observation boreholes, sixteen were drilled in the granitic terrains, while two were completed in Birimian phyllites and five in the Birimian schists In the granitoids, twelve boreholes obtain water from the weathered zone and four of the boreholes tapped water from weathered zones within the Birimian greenstones

About 61% of the boreholes were mainly completed in the moderately to slightly weathered zones as indicated in (Table 26): whilst 39% of the monitoring boreholes were completed in fresh bedrock. Nine of the monitoring boreholes tap water from fractured rock aquifers.

Generally, 65.2% of the monitoring boreholes obtain water from the weathered zone, while 17.4% of the boreholes have aquifers in fractured rocks and fractured quartz veined rocks respectively (Table 27). For instance, borehole 437E 5 at Furo obtains water from a decomposed fractured quartz vein schist and borehole 401A 7 taps water from a weathered schist aquifer at Jang. The weathered zone usually comprises areas of deep rock decomposition and are considered to have the highest potential for successful boreholes, when fractures and quartz veins are strewn within the weathered zone. The presence of these structural features serve as a guide to further drilling into the fresh bedrock.

Table 28 indicates that about 74.5% of the production boreholes tap water from the weathered zones whilst 15% obtain water from fractured quartz-vein rocks and 10% receive water from fractured rock aquifers. In Lawra, borehole 437E 8 taps water from a fractured greenstone aquifer, while at Kodouni, borehole 398G 4 receives water from a fractured quartz vein phyllitic aquifer.

A closer study of the borehole logs clearly reveal that about 70% of the aquifers in the production boreholes are within areas of moderately to slightly weathered zones.

TABLE 26: NUMBER AND PERCENTAGE OF DEGREES OF WEATHERING IN THE LITHOLOGIES OF MONITORING BOREHOLES

Degree of Decomposition	Number of Boreholes	Percentages
Highly Weathered	-	-
Moderately Weathered	14	61
Poorly Weathered	9	39
Total	**23**	**100**

TABLE 27: NUMBER AND PERCENTAGE OF AQUIFER TYPES IN THE MONITORING BOREHOLES, UPPER WEST REGION

AQUIFER TYPES	NUMBER OF BOREHOLES	PERCENTAGE
FRACTURED QUARTZ VEIN	4	17 4
FRACTURED	4	17.4
WEATHERED	15	65.2
TOTAL	23	100

TABLE 28: Numbers and Percentages of Aquifer Types in the Production Boreholes Upper West Region

AQUIFER TYPE	NUMBER	PERCENTAGES
Fractured Quartz Vein	26	15.5
Fractured	17	10.0
Weathered	126	74.5
Total	169	100

TABLE 29: Number and Percentages of Degrees of weathering in the Lithologies of the Production Boreholes

Degree of Decomposition	Number of Boreholes	Percentages
Highly Decomposed	20	12
Moderately to slightly weathered	119	70
Poorly weathered	30	18
Total	**169**	**100**

About 12% obtain water from the highly decomposed zones, unlike in the monitoring boreholes where no borehole taps water from the highly decomposed zones. 18% of the production boreholes obtain water from the poorly decomposed zones (Table 29).

5.10 DISCUSSION OF THE HYDROGEOLOGICAL REPRESENTATIVENESS OF MONITORING BOREHOLES

The network of groundwater monitoring of boreholes produces a set of data which depicts regional variations in the quantity and quality of groundwater and factors affecting these variations in geological, topographical and climatic environments.

Monitoring boreholes in the study area are specific boreholes used to produce water and at the same time to monitor production boreholes that surround them. According to Soveri (1994), monitoring may be defined as a scientifically designed surveillance system of continuing measurements and observations including procedures. Monitoring requires that data is obtained on a regular basis, whereby data can be effectively used to track borehole performance which is vital if the maximum long term yield of a borehole is to be realised.

Groundwater monitoring has been possible mainly in the use of observation boreholes. However, investigations conducted by Bannerman and Ayibotele (1984) in the study area suggest that the most efficient way to monitor production boreholes is to use the boreholes themselves, since the normal practice of having separate boreholes to monitor the performance of production boreholes would eventually involve high costs and logistical constraints.

During the project inception by CIDA/GWSC, a network of 23 observation boreholes were established throughout the region to collect information related to groundwater level fluctuations.

Figure 21 shows the location of these boreholes and some production boreholes surrounding them. The observation boreholes were selected upon the basis of easy access to data collection, high yields and low drawdown due to pumping.

To determine the adequacy or otherwise of the existing network of observation boreholes monitoring the aquifers being tapped in the Upper West region, the relation of the groundwater monitoring system with the hydrogeological conditions of producing boreholes in the five districts have been studied and verified in the present study. Based on the findings, it would be determined whether or not the current monitoring boreholes are representative of the production boreholes. From Table 30, elevations above mean sea level of some boreholes were measured with the Global Positioning System (GPS, GARMIN 75) during the study. These elevations have been used to reduce the borehole depths and aquifer depths to mean sea level as reference. To investigate whether the monitoring boreholes have any hydrogeological relationship with the production boreholes surrounding them in the study area, borehole depths and aquifer depths were calculated. This was done with a view of finding out if these monitoring boreholes were completed in aquifers that bottom at the same depths as those of the production boreholes surrounding them.

In the district of Tumu, five observation boreholes were studied alongside with thirteen production boreholes.

Observation borehole number 444F 2 located in Pulima is about 2.5 km from Tumu, the district capital. Production boreholes 444F 4 and 444F 3 are about 250 m and 275 m away from the observation borehole. They were all drilled in flatlands and tap water from weathered granitic-gneiss rock aquifers. Observation borehole 444F 2 and the production boreholes have the same aquifer thicknesses of 6 m.

The static water levels in the observation borehole and the production borehole 444F 4 are almost the same with values of 5.8 m and 5.2 m respectively, while the static water level of borehole 444F 3 is 2.1 m and is 275 m from the observation borehole.

Aquifer depths above mean sea level vary in the production and observation boreholes. The depth to top of the aquifer above mean sea level is 451.0 m in the production borehole 444F 4 and 320.0 m in the observation borehole 444F 2. There exists great variations in the yield despite the fact that these boreholes obtain water from the same rock type. The yield of the observation borehole is 103.5 l/min. and that for the production boreholes 444F 4 and 444F 3 are 13.5 l/min. and 31.7 l/min. respectively.

The high yield obtained from the observation borehole may be due to the presence of fractured quartz vein intrusions intersecting the thick overburden of 23 m which was not encountered in the production boreholes.

There is indication that there exists no hydraulic connection between the observation borehole and the production boreholes surrounding it. Though, the three boreholes have the same aquifer thicknesses, their yields, aquifer depths above mean sea level and overburden thicknesses are different.

Even though differences occur in the properties of these boreholes, they obtain water from the same rock type and aquifer and are also found in the same topographical settings.

Jeffisi, a town situated 30 km south-west of the Tumu township on the Tumu-Lawra highway is a town in the Tumu district. Borehole number 443I 1 is an observation borehole which is about 800 m away from the production borehole number 443I 2. The aquifer depths above mean sea level in the observation and production boreholes have close values of 300.8 m and 305.0 m respectively. However, the production borehole yields 99 l/min. of water from a weathered rock aquifer of granite-gneiss with an aquifer thickness of 6 m whilst the observation borehole yields 22.5 l/min. of water from an aquifer thickness of 4.6 m. The observation borehole was drilled in a weathered granite-gneiss rock aquifer. They both occur in flatlands.

Eight hundred meters apart, these boreholes differ in aquifer thicknesses with varying yields as well. However, there exists a significant hydraulic link between the observation borehole and production boreholes surrounding it, because they tap water from the same rock and aquifer types. In addition, they occur in the same topography and have close values of aquifer depths above mean sea level.

At Nandawala, also in the Tumu district, borehole number 441B 1, an observation borehole was drilled on a flatland and completed through a weathered granitic gneiss rock aquifer. About 40 m from the observation borehole is a production borehole number 441B 2. This borehole is situated on a hillside and also obtains water from a weathered granite-gneiss aquifer.

Both the observation and production borehole have the same static water levels and aquifer thicknesses with values of 13.4 m and 6.1 m respectively.

The observation borehole has a yield of 90 l/min. and aquifer depth above mean sea level of 270 m. The overburden thickness is 17 m, whilst the production borehole has a yield of 9 l/min. with an aquifer depth above mean sea level of 313 m. The overburden thickness is 27 m. It implies that, though the production borehole is quite near the observation borehole, it was situated at a hydrogeologically poor site. Besides, moderate to high yields are normally expected from boreholes drilled on flatlands and valleys than on hillsides.

Despite the short distance between the two boreholes, the differences in yield and aquifer depths above mean sea level, as well as the topography in which the boreholes were located, indicate that there is no relationship between the observation borehole and the production borehole.

In the Jirapa-Lambussie district, four monitoring boreholes and forty-five production boreholes were studied. Observation borehole number 438G 3 completed through a weathered greenstone aquifer is found in Jirapa-Yipala. This borehole is about 100 m from a production borehole number 438G 1.

This borehole was however screened through a weathered granitic rock aquifer in a flatland. These two boreholes have equal yields and aquifer thicknesses of 135 l/min. and 12.2 m each, despite the different rock types in which they occur. It is possible that there was a fracture related quartz vein system connecting the two boreholes. Surface manifestations also indicated localised zones of quartz veins surrounding the boreholes which had a relative significance to the hydrogeology.

Overburden thicknesses in the two boreholes are almost the same with 15.1 m recorded for the observation well and 13.0 m obtained for the production well. The depths to top of the aquifers above mean sea level in the observation and production boreholes are respectively 301.6 m and 304.0 m.

Depending on the distance between the two boreholes and the aquifer depths above mean sea level as well as the structural systems connecting them, they are likely to behave in a hydraulically similar manner. However, the extent of hydraulic link is minimal since monitoring may not be quite effective in boreholes tapping water from different rock types.

Observation borehole 438A 3 at Zumara in the Jirapa district is the only borehole in this town. It taps water from a fractured greenstone aquifer in a flatland. It has an aquifer thickness of 3.4 m and aquifer depth above mean sea level of 264 m. It produces water at a rate of 15 l/min. Production borehole 438A 4 at Baazing and 438A 5 at Lissa located 2.56 km and 1.35 km away from the observation borehole respectively also taps water in a flatland from weathered greenstone aquifers.

These two production boreholes produce the same yield of 22.5 l/min of water and also have the same aquifer thicknesses of 6.0 m. The aquifer depths above mean sea level in 438A 4 and 438A 5 are 349.9 m and 238.0 m respectively. The overburden thicknesses obtained are 23.0 m and 28.0 m respectively.

Due to the distances, different aquifer types and aquifer depths above mean sea level between the monitoring borehole and the production boreholes, there is no relationship between these boreholes, therefore, the production boreholes are not being monitored by the observation borehole

In Tuopare, observation borehole number 438C 3 was drilled in a flatland and screened through a weathered granitic aquifer. This borehole produces 18 l/min. of water and has an aquifer thickness of 6.1 m and aquifer depth above mean sea level of 280.7 m. A production borehole 438C 4 in Guri which is about 4 km away from the observation borehole in Tuopare was also drilled in a flatland but taps water from a weathered greenstone aquifer. It produces a yield of 18 l/min. and has an aquifer thickness of 6 m. The aquifer depth above mean sea level is 327.0 m. The same hydrogeological conditions could be persisting at these two places despite the distance between the boreholes. However, due to different values of aquifer depths above mean sea level and different rock types, there exists no relationship between them.

Seven observation wells and fifty-seven production boreholes were studied in the Lawra district. Observation borehole number 437H 9 in Babile was drilled through a weathered granitic aquifer in a valley. It has an aquifer thickness of 7 m.

The aquifer depth above mean sea level is 220.5 m. It produces water at a rate of 22.5 l/min. and has a transmissivity value of 12.8 m^2/day. Production borehole 437H 17 located about 600 m from the observation borehole encountered water from a weathered rock aquifer in granite. It has an aquifer thickness of 6.1 m and yields water at a rate of 13.5 l/min. The aquifer depth above mean sea level is 272.0 m. The transmissivity value obtained for this borehole is 5.3 m^2/day.

Even though the two boreholes tap water from the same rock type, they have different aquifer depths above mean sea level and different transmissivity values, resulting in no obvious hydraulic connection between them. Therefore, the observation borehole is not representative of the production borehole since it does not monitor the boreholes surrounding it.

Borehole number 437E 1 is an observation borehole in Yagtuuri. It obtains water from a weathered phyllite in a valley. It yields 27 l/min. of water and has an aquifer thickness of 6.1 m. The depth to top of the aquifer above mean sea level is 241.0 m.

Similarly, production borehole 437E 2 in Yagtuuri is about 600 m from 437E 1. It produces water at a rate of 18 l/min. from a weathered phyllitic aquifer in a valley. It has an aquifer thickness of 6.0 m and an aquifer depth above mean sea level of 153.0 m

Another production borehole 437E 31 also situated about 850 m from the observation borehole (437E 1) was screened through a fractured phyllite aquifer with quartz veins intruding the phyllite, but this borehole is located on a hillside and produces a relatively low yield of 9 l/min.

The aquifer thickness is 9.3 m and aquifer depth relative to mean sea level is 260.0 m The low yield of this borehole may be due to its physiographic location, since higher yields are usually obtained from valleys and flatlands than on hillsides.

Due to the different aquifer depths above mean sea level and the different aquifer types from which the monitoring and production boreholes tap water, there exists no hydrogeological relationship between the monitoring borehole and production boreholes at Yagtuuri.

Five monitoring boreholes were established in the Nadowli district. These wells were studied alongside with seventy-two production boreholes in the district. Borehole number 403D 1 is a monitoring borehole located at Fian. It obtains water from a fractured granitic aquifer in a flatland. It produces water at a rate of 4.7 [illegible]n. and has an aquifer thickness of 6.1 m. The aquifer depth above mean sea level [illegible]61.0 m

Approximately 700 m from this observation borehole is a production borehole 403D 4 also in Fian. It is situated on a hillside and obtains water from a weathered granitic aquifer. It yields 9.2 l/min. of water and has an aquifer thickness of 7 m. The aquifer depth above mean sea level is 298.0 m. The topographical location of the production borehole is unfavourable, but it has a higher yield than the observation borehole due to the presence of a thicker aquifer.

Because of the different aquifer types through which these boreholes were screened and the different aquifer depths above mean sea level of both the production and monitoring borehole, there is no hydrogeological similarity between them. The monitoring borehole is not representative of the production borehole.

Borehole number 400D 4 is the only borehole that is pumped for domestic use in Iziri. It also serves as a monitoring borehole in the vicinity.

It obtains water from a weathered schist aquifer and is located in a valley. It yields 27 l/min. of water and has an aquifer thickness of 9.2 m. The depth to the top of aquifer above mean sea level is 288.9 m.

Production borehole number 400D 2 in Tangasia is about 4000 m (4 km) away and taps water from a weathered greenstone aquifer. It yields water at a rate of 27 l/min. and has an aquifer thickness of 12.0 m. The aquifer depth above mean sea level is 260.0 m.

The geology which is important in the type of aquifer developed and the spacing between these two boreholes is too distant for any representativeness due to the localised nature of aquifers in the region. The same values of yield in these boreholes may be due to the occurrence of fracture openings and quartz veins encountered during drilling and possibly, the deeper extents of weathering in the different rock types. However, the rock types and the aquifer depths above mean sea level indicate that the monitoring borehole and the production borehole are not representative of each other.

The Wa district has only two monitoring boreholes. These boreholes were studied with sixty three production boreholes. In Gurungu, observation borehole number 358 C 3 was drilled through a fractured quartz vein granite on a hillside. It yields 90 l/min. of water and has an aquifer thickness of 20 m.

A production borehole 358C 2 about 400 m away from 358C 3 is in a flatland and was completed through a weathered granitic aquifer. The static water level is 1.5 m below ground level whilst the observation borehole is a flowing artesian well. It is obvious that these boreholes are not representative since they tap water from different aquifer types.

Gurungu is about 55 km from the district capital Wa, and it is doubtful whether this observation borehole is monitoring some production boreholes in and around Wa

Observation borehole number 401G 6 which is located in Wa produces twenty-seven litres of water. It obtains water from a weathered granite aquifer in a flatland. Production borehole 401G 9 at Jahan College is about 850 m away from 401G 6. It was drilled in a flatland and completed through a weathered granite aquifer. The yield is 4.7 l/min. with an aquifer thickness of 6.1 m. In this situation, there exists very little relationship between the two boreholes, though the yields are quite different, they have the same aquifer thicknesses and were drilled through the same rock types. The high yield in the observation borehole may be due to the presence of quartz vein intrusions persisting in the weathered aquifer and its thick overburden.

In the foregoing discussion, the study has shown that hydraulic connections between boreholes in the region depends on the topography in which the boreholes are sited, the rock type in which the aquifer is encountered, the extent of fracturing and weathering in the rocks, the aquifer depths above mean sea level as well as the spacing between the boreholes

The hydraulic link and area of influence are limited in boreholes which are too distant apart and there is minimum hydrogeological representativeness in such cases since aquifer systems in crystalline terrains are limited and localised in nature. Even boreholes located near each other can exhibit large differences in borehole properties.

The studies have indicated that there exists very little hydrogeological relationship between monitoring and production boreholes in the region. It has been noted that observation boreholes located about 150 m apart from production boreholes and those with the same elevations and depths relative to mean sea level are likely to monitor the performance of the boreholes surrounding it.

The groundwater monitoring network seems ineffective due to the relatively small number of observation boreholes across the whole region. The use of production boreholes as monitoring boreholes in the study area does not augur very well for any meaningful monitoring in the strictest sense. Typical examples can be found in communities such as Piina, Tuopare, Zumara and Iziiri where there is only one borehole which serves both as an observation and production borehole for a sizeable population.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The region is underlain by crystalline basement rocks which consist of granitoids, Birimian greenstones, schists, and phyllites. The Middle Precambrian granitoids and the Upper Birimian greenstones occupy about eighty percent of the study area. The Lower Birimian schists and phyllites occupy the rest of the area. Structural features such as fractures, folds, faults, joints, pegmatites and quartz veins are common in the basement rocks.

Groundwater in the region occurs within the overburden and in fractures within the bedrock. This occurrence of groundwater is in turn controlled by the depth and extent of fracturing and weathering, the presence of a thick overburden and the numerous fractures, quartz and pegmatite veins that intersect the overburden.

The weathered rock aquifer which is fracture-related, the fractured quartz vein and fractured unweathered rock aquifer types have been identified in the area. It is worth noting that these aquifer types are related and occur in association with quartz vein intrusions, pegmatites and aplites.

The weathered rock aquifer which is normally strewn with quartz veins and fractures is the dominant type of aquifer in the region found in the observation and production boreholes

About sixty five percent of the former taps water from the weathered aquifer and seventeen percent obtain water from the fractured quartz vein and fractured unweathered rock aquifers respectively; whilst in the latter, only ten percent get water from fractured unweathered aquifers, about seventy five percent obtain water from the weathered rock aquifers and sixteen percent tap water from the fractured quartz vein aquifers. A significant number of the boreholes were completed in the moderately weathered zones of the monitoring and production boreholes.

Rainfall is the main source of recharge to aquifers in the region. The mean annual rainfall is about 900 mm but it varies from year to year and from place to place.

Recharge to aquifers are intermittent and limited because of the barrier normally formed by the overlying clayey decomposed rock. Reduced recharge has been aggravated by cattle overgrazing, poor farming practices and deforestation which expose the land surface to the intense and scorching rays of the sun. The above factors including excessive withdrawal of water from boreholes account for the decline of water levels in the study area.

Ninety percent of the boreholes have depths between 20 m and 50 m. Generally deeper wells are common in flatlands than in the valleys and hillsides.

Overburden thicknesses exceeding 15 m are common in the observation and production boreholes with a mean value of 24 m in the former and a mean of 21 m in the latter. Phyllites were noted to have similar mean thicknesses of 36.2 m and 36 m in observation and production wells respectively. The geology of the study area has a great influence on overburden thickness.

Aquifers are small in size and may consist of veins of fractured quartz and of decomposed rocks up to about 30 m thick. Sometimes they form isolated pockets in which the groundwater flow is determined by the surface topography. Aquifers were noted to be thicker in flatlands than in valleys and hillsides in the study area.

Eighty five percent of the boreholes yield 30 litres/minute or less of water in the observation and production wells. There exists large variations in yields even with boreholes tapping water from the same types of aquifer. This reflects differences in borehole properties and suggests a high degree of aquifer heterogeneity in the study area. Reduced borehole yields in the region can be attributed to siltation and screen clogging from the accumulation of altered mica products in the boreholes. The decline of water levels in the region can also be a cause in the reduction of borehole yields making the boreholes unable to sustain a continuous supply of water.

Transmissivity values computed from Cooper-Jacob(1947) method varied greatly. The mean transmissivity obtained for 47 boreholes tested for one hour is 35.2 m^2/day.

Water level fluctuations in the region are seasonal. Water levels rise in the rainy season and fall during the dry season. The topography has a great influence on the depth to top of aquifer in the area. In the valleys and areas adjacent to water bodies, the aquifer depth may be near the land surface. On the flatlands, the aquifer depth generally range from a few meters to tens of meters beneath the surface. However on hillslopes, the aquifer may be at considerably great depths. In general, the depth to the top of the productive aquifer follows and replicates the topography.

Generally, comparing the number of observation boreholes to production boreholes in the region, the relatively small number of observation boreholes is not enough for any groundwater monitoring due to the fairly complex nature of the geology even on a local scale. Moreover, the use of one borehole to serve as a production well and an observation well in some communities is unsuitable.

The number of people per borehole has increased considerably in the past and more water is abstracted from the boreholes each day making it difficult for the water demands to be met in the region especially during the dry seasons

The present study indicates that the hydrogeological relationship between monitoring and production boreholes is fairly strong when they occur in similar geologic environments and when the distance between the production and monitoring boreholes are short. The topography also accounts for the representativeness of monitoring wells in the study area.

Further, indications however show that, it is doubtful whether any meaningful relationship between monitoring and production boreholes which are located farther apart from each other (about 400 m and above from each other can be established), as noted in about eighty percent of the monitoring boreholes and production boreholes surrounding them.

This amounts to virtually little or no effective groundwater monitoring network in the region in terms of numeric abundance and the spatial distribution of the observation boreholes.

The variable hydraulic characteristics over short distances and aquifer heterogeneity in the region makes monitoring not in the immediate vicinities of observation boreholes very limited and interference between aquifers is minimised due to the varied geological and hydrogeological conditions that prevail in the area

In the absence of enough funds, then the production boreholes can be used as monitoring boreholes, but continuous water level measurements need to be taken

The distances between monitoring and production boreholes surrounding should not exceed 400 m based on the fact that the aquifers in the study area are localised and heterogeneous in nature. The environment is destroyed as a result of bush-burning and felling of trees in the region. Those practices affect the rainfall pattern and give rise to high rates of evapotranspiration hence reducing the recharge processes. Therefore educational campaigns and laws should be promulgated so that these practices can be minimized.

Redevelopment of the boreholes by air-lifting has been suggested as the only remedy to tackle the issue of reduced borehole yields in the region. During the project, periodic redevelopment of the boreholes was recommended as part of the maintenance operations. However, little attention was given to this part of the maintenance programme and has resulted in the accumulation of mica in the boreholes over all these years.

Finally, there is the need to ensure that there is an improvement in the data processing, archiving and dissemination of all hydrogeological and hydrological data, since groundwater information in the region is inadequate. Governmental and non-governmental organisations involved in groundwater studies in the region should co-ordinate their operations and activities in order to provide a basis for the development of groundwater supplies in the region.

Alternate water supplies such as rain water harvesting should be provided particularly in places which are hydrogeologically unfavourable for groundwater.

TABLE 30

SUMMARY OF BOREHOLE AND AQUIFER CHARACTERISTICS.

BOREHOLE NUMBER	LOCATION	BOREHOLE DEPTH (M)	AQUIFER DEPTH (M)	ELEVATION (M)	B'HOLE DEPTH (m) ABOVE M.S.L	AQUIFER DEPTH (M)	O'B T'NESS (M)	AQUIFER T'NESS (M)	YIELD (L/M)	TRANSMI-SSIVITY (M2/DAY)	AQUIFER TYPE	GEOLOGY	BOREHOLE TYPE
368C 3	Gurungu	27.0	20.0				23.8	6.1	90.0		Frac Qtz Vein	Granite	Observation
401G 6	Wa South	30.0	23.5				27.4	6.1	27.0		Weathered	Granite	Observation
398C 1	Kaleo	18.0	12.0				14.0	5.1	18.0		Weathered	Greenstone	Observation
400D 4	Izin	39.0	29.1	318.0	279.0	288.9	30.5	9.2	27.0		Weathered	Schist	Observation
403D 1	Fian	30.0	23.0	384.0	354.0	361.0	30.0	6.1	4.7	13.2	Fractured	Granite	Observation
403A 1	Busie	18.0	11.6	429.0	410.7	417.4	15.2	6.1	18.1		Fractured	Granite	Observation
401A 7	Jang	0.0	17.1					4.3	108.0	17.4	Weathered	Schist	Observation
438G 3	Yipala	31.0	22.0	319.0	288.0	301.6	15.1	12.2	135.0		Weathered	Greenstone	Observation
438I 2	Sabuli	31.0	18.0				19.0	12.3	18.0		Weathered	Granite	Observation
438C 3	Tuoppare	26.0	19.3	300.0	273.0	280.7	24.1		18.0	23.1	Weathered	Granite	Observation
438A 3	Zumara	0.0	14.0	278.0		264.0		3.4	15.8		Fractured	Greenstone	Observation
443I 1	Jeffisi	20.0	15.2	316.0	296.0	300.8	20.0	4.6	22.5		Weathered	Granite	Observation
441B 1	Nandawale	28.0	18.0	288.0	260.0	270.0	17.0	6.1	90.0		Weathered	Granite	Observation
444F 2	Pulima	30.0	23.0	343.0	313.0	320.0	24.4	6.1	103.5		Weathered	Granite	Observation
448D 1	Pina	27.0	20.0	310.0	283.0	290.0	27.0	3.0	27.0		Weathered	Granite	Observation
447D 3	Tumu	24.0	15.0	271.0	247.0	256.0		9.0	18.0		Weathered	Granite	Observation
437F 1	Eremon	18.0	12.0	365.0	347.0	353.0	17.0	6.1	18.0	16.9	Weathered	Granite	Observation
437H 9	Babile	23.2	16.5	237.0	213.0	220.5		7.0	22.5	12.8	Weathered	Granite	Observation
438D 3	Downe-Ko	35.0	22.0	320.0	285.0	298.0	30.5	12.2	22.5		Fractured	Granite	Observation
437E 1	Yaguun	43.0	35.0	276.0	233.0	241.0	43.0	6.1	27.0		Weathered	Phyllite	Observation
438D 1	Downe	31.0	22.0	317.0	286.0	295.0	29.3	6.1	13.5	48.8	Frac Qtz Vein	Phyllite	Observation
437E 13	Lawra	0.0	41.0	274.0		233.0		7.6	148.5		Frac Qtz Vein	Phyllite	Observation
437E 5	Furo	0.0	20.0	285.0	255.0	265.0		6.1	13.5		Frac Qtz Vein	Schist	Production
400E 6	Tangasia	42.7	20.1	362.0	319.0	341.9					Weathered	Schist	Production
400D 2	Tangasia	24.0	12.0	272.0	248.0	260.0	18.0	12.0	27.0		Weathered	Greenstone	Production
400D 3	Tangasia	31.0	21.0	317.0	286.0	308.0	24.0	9.0	9.0		Weathered	Greenstone	Production
403D 3	Fian	35.4	30.0	357.0	322.0	327.0					Weathered	Greenstone	Production
403D 4	Fian	33.0	28.0	326.0	293.0	298.0					Weathered	Greenstone	Production
438I 3	Sabuli	17.1	11.2	386.0	368.9	374.8					Weathered	Greenstone	Production
438G 6	Jirapa	40.5	10.6	307.0	266.5	296.4					Weathered	Greenstone	Production
438G 7	Pare	43.9	31.7	318.0	274.1	315.0					Fractured	Greenstone	Production
438D 2	Downe	31.0	24.0	333.0	302.0	307.0	26.0	6.1	14.9		Fractured	Greenstone	Production
438A 4	Baazing	23.0	6.1	256.0	333.0	349.9	23.0	6.1	22.5		Weathered	Greenstone	Production
438A 5	Lissa	30.0	20.0	258.0	228.0	238.0	28.0	6.0	22.5		Weathered	Greenstone	Production
437H 10	Babile	12.0	5.5	236.0	224.0	230.5	9.0	8.2	13.5		Weathered	Granite	Production
437H 17	Babile	24.0	18.0	290.0	266.0	272.0	16.0	6.1	13.5	5.3	Weathered	Granite	Production

BOREHOLE NUMBER	LOCATION	BOREHOLE DEPTH (M)	AQUIFER DEPTH (M)	ELEVATION (M)	ABOVE M.S.L BOREHOL DEPTH (M)	ABOVE M.S.L AQUIFER DEPTH (M)	OVERBURDEN THICKNESS (M)	AQUIFER TNESS (M)	YIELD (L/M)	TRANSMISSIVITY (M2/DAY)	ACUIFER TYPE	GEOLOGY	BOREHOLE TYPE
437F 2	Eremon Tanzu	37.00	29.00	440	403.0	411.0	19.0	6.0	18.0		Weathered	Granite	Production
437F 7	Eremon Yagra	27.15	15.00	278	250.0	263.0							Production
437E 11	Zambo	32.00	37.20	408	376.0	370.0	23.0	9.0			Weathered	Greenstone	Production
437E 14	Lawra	77.40	9.50	322	244.6	312.5					Weathered		Production
437E 2	Yagtuun	42.00	35.00	188	146.0	153.0	38.0	6.0	18.0	19.6	Frac. Qtz Vein	Phyllite	Production
443I 2	Jeffisi	20.30	13.00	318	297.7	305.0					Weathered	Granite	Production
441B2	Nandawala	27.00	21.00	334	307.0	313.0	27.0	6.0	9.0	108.2	Weathered	Granite	Production
438C 4	Gun	27.00	21.00	348	321.0	327.0			18.0		Weathered	Greenstone	Production
400E 8	Tayimple	19.80	11.90	264	244.0	252.0	19.6	6.1	18.1		Weathered	Granite	Production
400E 2	Mwaanwore	14.80	14.20	270	255.4	255.8	12.2	6.1	18.0		Weathered	Granite	Production
400E 4	Moyin	21.50	15.00	275	253.5	247.5	17.7	6.1	13.5		Fractured	Granite	Production
398C 3	Ombo	23.50	15.20				11.6	6.1	18.0		Fractured	Granite	Production
437F 16	Duon	38.00	28.00	250	212.0	222.0	37.5	9.0	9.0		Fractured	Granite	Production
437F 14	Duon-Djan	29.60	23.20	249	219.4	225.8	23.5	6.3	9.0	2.6	Weathered	Granite	Production
438G 17	Nibare	28.00	21.00	314	286.0	293.0	27.0	6.1	13.5	46.2	Weathered	Granite	Production
398C 4	Kalun	21.00	14.20				19.2	5.7	18.0		Fractured	Granite	Production
398C 9	Gure	30.00	22.70				23.0	6.2	9.2		Weathered	Granite	Production
438G 18	Tizza	20.00	17.00	401	379.0	384.0	20.0	3.2	13.5		Weathered	Granite	Production
398D 7	Sukpere	39.00	32.00				26.0	6.1	13.5		Weathered	Granite	Production
438E-1	Janwore	24.00	18.00	250	226.0	232.0	23.0	6.1	9.0	5.4	Fractured	Granite	Production
438E-2	Vinving	18.00	12.00	254	236.0	242.0	17.6	6.1	18.0		Weathered	Granite	Production
438G 11	Akoro	18.00	11.00	462	444.0	451.0	17.6	6.1	22.5		Fractured	Granite	Production
438E 3	Sign	27.00	17.20	329	302.0	311.8	17.6	69.0	31.5		Fractured	Granite	Production
437E 30	Lawra Forest	35.00	28.00	327	292.0	299.0	24.0	6.1	9.0		Weathered	Granite	Production
400F 8	Daffiama	35.00	18.00				30.0	12.0	135.0		Weathered	Granite	Production
400C 3	Tuon	18.00	11.50	337	319.0	325.5	14.0	6.1	18.0		Weathered	Granite	Production
400C 1	Busie	30.00	17.00	366	336.0	349.0	25.0	12.2	9.0		Weathered	Granite	Production
400F 7	Uolo	30.00	24.00	390	360.0	366.0	29.0	6.0	18.0		Weathered	Granite	Production
400F 4	Duong	23.00	11.00	350	327.0	339.0	19.5	12.2	27.0	18.7	Frac. Qtz Vein	Granite	Production
401A 4	Chang	30.00	24.00				21.0	6.1	54.0		Weathered	Granite	Production
400H 11	Duori	23.00	15.00				18.0	6.0	18.0		Weathered	Granite	Production
437F 13	Zukpure	29.50	22.00	339	309.5	317.0	24.0	6.1	6.8		Weathered	Granite	Production
400B 11	Dapon	24.00	18.00				18.0	6.0	4.5		Weathered	Granite	Production
400H 7	Kaabogo	32.00	25.00				30.0	6.0	13.5		Weathered	Granite	Production
400E 10	Dauri	24.00	17.00				18.0	6.0	9.0		Weathered	Granite	Production
403A 3	Chebaa	30.00	24.00	284	254.0	260	23	6.1	18.0		Weathered	Granite	Production

Above M.S.L

BOREHOLE NUMBER	LOCATION	BOREHOLE DEPTH (M)	AQUIFER DEPTH (M)	ELEVATION (M)	BOREHOLE DEPTH (m)	AQUIFER DEPTH (M)	OVERBURDEN THICKNESS (M)	AQUIFER THICKNESS (M)	YIELD (L/M)	TRANSMISSIVITY (M2/DAY)	AQUIFER TYPE	GEOLOGY	BOREHOLE TYPE
399C 7	Onfan	23.0	16.8				23.0	3.4	[illegible]		Weathered	Greenstone	Production
399F 5	Sabasia	17.0	10.5				13.0	6.1	27.0		Weathered	Greenstone	Production
399H 2	Sampina	20.0	13.5				17.0	6.1	[illegible]	28.4	Weathered	Greenstone	Production
400F 5	Duong	19.3	10.0				19.0	9.1	27.0		Fractured	Greenstone	Production
400F 2	Doic	21.0	11.2				18.0	3.1	4.5		Frac. Qtz Vein	Greenstone	Production
400F 1	Doic	28.0	19.0				24.0	8.6	22.5		Weathered	Greenstone	Production
400F 3	Duong	28.0	22.0				21.0	6.1	9.0		Weathered	Greenstone	Production
400E 1	Karsam	40.0	24.0				37.0	[illegible]	13.5	15.3	Weathered	Greenstone	Production
438B 3	Tampoe	27.0	17.0	280.0	[illegible]	[illegible]	24.0	[illegible]	15.8		Fractured	Greenstone	Production
400C 2	Tuori	24.0	15.0				14.0	[illegible]	9.0		Weathered	Greenstone	Production
400G 2	Nator	30.0	17.0				26.0	[illegible]	4.5		Fractured	Greenstone	Production
438C 4	Gur	29.0	21.0	348.0		[illegible]	21.0	[illegible]	18.0		Weathered	Greenstone	Production
401H 5	Busie	23.0	13.0				23.0	4.5	[illegible]		Frac. Qtz Vein	Greenstone	Production
401H 1	Jongo	24.0	16.5				24.0	5.0	113.0		Fractured	Greenstone	Production
400D 3	Tangasia	31.0	21.0				24.0	9.0	9.0		Weathered	Greenstone	Production
400D 2	Tangasia	34.0	12.0				18.0	12.0	27.0		Weathered	Greenstone	Production
438A 4	Baaping	23.0	17.0				23.0	6.1	22.5		Weathered	Greenstone	Production
438B 6	Kuon	31.0	22.0	253.0	252.0	252.0	30.0	6.1	6.1		Weathered	Greenstone	Production
438E 5	Ola	32.0	29.0				30.0	4.0	27.0		Fractured	Greenstone	Production
438G 13	Piiyen	35.0	[illegible]	216.0	181.0	181.0	34.0	6.4	4.5		Fractured	Greenstone	Production
437F 4	Tampie	48.0	34.0	289.0	241.0	241.0	44.0	12.1	27.0		Fractured	Greenstone	Production
401H 4	Busa	18.0	10.0				15.8	6.0	22.5		Fractured	Greenstone	Production
437E 8	Lawra	48.0	28.0				43.0	17.0	112.5		Fractured	Greenstone	Production
401A 5	Tang	14.0	11.0				12.0	3.0	13.5		Weathered	Greenstone	Production
437E 11	Zambo	30.0	20.0				23.0	9.0	45.0		Weathered	Greenstone	Production
399F 2	Saan	90.0	12.0				19.0	6.0	27.0	56.5	Weathered	Greenstone	Production
438D 19	Kpaayin	35.0	29.0	335.0	300.0	300.0	35.0	6.0	9.0		Weathered	Greenstone	Production
438D 17	Tizza-Boo	30.0	21.0	358.0	328.0	328.0	22.0	9.0	18.0		Weathered	Greenstone	Production
438D 4	Baakyelo	20.0	16.0	371.0	351.0	351.0	13.0	3.0	6.0		Weathered	Greenstone	Production
401H 2	Jong	37.0	14.0				27.0	13.0	18.0		Fractured	Greenstone	Production
401H 3	Busie	21.0	13.0				13.0	6.0	27.0		Weathered	Greenstone	Production
401H 7	Kaabogu	22.0	6.0				19.0	6.0	9.0		Weathered	Greenstone	Production
399I 01	Sampina	17.0	11.0				15.0	5.0	27.0	57.9	Weathered	Greenstone	Production
438A 5	Lissa	30.0	20.0	265.0	235.0	235	28.0	6.0	22.5		Weathered	Greenstone	Production
437H 20	Manow	23.0	17.0				21.0	6.0	27.0		Weathered	Greenstone	Production
438D 13	Tizza-Boo	19.0	13.0	305.0	286.0	286.0	15.0	6.0	18.0		Weathered	Greenstone	Production
438E 1	Janguro	24.0	18.0				23.0	6.0			Fractured	Greenstone	Production

BOREHOLE NUMBER	LOCATION	BOREHOLE DEPTH (M)	AQUIFER DEPTH (M)	ELEVATION (m)	ABOVE M.S.L BOREHOLE DEPTH (m)	ABOVE M.S.L AQUIFER DEPTH M	OVERBURDEN THICKNESS M	AQUIFER THICKNESS (M)	YIELD (L/M)	TRANSMISSIVITY (M2/DAY)	AQUIFER TYPE	GEOLOGY	BOREHOLE TYPE
438G [illegible]	[illegible]	24.0	16.0				[illegible]	6.0	6.8		Weathered	Greenstone	Production
438E 4	[illegible]	23.0	15.0				[illegible]	6.0	33.8		Weathered	Greenstone	Production
437H 4	[illegible]	30.0	19.0				[illegible]	[illegible]	18.0		Weathered	Greenstone	Production
438D 15	[illegible]	42.0	33.0	530.0	[illegible]	[illegible]	[illegible]	9.1	13.5		Weathered	Greenstone	Production
438- 5	[illegible]	20.0	13.0				[illegible]	6.0	18.0		Weathered	Greenstone	Production
401A 3	[illegible]	[illegible]	18.0				12.0	9.0	13.5		Weathered	Greenstone	Production
438I 4	[illegible]	18.0	15.0				[illegible]	6.0	10.8		Weathered	Greenstone	Production
401A 2	[illegible]	[illegible]	13.0				28.0	12.0	13.5		Weathered	Greenstone	Production
399F 7	Benkeme	24.0	19.5				24.0	6.0	22.5		Weathered	Greenstone	Production
399F 8	Yaro	[illegible]	[illegible]				17.0	6.0	27.0	91.5	Weathered	Greenstone	Production
439F 7	Pohen	30.0	[illegible]				28.0	12.0	18.0		Weathered	Greenstone	Production
438D 10	Tizza	22.0	[illegible]	[illegible]	[illegible]	[illegible]	12.0	9.0	18.0		Weathered	Greenstone	Production
444F 7	Sibelle	19.0	[illegible]				17.0	3.0	27.0		Weathered	Greenstone	Production
444F 6	Sorbelle	37.0	24				30.0	6.0	27.0		Weathered	Greenstone	Production
444F 4	Pulima	23.0	[illegible]	[illegible]	[illegible]	[illegible]	17.0	6.0	13.5		Weathered	Greenstone	Production
438B 7	Kpan	23.0	12.0				16.0	6.0	13.5		Weathered	Greenstone	Production
444F 5	Sorbelle	30.0	24.0				27.0	3.0	27.0		Weathered	Greenstone	Production
401G 9	Jahan College	24.0	[illegible]				22.0	6.1	[illegible]		Weathered	Greenstone	Production
438H 15	Kumasal	24.0	11.0	[illegible]	[illegible]	[illegible]	18.0	6.0	22.5	18.8	Weathered	Greenstone	Production
438B 2	Karni	30.0	[illegible]				23.0	12.0	13.5		Frac. Qtz Vein	Greenstone	Production
399I 7	Bire	16.0	12.0				15.0	3.0	18.0		Fractured	Greenstone	Production
400E 11	Vogoni	32.0	23.0				26.2	6.1	4.6		Fractured	Greenstone	Production
400E 9	Kandowine	30.0	22.0				25.0	6.1	13.5		Fractured	Greenstone	Production
398H 6	Joko	22.5	16.0				19.0	6.1	13.5		Weathered	Greenstone	Production
398G 5	Kalinguu	43.0	36.0				39.0	6.1	9.0		Weathered	Greenstone	Production
398C 5	Nyugluu	16.5	9.0				12.8	6.1	[illegible]		Weathered	Greenstone	Production
398C 13	Kahaa	42.0	35.0				29.0	6.1	9.0		Weathered	Greenstone	Production
398D 5	Eggy	18.0	12.0				16.0	6.1	13.5		Weathered	Greenstone	Production
438G 21	Gimane	42.0	[illegible]				16.8	5.8	22.5		Weathered	Greenstone	Production
438G 22	Naayiri	28.0	21.0				26.0	5.7	45.0		Fractured	Greenstone	Production
398D 4	Dole	29.5	23.0				26.0	61.0	9.2		Weathered	Greenstone	Production
398D 6	Zan	20.0	17.0				17.0	30.0	13.5		Weathered	Greenstone	Production
437H 4	[illegible]	29.5	20.0	[illegible]	[illegible]	[illegible]	29.0	9.0	6.8		Weathered	Greenstone	Production
437F 21	Duori	48.0	37.0				47.0	9.0	27.0		Weathered	Greenstone	Production
437F 3	Kondope	42.0	28.0	[illegible]		[illegible]	40.0	12.0	22.5	153.0	Weathered	Greenstone	Production

BOREHOLE NUMBER	LOCATION	BOREHOLE DEPTH (M)	AQUIFER DEPTH (M)	ELEVATION (m)	BOREHOLE DEPTH ABOVE MSL	AQUIFER DEPTH (M)	OVERBURDEN THICKNESS (M)	AQUIFER THICKNESS	M. YIELD (L/M)	TRANSMISSIVITY (M2/DAY)	AQUIFER TYPE	GEOLOGY	BOREHOLE TYPE
400E 6	Damba	[illegible]	21.6				20.0	6.1	9.2		Weathered	Schist	Production
400E 12	Nadowli	[illegible]	31.4				33.0	5.9	13.5		Frac. Qtz Vein	Schist	Production
437F 17	Gegn-Duor	[illegible]	37.0	323.0	275.1	288.0	47.0	9.1	22.5		Weathered	Schist	Production
398E 2	Nyimbare	24.6	18.5				23.8	6.1	9.0		Weathered	Schist	Production
398C 11	Kaleo	42.0	30.2				29.5	12.0	67.5		Weathered	Schist	Production
438G 16	Nyeni	30.0	23.6				21.3	6.0	4.5		Fractured	Schist	Production
398D 3	Daku	29.0	[illegible]				23.0	6.0	18.0		Weathered	Schist	Production
438G 19	[illegible]apa Sec Sch	29.0	[illegible]				25.3	6.1	13.5	23.2	Weathered	Schist	Production
438G 20	Wuoyin	32.0	[illegible]				27.0	6.0	18.0		Weathered	Schist	Production
398H 7	Zogb	23.0	[illegible]				21.0	6.1	13.5		Weathered	Schist	Production
398G 6	Dong	30.0	[illegible]				28.0	3.0	9.0		Weathered	Schist	Production
438G 15	Zage	36.0	[illegible]				33.0	6.1	10.8		Weathered	Schist	Production
438G 14	Zakpayin	[illegible]	[illegible]				25.0	4.0	9.0	8.1	Weathered	Schist	Production
437F 5	Nyanyaan	47.0	47.4	[illegible]	243.0	249.6	35.0	6.1	22.5		Weathered	Schist	Production
398C 5	Kulbure	42.0	[illegible]				36.0	6.1	18.0		Weathered	Schist	Production
437F 12	Gbangbee	37.0	[illegible]	[illegible]	234.0	242.0	30.0	6.1	13.1		Frac. Qtz Vein	Schist	Production
398I 5	Kuo	30.0	23.0				25.0	6.0	13.5		Weathered	Schist	Production
400D 1	Nadowli	34.0	22.0				27.0	12.0	13.5		Weathered	Schist	Production
400G 3	Sombor	30.0	24.0				29.0	4.0	13.5		Fractured	Schist	Production
400H 6	Nator	33.0	19.6				23.0	11.8	135.0		Frac. Qtz Vein	Schist	Production
439F 20	Nandomie	29.5	23.0				24.0	6.0	22.5		Fractured	Schist	Production
437F 11	Tankun	27.0	19.0	276.0	[illegible]	257.0	26.0	6.0	27.0		Weathered	Schist	Production
439F 8	Nandom	38.0	23.0				30.0	15.0	135.0	107.3	Frac. Qtz Vein	Schist	Production
401H 8	Busa	26.0	29.0				34.0	6.0	9.2		Weathered	Schist	Production
437D 5	Buoyin	30.0	20.0				26.0	6.0	22.5		Weathered	Schist	Production
437E 10	Zambo	27.0	14.0				21.0	[illegible]	58.5		Frac. Qtz Vein	Schist	Production
399C 4	Kpanyagha	42.0	33.0				29.0	6.0	9.0		Weathered	Schist	Production
438C 13	Tizza	29.0	23.0				16.0	6.1	18.0		Weathered	Schist	Production
437F 9	[illegible]ara Sec Sch	48.0	36.0				46.0	12.0	18.0		Weathered	Schist	Production
437E 6	Tuon	42.0	24.0				42.0	12.0	9.0		Frac. Qtz Vein	Schist	Production
437E 33	Lawra	65.0	56.0				[illegible]	9.0	270.0		Fractured	Schist	Production
399F 5	Gabile	25.0	18.0				[illegible]	6.0	27.0		Weathered	Schist	Production
437E 16	Kassagn	42.0	34.0				[illegible]	6.0	13.5		Weathered	Schist	Production
399F 6	Charekpon	26.0	19.0				[illegible]	6.0	13.5		Weathered	Schist	Production
399I 6	Konner	40.0	34.0				[illegible]	6.0	4.5		Weathered	Schist	Production
399I 4	Naraboe	23.0	17.0				[illegible]	6.0	27.0		Weathered	Schist	Production

BOREHOLE NUMBER	LOCATION	BOREHOLE DEPTH (M)	AQUIFER EPTH (M)	ELEVATION (m,	BOREHOLE DEPTH(M) ABOVE	AQUIFER DEPTH (M) M.S.L	OVERBURDEN THICKNESS (M)	AQUIFER THICKNESS (M)	YIELD (L/M)	TRANSMISSIVITY M2/DAY)	AQUIFER TYPE	GEOLOGY	BOREHOLE TYPE
437F 20	Munvie	48.0	41.0	441.0	393.0	400.0	36.0	6.1	27.0		Weathered	Phyllite	Production
437F 8	Gbengbee	35.0	23.0	278.0	243.0	225.0	29.0	12.0	27.0		Weathered	Phyllite	Production
437F 5	Nyanyagn	26.5	20.0	290.0	263.5	270.0	26.0	6.1	24.6		Weathered	Phyllite	Production
398G 4	Kodouni	25.0	19.0				19.2	6.1	27.0		Frac. Qtz Vein	Phyllite	Production
398G 3	Pase-Guaha	27.0	19.0				27.0	6.1	18.0		Weathered	Phyllite	Production
398D 9	Gongo	36.0	29.0				36.0	6.1	22.5		Weathered	Phyllite	Production
437E 32	Lawra	42.0	29.0				42.0	12.0	27.0		Weathered	Phyllite	Production
437 31	Yagtuun	42.0	37.0	297.0	255.0	260.0	42.0	9.3	9.0		Fractured	Phyllite	Production
399C 9	Boyele	48.0	39.0				47.0	8.6	22.5		Weathered	Phyllite	Production
399C 8	Boin	60.0	48.0				57.0	9.7	9.2		Weathered	Phyllite	Production
399C 10	Guorpuo	60.0	48.0				60.0	12.0	9.0		Frac. Qtz Vein	Phyllite	Production
400G 5	Kuun	48.0	41.6				46.0	5.9	9.2		Fractured	Phyllite	Production
437H 7	Tanchara	48.0	18.0	327.0	279.0	309.0	38.0	18.0	18.0	58.0	Weathered	Phyllite	Production
437E 3	Zambo Kakala	39.0	32.0				38.0	6.0	9.0	[illegible]	Weathered	Phyllite	Production
399C 3	Tuolu	54.0	33.0				47.0	15.0	4.5		Weathered	Phyllite	Production
399C 2	Yagha	42.0	29.0				41.0	12.2	9.0		Fractured	Phyllite	Production
437H 13	Gbolkan	37.0	28.0				29.0	6.0	18.0		Weathered	Phyllite	Production
437H 11	Birifu	42.0	35.0	213.0	[illegible]	184.0	30.0	6.4	33.3	92.3	Weathered	Phyllite	Production
437E 4	Zambo	40.0	34.0				37.0	6.0	22.5		Frac. Qtz Vein	Phyllite	Production
437E 28	Lawra Sec Sch	43.0	36.0				36.0	6.0	9.0		Fractured	Phyllite	Production
437E 18	Ambun	24.0	15.0				18.0	9.0	38.0		Weathered	Phyllite	Production
438D 6	Tizza	26.0	16.0				22.0	6.0	18.0		Weathered	Phyllite	Production
437H 18	Birifu	46.0	[illegible]	[illegible]	[illegible]	[illegible]	44.0	9.0	13.5		Weathered	Phyllite	Production
437H 16	Birifu	64.0	[illegible]			[illegible]	60.0	9.0	18.0		Weathered	Phyllite	Production
437H 14	Birifu	49.0	[illegible]		[illegible]	[illegible]	45.0	9.0	18.0		Weathered	Phyllite	Production
437H 19	Birifu	37.0	[illegible]			[illegible]	34.0	6.0	4.5		Weathered	Phyllite	Production

B HOLE DEPTH =BOREHOLE DEPTH
OB T'NESS =OVERBURDEN THICKNESS
M S L= MEAN SEA LEVEL
FRAC QTZ VEIN= FRACTURED QUARTZ VEIN

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