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Assessment of Groundwater Quality and Health Risks in the Basement Complex of Gusau and Its Environs, Zamfara State, Nigeria: Heavy Metal and Microbial Insights

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ABSTRACT

This study evaluates groundwater quality in the Basement Complex of Gusau and its environs in Zamfara State, Nigeria, a region heavily reliant on groundwater for domestic, agricultural, and industrial use. Thirty groundwater samples were collected from a variety of sources, including boreholes, hand-dug wells, and other wells across the study area, to assess their physical, chemical, and bacteriological characteristics. Key parameters analyzed included pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, heavy metals (such as iron, lead, and arsenic), and bacterial contaminants (including *E. coli* and total coliforms). The findings indicate that the groundwater is predominantly acidic to neutral, with pH values generally within acceptable ranges for drinking water. Electrical conductivity and TDS levels varied, reflecting diverse mineralization levels, with most samples falling within permissible limits for potable water. However, certain locations exhibited elevated concentrations of heavy metals, surpassing the World Health Organization (WHO) and Nigerian Industrial Standards (NIS) thresholds, posing potential health risks. Bacteriological analysis revealed significant contamination in several samples, with the presence of *E. coli* and coliforms indicating fecal pollution and highlighting a critical public health concern. These findings suggest that while the groundwater in the Gusau Basement Complex is a vital resource, it faces challenges from localized pollution and microbial contamination. The study underscores the urgent need for improved water management

strategies, including regular monitoring, enhanced treatment processes, and infrastructure development to safeguard water quality. Recommendations include the implementation of geophysical surveys to better locate productive aquifers and the establishment of systematic hydrogeological data collection to support sustainable groundwater development. Addressing these issues is essential to ensure the provision of safe and clean drinking water, thereby protecting the health and well-being of the local population in Gusau and its surrounding areas.

Keywords: Groundwater Quality, Basement Complex, Hydrogeology, Heavy Metals, Physicochemical parameters, Water Quality Assessment, Environmental Health

1. INTRODUCTION

Water is essential for human survival. Its quality must be maintained to prevent any potential health problems [16]. Groundwater constitutes one of the major sources of water supply, especially in most rural communities in Nigeria, in addition to rainwater and surface water bodies. For this reason, there has been a consistent demand for groundwater through the construction of boreholes and hand-dug wells. The physicochemical groundwater quality, as captured by the Water Quality Index, classifies water across categories of excellent, good, and 'poor' for drinking purposes, depending on spatial and seasonal variation [5].

The groundwater potential of the basement complex has generally been considered low and sometimes highly underestimated. This is partly due to the fact that groundwater occurrence in this terrain has not been adequately investigated and assessed. Consequently, the potential of the weathered and fractured basement as an aquifer has not been fully tapped or harnessed for agricultural, industrial, and domestic purposes. Rapid industrialization increased the human population, and anthropogenic activities led to groundwater pollution [7].

Acknowledged [6] that the groundwater potential of a basement complex area is determined by a complex inter-relationship between the geology, post-emplacement tectonic history, weathering processes, and depth, nature of the weathered layer, groundwater flow pattern, recharge, and discharge processes. The occurrence of groundwater in recoverable quantities, as well as its circulation in the Precambrian Basement Complex, is controlled by geological factors [14]. Upheld that most often, the occurrence of groundwater in the Basement Complex terrain is localized and confined to weathered/fractured zones [12]. The Gusau area of Zamfara State, northwestern Nigeria, was investigated for the evaluation of groundwater potential. The study is geared towards evaluating the subsurface geologic and geoelectric properties that might contribute to the problems associated with groundwater development within the area. The quality of groundwater is influenced by various factors, including subsurface hydro-geochemical processes, soil characteristics, seasonal variations, natural and anthropogenic activities, climate change, and groundwater recharge processes [17]

2. METHODOLOGY

2. 1. Materials

The following materials were acquired and used in the course of carrying out the present study. These include:

- 1) Field Materials: Global Positioning System (GPS), compass-clinometers, geological hammer, masking tape, measuring tape, marker, field notebook, sample bags, field boots, dip meter, and combined meter Mi 806 (4 in 1) for sampling and measurement of groundwater parameters, plastic sampling bottles, etc.
- 2) Maps: Topographic map of the study area and political map of Zamfara State.
- 3) Computer Software: Surfer 12, Global Mapper 15, Rockworks 15, Aquachem, ArcGIS 9.3, Expert Choice 10.0, etc.
- 4) Satellite imagery: Digital Elevation Model (DEM), etc.

2. 2. Research Methodology

The methodology employed for this present research was undertaken using the following procedures:

- 1) Literature review during which both published and unpublished materials relevant to the present research and the study area were collected and studied. These include textbooks, dissertations, theses, journals, bulletins, conference proceedings, and existing maps of the study area for updating. Existing borehole data were also studied for functional and abortive boreholes.
- 2) Acquisition and interpretation of satellite imagery using different remote sensing techniques. Satellite imagery, such as Digital Elevation Model (DEM) etc were used.
- 3) Field work involves the collection of water samples from boreholes and hand-dug wells within the study area, and also geological mapping of the area to identify the different lithologic units. A geophysical survey was carried out in places where such reports are not available. Laboratory analysis for both water samples obtained and thin section preparation from selected rock types of the study area.

2. 3. Geological Mapping of the Study Area

A topographical map on a scale of 1:50,000 covering the study area was obtained from the Federal Survey Office in Kaduna. This map was used as a base map for this study. A reconnaissance survey of the study area was conducted, which allowed the researcher to familiarize themselves with the terrain and also establish a traverse grid aimed at identifying the existing rock exposure and its distribution.

A more detailed field mapping using the Global Positioning System (GPS) was carried out for about two weeks. A compass clinometer was used to measure trends and dips of lithological and structural features on outcrops. All observations made at different locations were recorded in a field notebook. Representative rock samples for petrographic studies were collected from outcrops with sledge hammer. A digital camera, which allows photographs of important structures and rocks to be taken, was also used.

2. 4. Hydrogeological Mapping of the Study Area

The depth to static water level (SWL), otherwise known as the depth to water level of 28 hand-dug wells were measured using a measuring tape. These measurements were done in two phases, namely, measurement during the peak of the dry season in May 2015, while the second phase was undertaken at the end of the rainy season in November 2015.

Measurements were made during the day so that it would be more convenient to observe when the tape makes contact with the surface of water in the well. The depth of the static water

level was calculated by noting the length of the tape from the surface of the water to the ground level as soon as the tip of the tape made contact with water in the well. It is noteworthy that precaution was taken in ensuring that measurements of static water level were made with particular reference to the ground surface and not the cover of the wells. This procedure was repeated for all the water sampling locations for both the peaks of the dry season and the end of the rainy season.

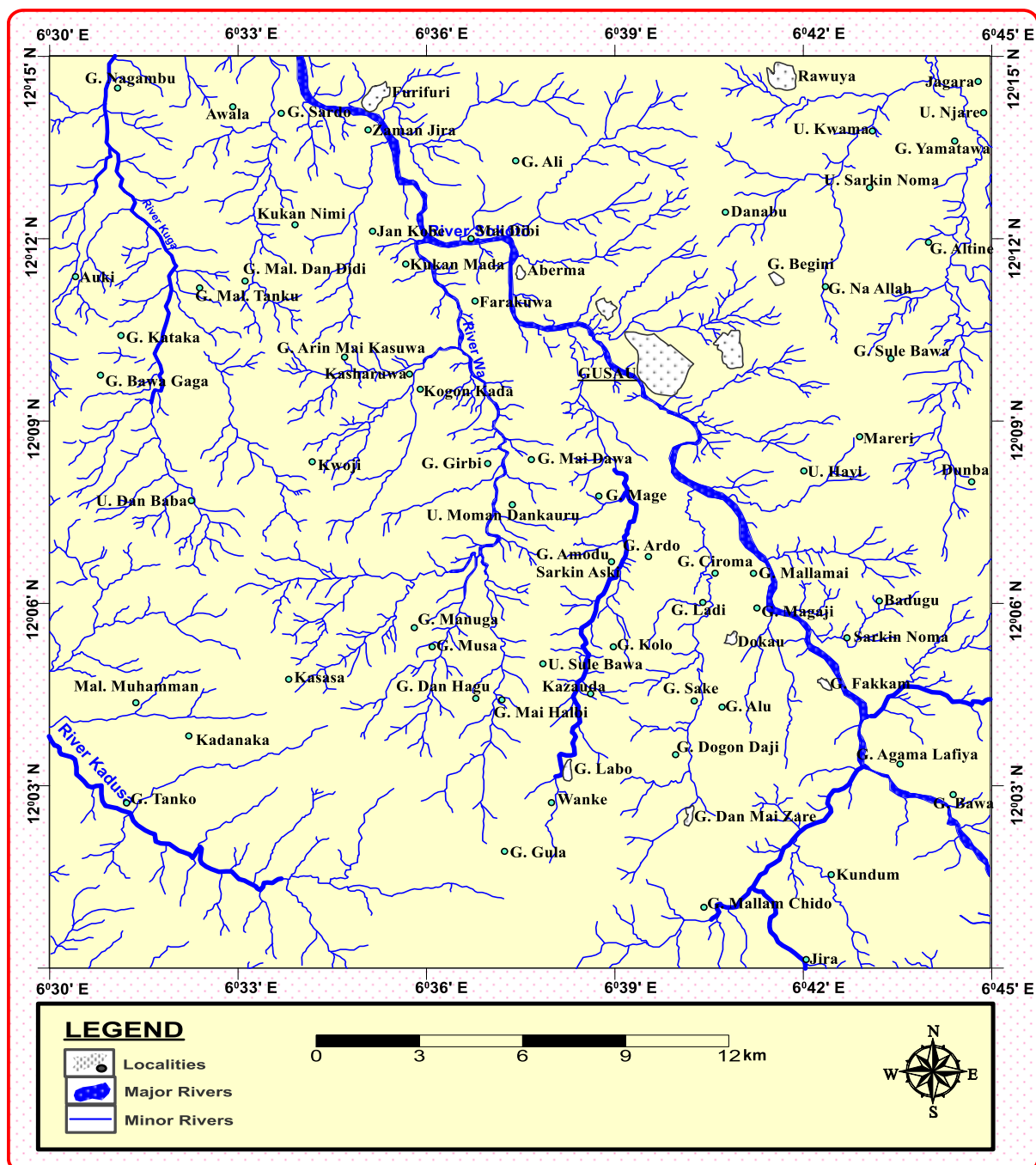


Figure 1. Drainage Map of the Study Area.

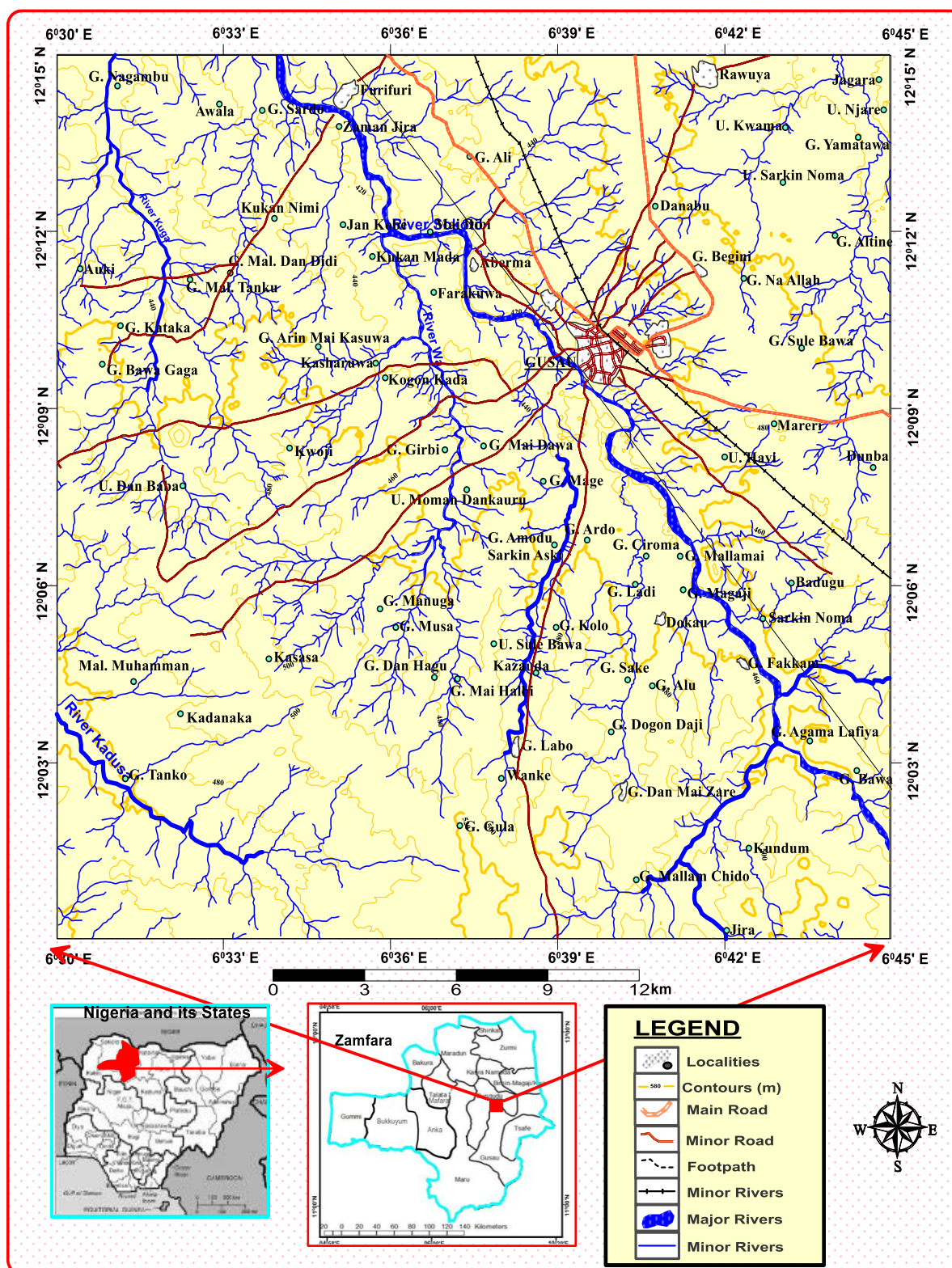


Figure 2. Measurement of static water level at Yar Dantse village.
Location: (12° 09' 16.0" N 06° 40' 25.0" E).

2. 5. Geophysical Investigations

Eight (8) VES soundings data were obtained from Nayaya Water Engineering Company Ltd, Gusau, for interpretation and analysis. The values of resistivity, depth, and thickness of each layer are presented (Table 1).

2. 6. Pumping Test Analysis

The successful completion of borehole drilling is usually followed by a pumping test programme to determine the borehole yield, drawdown, and the optimum extraction rate. This is another way of ascertaining the performance or otherwise of an aquifer under field conditions. The primary aim pumping test is to obtain field data that permit the study of the time-drawdown relationship during the period of pumping and during the period of recovery after pumping is stopped. The test usually allows the determination of two quantities, yield and drawdown. Arrangements for a proper pump testing programme usually permit the following controls and measurements:

- 1) Constant pumping rate, even though the pumping level may vary during the pumping period.
- 2) Accurate measurement of drawdown in the pumped borehole.
- 3) Accurate record of the time each measurement is taken as pumping proceeds.
- 4) Accurate measurement of water level and recovery in each borehole with time after stopping the pump.

The non-equilibrium or Theis's equation permits determination of the aquifer constants (S and T). The equation is widely used in practice and is preferable to the equilibrium equation because:

- 1) A value of S can be determined,
- 2) Only one observation well is required,
- 3) A shorter period of pumping is necessary, and
- 4) No assumption of steady state is required.

However, as a derivative of Theis non equilibrium equation, in 1950, Jacob introduced a simplified equation for one observation well for small values of u (i.e., for small r and/or large t), less than 0.01, so that from the drawdown time graph plotted on a semi-logarithmic paper, we have:

$$\text{Drawdown } s = \log 2.25Tt/r^2S \dots s = \frac{2.3 Q}{4\pi T} \log 2.25Tt/r^2S \dots \dots \dots (1)$$

This is the equation of a straight line whose slope is equal to $\frac{2.3 Q}{4\pi T}$ and is found as the vertical projection of the intercept of the straight line between two numbers on the time scale that have logarithmic units apart, say 1000 and 100. T may be found from the slope, and S may be found from equation (1) for pump testing above.

When, however, one observation well is used, $\log 2.25Tt/r^2S$ in equation (1) above is equal to 1. Hence, the equation becomes;

$$\text{Drawdown } s = \frac{2.3 Q}{4\pi T} \dots \dots \dots (2)$$

Q is known from the pumping test,
s is found from the slope,
Hence, transmissivity T can be calculated by substitution in equation (2).

2. 7. Physico-Chemical Analysis

Thirty-eight (38) samples obtained from nineteen (19) different wells were collected during the exercise. Plastic sampling bottles were used for the collection of water samples before conveying them to the laboratory for analysis. The bottle was rinsed with the water to be sampled at each sampling point before water was collected.

Two (2) water samples from each of these wells were obtained, with one acidified and the other not-acidified, carefully collected, labeled, packaged, and transported to the laboratory for analysis. The acidified water samples were used for the analysis of cations, while the non-acidified water samples were used for anions.

A few drops of concentrated nitric acid solution were added to the samples at the sampling points for the purpose of keeping the ions in solution and to minimize reaction with the wall of the container. During sample collection, physical parameters such as electrical conductivity, pH, temperature, and total dissolved solids were obtained using a four-in-one meter (Mi 806 combined meter).

The heavy metals such as cadmium, chromium, lead etc and some cations such as calcium and magnesium were analyzed at the Multi-User Research Laboratory, Chemistry department, ABU Zaria, using Atomic Absorption Spectrophotometer, while the anions (Cl^- , NO_3^- , HCO_3^- etc) were analysed at the Public Health Engineering Laboratory, Department of Water Resources and Environmental Engineering, A. B. U., Zaria. Similarly, the analysis for potassium (K) and sodium (Na) was carried out at the Department of Soil Science, Faculty of Agriculture, A. B. U., Zaria.

2. 8. Lineament Mapping

Lineaments are manifestations of linear features that can be identified directly on the rock units or from remote sensing area data. The Lineament map was prepared using automatic line extraction from a shaded relief image using PCI Geomatica 10.0. However, prior to automatic lineament extraction, shaded relief images were prepared using ERDAS Imagine 9.2 software. Successive shaded relief images were created by varying the azimuth of the Digital Elevation Model (DEM) from 0° to 45° , 90° , 135° , 180° , 225° , 270° and 315° .

Structural lineaments were extracted from ASTER DEM. Manipulation was done in three GIS environments. Erdas Imagine 9.2 GIS Environment was used to generate the shaded relief; PCI Geomatics 10.0 GIS Environment was used for automatic generation of lineaments. Lastly, ArcMap 9.3 software GIS Environment was used to determine the coincidence between the two extracted lineaments, and these points formed the lineaments that were digitized and used for the lineament density thematic map.

3. RESULTS

3. 1. Geology of The Study Area

The major lithologic units in the study area comprise migmatite, gneiss (banded gneiss), metasediments (mica schists and phyllites), quartzites, and granites (medium-grained biotite

granite and medium-coarse-grained biotite and biotite hornblende granite). The minor rock types are pegmatites, quartz veins, and quartzofeldspathic intrusions, as shown on the geological map (Fig. 4). Structurally, both ductile (foliations and folds) and brittle structures (joints and faults) were mapped in the study area.

3. 2. Migmatite

The migmatite (M) constitutes about 35 % of the rock types in the study area, occupying most of the central part. These are high-grade metamorphic rocks with light coloured minerals (leucosome) and the dark coloured minerals (melanosome or palaeosome). There were lots of pegmatites on the outcrop, indicating high mineralization potential of the area, especially the presence of metallic minerals such as tantalite, as well as other minerals suspected to be gemstones.

Muscovite, quartz, and plagioclase feldspar are the major minerals that form the matrix in this rock, while distinctively abundant, heterogeneous, and cloudy orthoclase with very large grain size stands out in the ground mass. The plagioclase feldspars are well-formed, rectangular, with well-defined albite twinning.



Figure 3. Photograph showing a fold in migmatite.
Location: (12° 06' 40.0" N and 06° 38' 22.2" E).

In PPL view, biotite crystals have moderate relief, perfect cleavage, anhedral in shape, and are pleiochroic. The rock contains very abundant brown elongations of biotite mineral spread all over, having a well-preferred orientation.

In XPL view, the biotite has a moderate birefringence and an interference colour of dark brown with patches of dark purple.

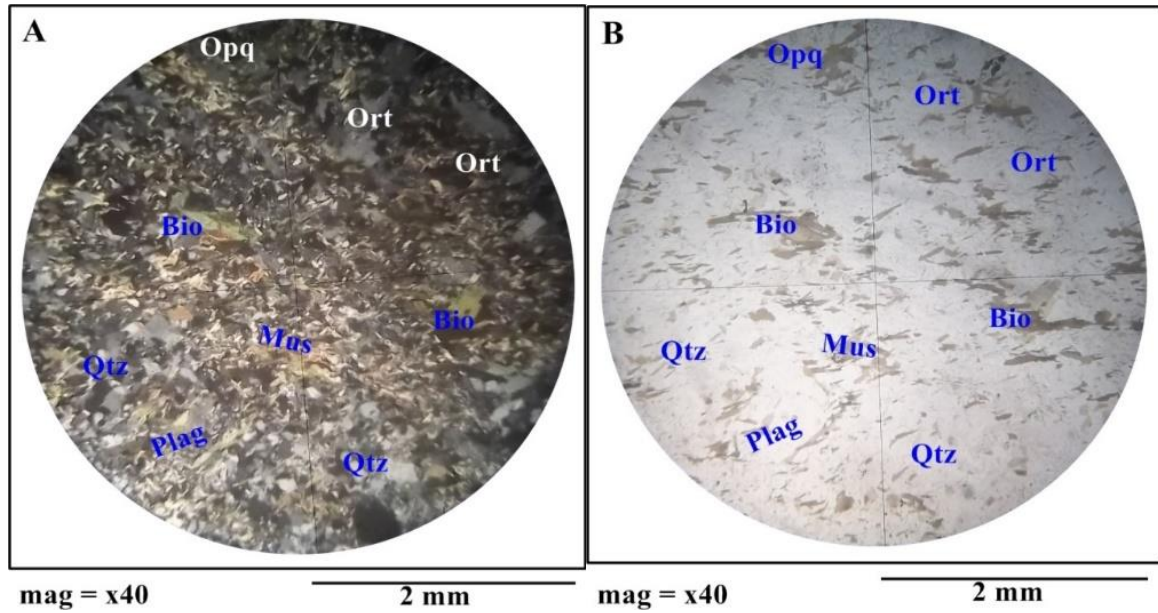


Figure 4. Photomicrograph of migmatite (A) view in XPL (B) view in PPL. Bio = biotite, Opq = opaque mineral, Qtz = quartz, Plg = plagioclase, Mus = muscovite, Ort = orthoclase

3. 2. 1. Banded gneiss



Figure 5. Photograph of Banded Gneiss (BGn) with alternating light and dark coloured bands. Location: (12° 14' 24.0" N and 06° 36' 47.0").

Banded gneiss (BGn) constitutes about 8% and occurs in the upper northwestern part of the study area around Furfuri town. Other occurrences include Gidan Ali, Gidan Sardo, Zaman, and Awala. This rock type occurs mainly as a weathered low-lying unit. It is generally dark to grey (when fresh) and light brown when weathered.

Texturally, it is medium to coarse-grained. Underhand lens observation, the rock contains feldspar and quartz as the light-coloured minerals, and flakes of biotite dominate the dark ferromagnesian minerals. Both the light and dark coloured minerals are aligned and foliated.

In the hand specimen, the banded gneiss displays distinct banding of grey and white coloured minerals. The white bands are coarse-grained and very poor in mafic minerals, while the grey to dark brown bands contain mafic minerals, predominantly biotite.

In PPL, felsic bands composed mainly of quartz and plagioclase feldspars predominates, while mesocratic bands consist of foliated biotite. The quartz is colourless with low relief and anhedral. The plagioclase is also colourless but cloudy.

In XPL, microcline displays cross-hatch twinning. Muscovite is abundant in this rock and has moderate to high relief.

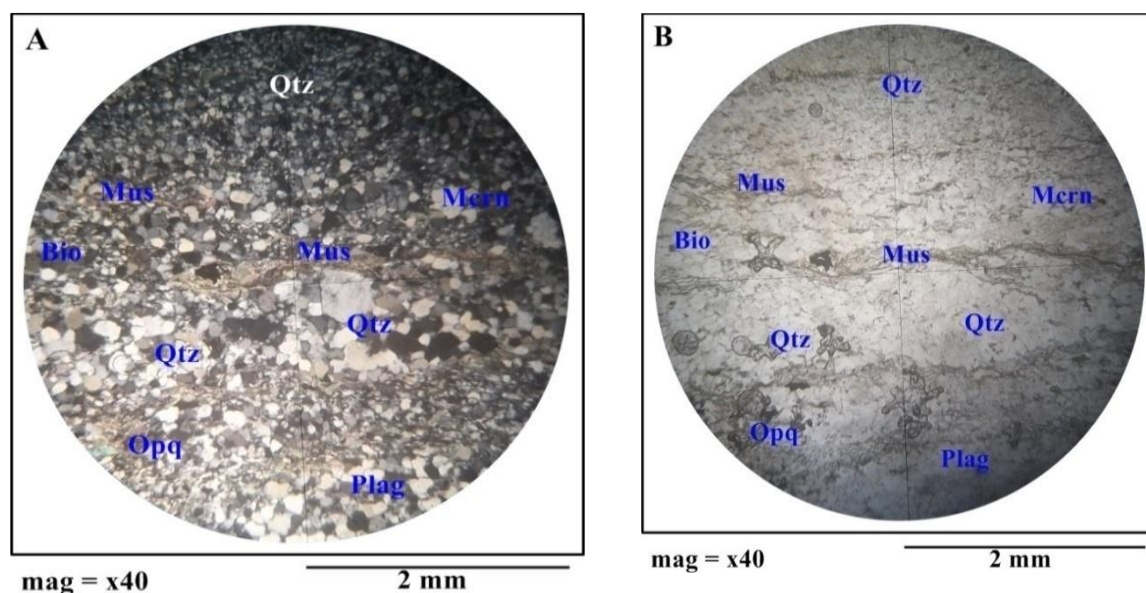


Figure 6. Photomicrograph of banded gneiss (A) view in XPL (B) view in PPL.
Mus = muscovite, Bio = biotite, Qtz = quartz, Plg = plagioclase, Micro = Microcline,
Opq = opaque mineral.

3. 2. 2. Quartzite

Quartzites occur very frequently in the area, often intercalated with the phyllites and schists. They occupy about 3% of the study area and are more resistant to weathering. They therefore stand out higher above the surrounding schists, forming some relatively low ridges. In thin section, they consist mainly of quartz, 90-95%, and accessory minerals <5%. Also, the thin-section view of this rock shows tight packing and recrystallization of quartz grains characteristic of quartzite. The brownish and purple colour of the quartz crystals in Cross-

Polarized Light is a result of its thickness on the thin-section slide, which is a little greater than normal.

Quartzes are fine to medium-grained, subhedral in shape, and occur as phenocrysts. These crystals are colourless with low relief and undergo wavy extinction.



Figure 7. Photograph of large boulders of Quartzite (Qs) within weathered schist. Location: (12° 06' 00" N and 06° 33' 14.5" E).

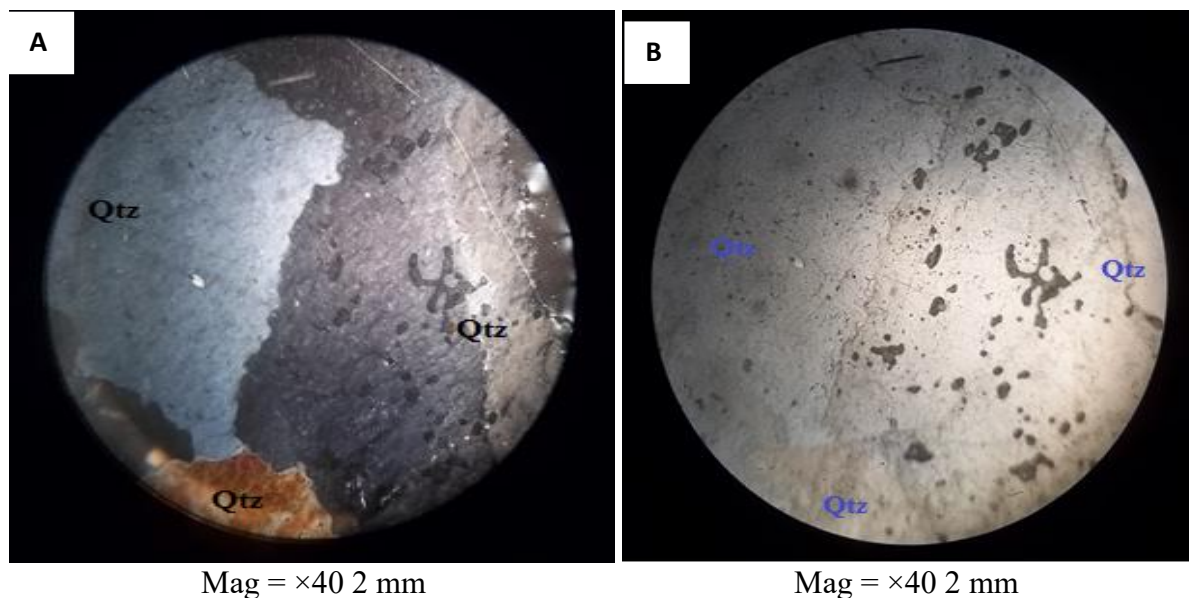


Figure 8. Photomicrograph of Quartzite (A) view in XPL (B) view in PPL. Qtz = quartz.

3. 2. 3. Mica Schist

The mica schist occurs as low-lying outcrops, road cuts, and riverbank exposures. It constitutes about 16% of the rocks in the study area. It predominates the southeastern part of the study area around Gidan Mal Chindo, Gidan Dan Maizare, Wanke, Ungwar Sule Bawa, Dokau, and Gidan Ardo. It has inferred boundaries with migmatite on the western part and with medium-grained biotite granite and phyllitic schist on the eastern and northern parts, respectively. In hand specimen, the mica schist is generally fine-grained with mineral lineation of ductile white mica (muscovite).

In PPL, Muscovite flakes are foliated and separated by light- brown coloured materials, which are mostly in millimeter-centimeter sized quartz crystals. The quartz is colourless with low relief. Also, some muscovites have perfect basal cleavage.

In XPL, Muscovite has a blue polarizing colour

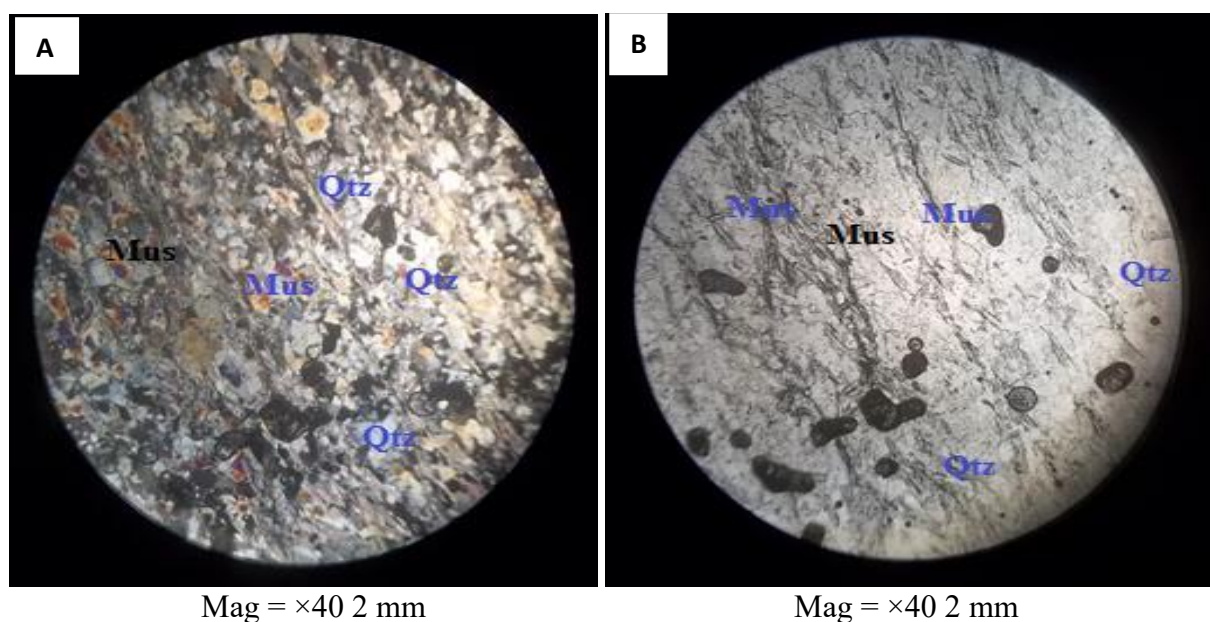


Figure 9. Photomicrograph of Mica Schist (A) view in XPL (B) view in PPL.
Mus = muscovite, Qtz = quartz, Plag = plagioclase.

3. 2. 4. Pelitic schist/Phyllite

Pelitic schist or phyllites occur as an exposure close to a mini earth dam along Gusau-Dansadau road (river Sokoto) within Gusau metropolis. It constitutes about 4% and covers eastcentral part of the study area. The rock is fine-grained, brownish to light grayish in colour. Some of these phyllites are found as silicified rocks, highly indurated and tough. Hence, informal miners are seen quarrying the rock for construction purposes.

In hand specimen, the phyllites appear flattened with tiny platy minerals aligned in the same direction, giving the rock a cleavage. It readily splits into thin sheets along the cleavage. The rock is highly foliated due to the presence of mica minerals and comprises predominantly of muscovite (65%), quartz (25%), with other accessory minerals.

In PPL, equigranular colourless quartz with low relief and weak birefringence was observed. It also shows wavy phyllitic texture, moderate relief, and strong pleochroism from light to dark brown.

In XPL, it displays straight extinction parallel to the cleavage planes. Mineralogically, the phyllite is composed mainly of mica (muscovite), quartz, and chlorite are muscovite and quartz while the minor ones are the opaque minerals. There is an enormous amount of these white micas (muscovite), constituting about 65% of this rock. It has an interference colour ranging from green to pink; a perfect cleavage and a high birefringence. Quartz in this rock is anhedral in shape, fine to medium-grained, and occurs as phenocrysts. These crystals are colourless and have a low relief.

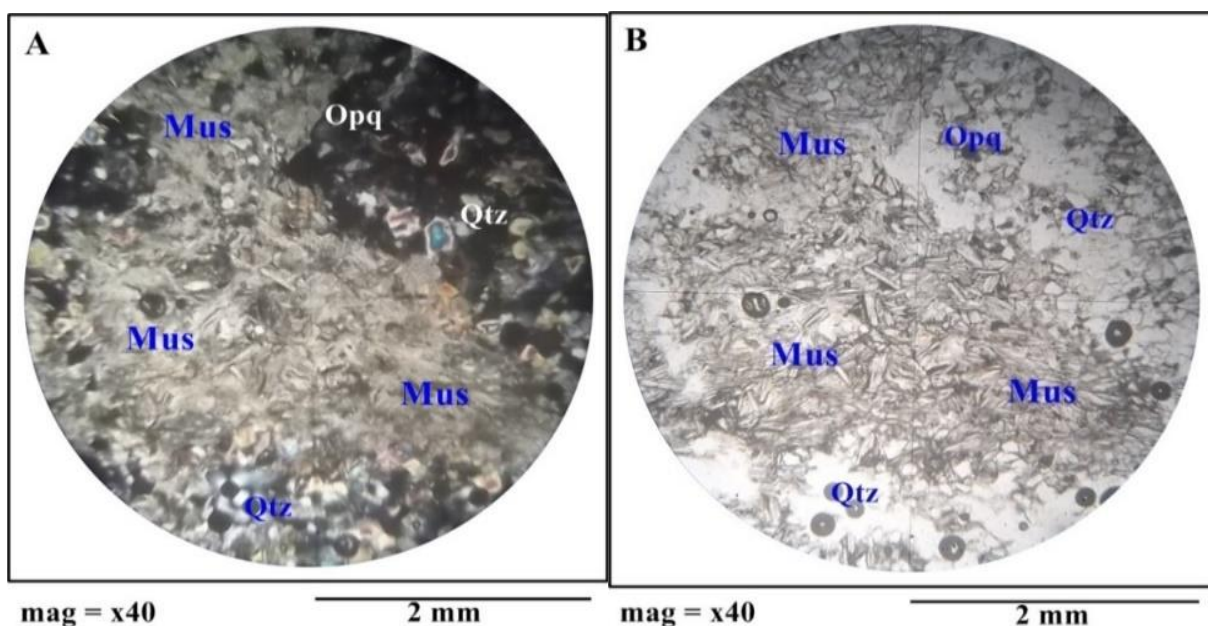


Figure 10. Photomicrographs of pelitic schist/Phyllite. (A) View in XPL. (B) View in PPL. Qtz = quartz, Mus = muscovite, Bio = biotite, Opq = opaque mineral.

3. 2. 5. Medium-grained biotite granite

Outcrops of medium-grained biotite granite (OGm) were observed on the northeastern (around Mareri and Rawayya) and northwestern part of the study area (around Auki town). This rock type constitutes about 30 % of the different lithologies in the area. The contacts with metasediments are largely inferred as they are covered by secondary alluvium and laterites. They are mainly low-lying with aplite vein of varying lengths and widths showing evidence of displacement as well as quartzofeldspathic veins.



Figure 11. Informal quarry activity on medium-grained biotite granite at Sarkin Pawa. Quarry site, Mareri, Gusau metropolis. Location: ($12^{\circ} 08' 49.1''$ N and $06^{\circ} 42' 37.6''$ E).

3. 2. 6. Medium to coarse-grained biotite and biotite hornblende granite

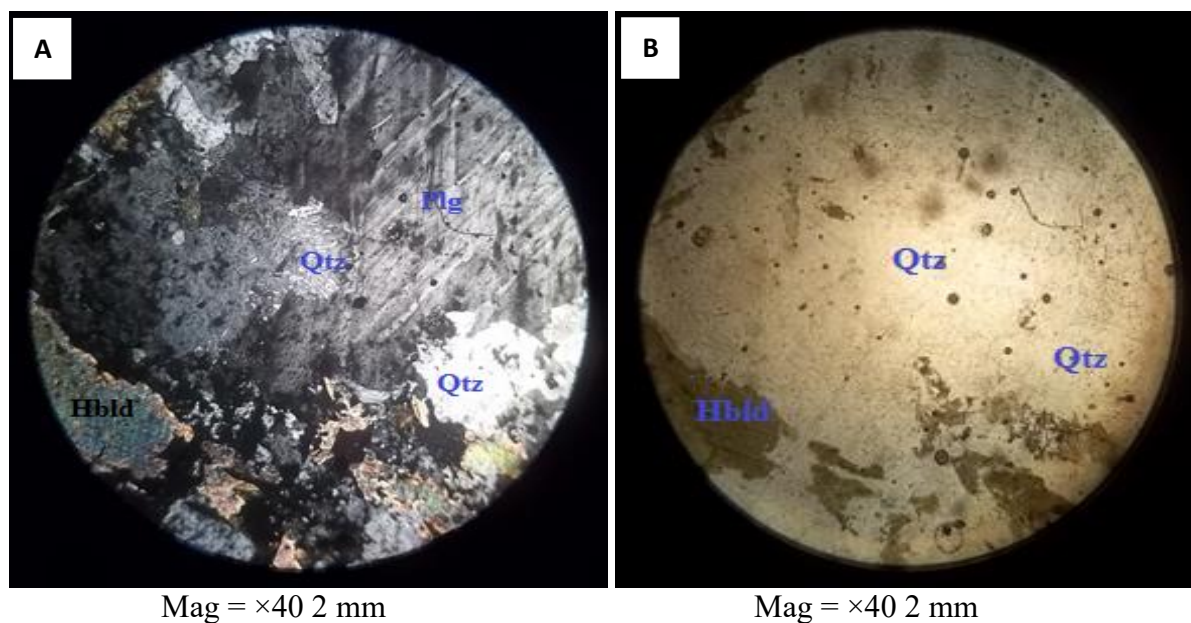


Figure 12. Photomicrograph of medium to coarse-grained biotite and biotite hornblende granite. Hbld = hornblende, Qtz = quartz, Plg = plagioclase, Bt = biotite.

Outcrops of medium to coarse-grained biotite and biotite hornblende granite (OGmc) were observed on the north-central (around Gidan Abarma) part of the study area. This rock type constitutes about 3 % of the different lithologies in the area. The rock type forms a boundary with banded gneiss on the western part, as well as migmatite. In the hand specimen, the rock is composed of feldspars and quartz, but also contains small amounts of hornblende and mica.

The Specks of mica (biotite) are visible with the aid of a hand lens. Hornblende, the calcium-rich amphibole, which generally ranges in colour from a pure green to greenish black, usually develops as short, thick prismatic crystals. In thin section, myrmekitic intergrowth texture (i.e radial growth of quartz in orthoclase feldspar) was observed. Hornblende shows high relief and is greenish under cross-polarized light.

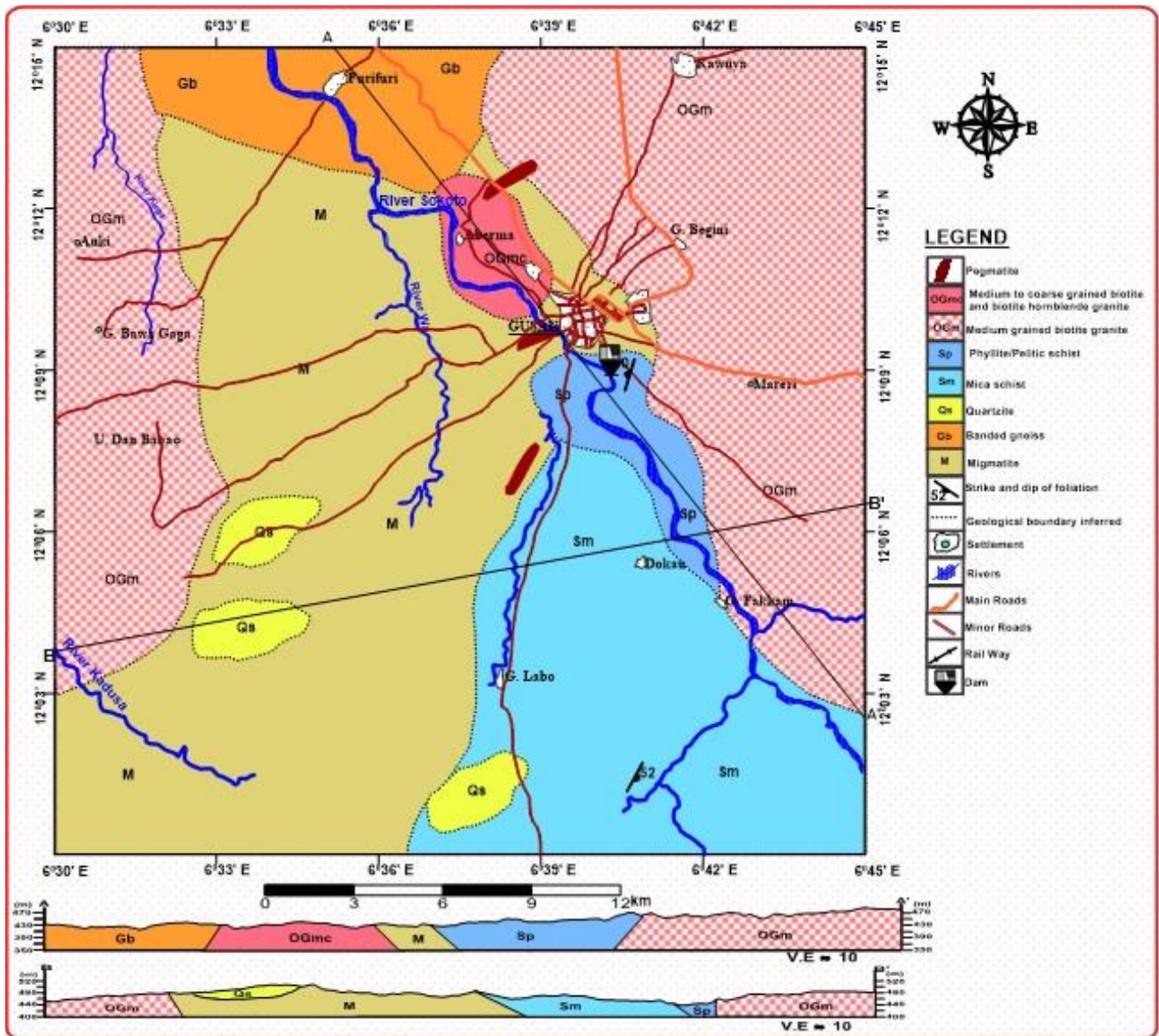


Figure 13. Geological map and two cross-sections of the study area.

3. 3. Minor Lithologies

The minor lithologies constitute about 4% of the rocks in the study area. These include pegmatites, quartz veins, quartzofeldspathic intrusions, as well as numerous micro veins. Most pegmatites are composed of quartz, feldspars, and mica, having a similar basic composition to granite. The crystal size is the most striking feature of pegmatites, with crystals usually over 5 cm in size and occurring mainly in migmatites around an existing quarry, along Wanke road, and also in the metasediments, while the leucocratic aplite dyke is mostly observed on medium-grained biotite granite at the S. Pawa quarry site, Mareri, Gusau.

3. 3. 1. Pegmatites

In the study area, the pegmatites occur as intrusions of discrete dykes into the migmatites, metasediments, Older Granite rocks, and rarely in the gneisses. They constitute about 1% of the rock types and vary in size up to 1m wide and extend several kilometers in length. They consist of quartz, feldspars, muscovite, biotite, tourmaline, and rare metals believed to have been injected into older rocks following zones of weakness.



Figure 14. Photograph of Pegmatite (P) within migmatite. Note the foliation trend in the migmatite parallel to the vein. Location: (12° 06' 40.0" N and 06° 38' 22.2" E).

3. 3. 2. Aplite

An aplite is an intrusive igneous rock in which the mineral composition is the same as granite, but in which the grains are much finer. Quartz and feldspar (alkali feldspar) are the dominant minerals. Dykes and veins of aplite are commonly observed traversing granitic bodies. In the study area, aplite dykes are found mostly in the medium-grained biotite granite forming a fault.

3. 4. Structures

3. 4. 1. Foliation

Foliation is defined as a texture (also structure) characterized by a parallelism of platy and acicular minerals in the rock. Foliation represents the most conspicuous structural feature in the migmatites, gneisses, and the metasediments (schist and phyllites) in the study area. In the gneisses, it is defined by parallel alignment of felsic and mafic minerals with a major trend along the NNE-SSW direction. Similarly, in the metasediments (mica schist and phyllite), it is defined by the alignment of platy minerals (muscovite and biotite) with quartz or eldspathic veining having a trend in the NE-SW direction (Fig. 15).

Generally, the dominant strike of the foliation is mostly NNE-SSW direction, with variation between NE-SW and very rare cases of NW-SE direction. The dominant strike of foliation in the Nigerian basement complex is in the N-S direction, with variation between NW-SE and NE-SW.

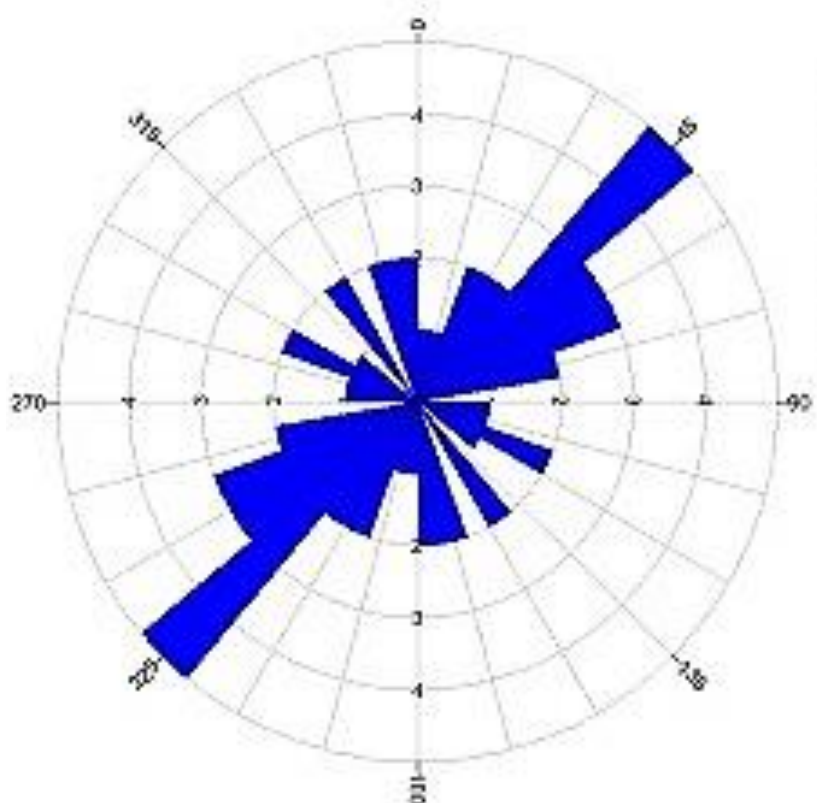


Figure 15. Rose diagram of foliation trends in metasediments (mica schist and phyllite).

3. 4. 2. Groundwater Configuration Maps

The elevation of water levels above sea level measured at the field was used to construct groundwater configuration maps for both the peak of the dry and wet seasons. Figures 16 and 17 show the peak of the dry and wet seasons' groundwater elevation maps, respectively, constructed using a combination of manual and software tools. They were done by placing the groundwater level elevation (difference between surface elevation and groundwater level measured from the hand-dug wells with reference to sea level) on the map of the study area.

This was followed by manual plotting of groundwater contour lines on the map. Directions of groundwater movement were drawn, usually from higher elevations to lower elevations and perpendicular to groundwater contours, thereby joining the second-order streams of the area on the map. The last stage was digitization and other necessary manipulations of the maps using global mapper software.

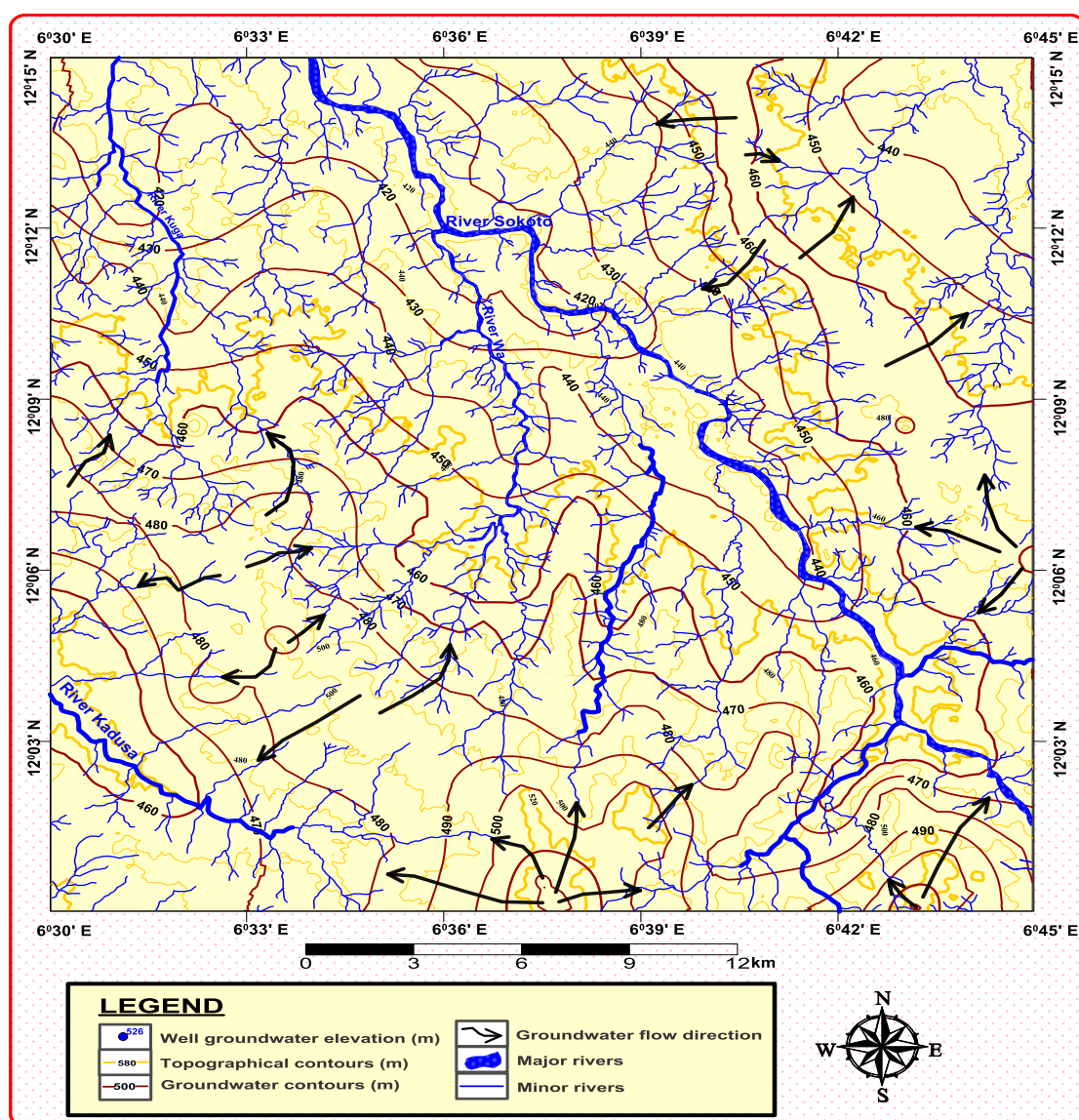


Figure 16. Groundwater Configuration Map at the peak of dry season (May, 2015).

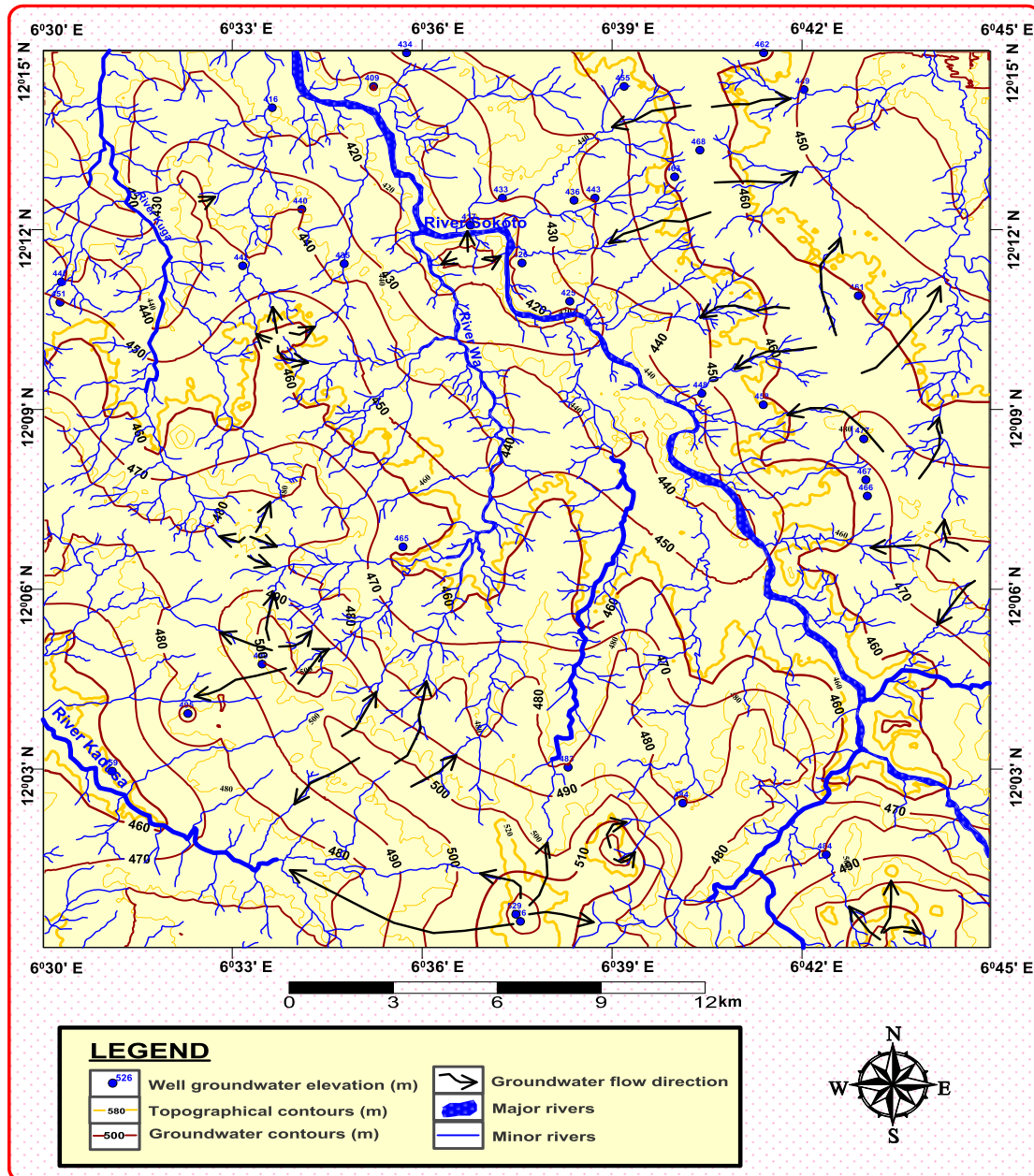


Figure 17. Groundwater Configuration Map at the end of the wet season (November, 2015).

The groundwater configuration map shows that during the dry and wet seasons, flows from the high groundwater elevation contours of 520 m around the ridge of quartzite within schist (Gidan Gula) at the extreme southern part of the study area to 420 m in the northwestern part (Kukan Nini).

The flow in the area is from areas of recharge to those of discharge. Along rivers or streams; the static water level is found to be shallow (i.e. within few meters from the surface) as observed in the northwestern and the central parts of the study area.

3. 5. Groundwater Hydrochemistry

Hydrochemical characteristics play an important role in groundwater quality [20]. The goal of evaluating groundwater quality is to determine if the resource meets the requirements for its many different uses. Correlation analysis between the different parameters showed that the basic ionic composition of the water samples is directly influenced by physicochemical parameters and anthropogenic activities [8]. Groundwater contained in crystalline igneous and metamorphic rocks is commonly soft and slightly acidic, with low concentration of total dissolved solids (TDS) and high concentration of dissolved silica [19]. Groundwater quality can be adversely affected or degraded as a result of human activities that introduce contaminants into the environment.

It can also be affected by natural processes that result in elevated concentrations of certain constituents in the groundwater.

For instance, despite that soil provides a protective “filter” or “barrier” that immobilized the downward migration of contaminants released on the land surface, elevated metal concentration can result when metals are leached into the groundwater from minerals present in the earth. Therefore, any water described as potable must comply with the Nigerian Industrial Standards as well as World Health Organization standards for domestic (drinking), industrial and agricultural purposes.

3. 6. Physical Parameters

3. 6. 1. Electrical Conductivity (EC)

Conductivity is a numerical expression of the ability of an aqueous solution to carry an electric current, or a measure of how well water can conduct an electrical current. It is an indirect measure of the presence of inorganic dissolved solids such as chloride, nitrate, sulphate, phosphate, sodium, magnesium, calcium, iron, and aluminum. This ability depends on the presence of ions, their total concentration, and mobility, and on the temperature of measurement. The term is reported in microhms per cm ($\mu\text{ohms/cm}$). In the SI units, the reciprocal of the ohm is the Siemens (S).

The electrical conductivity measured from the study area ranges from 150-1920 $\mu\text{S/cm}$, with an average value of 1310 $\mu\text{S/cm}$ (Table 1). The range falls within the maximum permissible limit of the Nigerian Standards for Drinking Water, except for three locations, L19 (Auki), L13 (Nakwanso), and L8 (Low cost), that have values above the maximum permissible limit. Conductivity can be used as an index of salinity hazard in the assessment of water quality for irrigation. When the conductivity is less than 250 $\mu\text{S/cm}$, the water is excellent for irrigation; when it is 250-750 $\mu\text{S/cm}$, the water is good for irrigation. Values ranging between 750-2250 $\mu\text{S/cm}$ make the water moderately good for irrigation. Many samples obtained from both hand-dug wells and boreholes fall within the category of excellent and good for irrigation.

3. 6. 2. Temperature (°C)

Temperature is one of the most important chemical parameters of water. It is significant because it affects the amount of dissolved oxygen in water. The amount of oxygen that will dissolve in water increases as the temperature decreases. Water at 0 °C will hold up to 14.6 mg of oxygen per litre, while at 30 °C it will hold only up to 7.6 mg of oxygen per litre.

Most of the boreholes and hand-dug wells sampled have in-situ temperature, which varies from 27.6 °C to 32.3 °C with an average of 30.35 °C (Table 12). However, two (2) boreholes at

L4 (Daza) and L7 (Madidi A) show a slightly high temperature due to their depth. Four other boreholes and two hand-dug wells also show relatively high temperatures. These include Furfuri road junction, Gidan dan Kado, Wanke, Abarma villages, as well as Gidan Dawa and Tudun Baila respectively.

3. 6. 3. Total Dissolved Solids (Mineralization)

The total dissolved solids include ionized and non-ionized matter, but only the former is reflected in the conductivity. Where TDS are high, the water may be "saline" and the applicable parameter is "Salinity".

Total dissolved solids (TDS) or mineralization is a measure of salinity that can have an important effect on the taste of drinking water. The palatability of water with a TDS level of less than 600 mg/l is generally considered to be good, while drinking water becomes significantly unpalatable at TDS levels greater than 1000 mg/l according to UNICEF.

The mineralization (TDS) of groundwater in the hand-dug wells and boreholes sampled from the study area ranges from 70 mg/l to 1080 mg/l with an average of 735 mg/l. Therefore, the water sampled within the study area is good for drinking, as it is within the maximum permissible limit. Relatively high mineralization was recorded from L13 (Nakwanso) and L19 (Auki) with values of 810 mg/l and 1080 mg/l, respectively.

Table 1. Physical parameters of water from boreholes and hand dug wells. Source: field data.

S/No	Location	Northing	Easting	pH	Temp (°C)	EC (μS/cm)	TDS (Mg/l)
1	Mareri	12.141806	6.716250001	6.69	29.6	700	390
2	Tsauni	12.181639	6.71483333	6.44	30.7	370	210
3	Rawayya	12.238972	6.7005	6.34	31.1	150	70
4	Daza	12.222111	6.67311111	5.97	32.2	260	140
5	G/Dawa	12.208167	6.63997222	6.7	31.8	560	320
6	Fufuri	12.249167	6.59588889	6.35	31.8	180	100
7	Madidi (A)	12.208806	6.62111111	6.04	32.3	270	150
8	Low Cost	12.249167	6.68988889	6.98	27.6	980	550
9	G/Kado	12.239833	6.65316667	6.35	30	890	500
10	Kolo Vill	12.208806	6.64547222	6.39	28.8	610	340
11	Wanke	12.0505	6.63841667	6.29	30	490	280
12	G/ M Zare	12.040528	6.66861111	6.35	29.8	370	200

13	Nakwanso	12.026222	6.70636111	6.28	29.2	1430	810
14	Iyar Dantse	12.154444	6.67361111	6.05	30.1	240	140
15	Abarma	12.190722	6.+62627778	6.09	31.2	380	210
16	T/ Baila	12.180083	6.63886111	5.96	31.1	350	190
17	Madidi (B)	12.201222	6.61269444	5.84	29.9	480	270
18	Kukan Nini	12.205667	6.56830556	6.43	31.8	280	150
19	Auki	12.179806	6.50466667	6.95	31.1	1920	1080

3. 7. Hydrochemical Parameters Cations

3. 7. 1. Sodium

Sodium salts (e.g., sodium chloride) are found in drinking water. Although concentrations of sodium in potable water are typically less than 20 mg/litre, they can greatly exceed this in some localities. Concentrations in excess of 200 mg/litre may give rise to unacceptable taste. The water analysis indicates a sodium concentration in groundwater of the study area with a value ranging from 21 mg/l to 166 mg/l, with an average of 116 mg/l. The samples have values which are far below those of the Drinking Water Standards as well as Nigerian Standards for Drinking Water, with recommended and maximum permissible limits of 150 mg/l and 200 mg/l respectively (Appendix I).

3. 7. 2. Potassium

Potassium can occur naturally in minerals and in soils. High levels in surface water, especially in areas where there are agricultural activities is indicative of the introduction of Potassium due to the application of fertilizers.

The concentration of Potassium in groundwater in the study area ranges from 0.6 mg/l to 4.7 mg/l with an average of 4.25 mg/l. Most of the samples analyzed are within the maximum permissible limit (15mg/l) with respect to the WHO standard, as shown in Appendix I.

3. 7. 3. Calcium

Calcium ion concentrations in the water sampled within the study area range from 3.6 mg/l to 159 mg/l, with an average of 76.74 mg/l. All the samples have values below the maximum permissible limits of 200 mg/l of both International Standards for Drinking Water and Nigerian Standards for Drinking Water.

Calcium is essential for human body development, especially for bones and teeth. Similarly, calcium-deficient children show rickets, which is a condition of undermineralized bone resulting in structural deformities of growing bones. In adults, this can result in osteoporosis with associated increases in fracture risk. It is noteworthy, therefore, that the main sources of this element are from the rock-water interaction of silicate minerals in granitic rocks.

3. 7. 4. Magnesium

Magnesium concentrations in both boreholes and hand-dug wells in the study area range from 0.98 mg/l to 15.72 mg/l with an average of 10.40 mg/l. These values fall far below the permissible limit of about 50 mg/l. It is an essential element needed for the stimulation of bone and teeth in the human body. The source of these ions in groundwater is mostly from the weathering of silicate minerals.

3. 7. 5. Anions Bicarbonate

Bicarbonate usually originates or has its sources from atmospheric carbon dioxide dissolved by rainwater and carbon dioxide present in the humus soil absorbed by water during percolation. The concentration of bicarbonate ranges from 8 mg/l to 348 mg/l with an average of 194 mg/l. All the water samples analyzed have bicarbonate concentration far below the recommended limit of WHO and the maximum permissible limit of WHO put at 500 mg/l and 200mg/l respectively. The major process governing groundwater chemistry is the dissolution of carbonate rock [15].

3. 7. 6. Sulphate

The source of sulphates in water is decaying organic matter through hydrogen sulphide. Sulphate is an indicator of organic pollution in water, especially in shallow aquifers and hand-dug wells. The concentration of sulphate in groundwater of the study area ranges from 0.00 mg/l to 22.33 mg/l with an average of 2.84 mg/l. Even the highest concentration at L18 (Kukan Nini), 22.33 mg/l, falls far below the recommended limits of 250 mg/l. Similarly, the recommended limit of 100 mg/l is reported for SON and NIS standards for drinking water.

3. 7. 7. Chloride

High concentrations of chloride give a salty taste to water. Taste thresholds for the chloride ion depend on the associated cation, and are in the range of 200–300 mg/litre for sodium, potassium, and calcium chloride. Concentrations in excess of 250 mg/litre indicate organic pollution of water and are increasingly likely to be detected by taste.

The concentration of chloride in groundwater of the area ranges from 0.47 mg/l to 330 mg/l, with an average of 159 mg/l. The concentration is far below the WHO 2011, as well as SON and NIS recommended limits of 250 mg/l, except for L18 (Kukan Nini), which has a concentration of 330 mg/l. This indicates that the water in this location is not suitable for drinking due to organic pollution. The other samples analysed indicated that the water in the area is suitable for drinking and other domestic uses.

4. DISCUSSIONS

4. 1. General Geology

The migmatite-gneiss complex is generally considered the basement complex. About half of the Nigerian Basement consists of the migmatite-gneiss complex. It is a heterogeneous assemblage including migmatized gneisses, banded gneisses, and a series of metamorphosed basic and ultrabasic rocks. The migmatite and banded gneiss, which are characteristic lithologies in the Migmatite-Gneiss Complex (MGC), grouped by [4], are the oldest rocks in

the area. Quartzites, which are a non-foliated metamorphic rock, also form part of the migmatite gneiss complex and are found in this area. The metasediments are divided into “Older Metasediments” and “Younger Metasediments” [11]. The “Ancient Metasediments” or Older Metasediments are high-grade metasedimentary remnants in the gneisses and migmatites and are believed to have been formed about 2,500 Ma. The mica schist mapped in this area belongs to this category of rock type, whereas the pelitic schist/pellite belongs to the younger metasediments. Next to the metasediments are the coarse-grained granites and the medium-grained granites. These Pan-African granitoids are referred to as the Older Granites in Nigeria to distinguish them from the Mesozoic anorogenic granite ring complexes (the Younger Granites).

The three commonly recognised phases of the Older Granite suite are

- a) Early phase, which comprises rocks of high colour index and relatively complex mineralogy. The phase comprises closely intermingled gabbroic, doleritic, and granitic rocks usually intruded by acid veins.
- b) The main phase includes the most dominant and extensive unit of the Older Granite suites. The rocks, predominantly medium-grained biotite-hornblende granite and porphyritic biotite granite, are readily distinguished from others by their characteristic large subhedral pinkish to reddish (occasionally whitish) alkali feldspar set in a medium to fine-grained groundmass of quartz, microcline, oligoclase, biotite, and hornblende.
- c) Late phase comprises homogeneous granite, as well as pegmatite and aplite dykes. Homogenous granites comprise fine to medium-grained biotite and biotite muscovite granites and granodiorite.

4. 2. Groundwater potential of the study area

Thematic layers influencing the availability of groundwater were used. These include: Drainage, Elevation, Geology, Slope, Lineament, and Lineament density, as well as Soil. Based on favorability, these layers were weighted and classified, which led to the production of a groundwater potential map of the study area.

4. 2. 1. Elevation

Use of elevation to determine favorable zones for groundwater is based on the fact that highlands are less favorable than lowlands. For highlands, the distance for percolation of groundwater to the subsurface is further. Elevated concentrations of certain physico-chemical parameters were linked to prolonged water–rock contact and mineral dissolution processes [2]. The use of elevation as a thematic layer was based on the premise that the lower the elevation, the higher the groundwater potential. This is based on the fact that highlands are less favorable than lowlands. Water tends to store at lower topography than at higher topography. Elevated concentrations of certain chemical constituents were identified as major contributors to groundwater quality deterioration [13].

4. 2. 2. Geology

Generally, the geology of an area determines the aquifer where groundwater is stored. Porosity and permeability of a formation determine its functionality and effectiveness as an aquifer. Rock weathering is the primary process regulating the chemistry of the groundwater [1]. The use of geology during this research work is therefore based on the fact that certain

lithologies are more permeable and porous than others. However, fracturing can greatly enhance the ability of crystalline rocks to serve as an aquifer.

For instance, migmatite, banded gneiss, medium-grained biotite granite, and medium to coarse-grained biotite and hornblende biotite granite were weighted as having a slightly lower normalized groundwater potential of 7 each. Similarly, mica schist, phyllite, and quartzite each got higher normalized weights of 22 compared with pegmatite, having moderate weights of 13.

4. 2. 3. Slope

Slope has been discovered to be one of the most important factors that influence the groundwater potential of the study area. Slope influences the rate of percolation of water into the subsurface. Gentle slopes allow more time for percolation of water into the subsurface thus are highly favorable. A steep slope gives less time for percolation of water into the subsurface, thus less favorable.

The influence of slope on the final groundwater potential map is evident as most of the areas with low groundwater potential are located on steep to very steep slopes, while areas with high groundwater potential are located on gentle to flat slopes.

4. 2. 4. Drainage

The use of drainage is based on the fact that areas close to streams are more favorable to groundwater accumulation than areas further away from the streams. This often gives an idea of the amount of infiltration taking place in an area. The drainage system of the study area is characterized by a dendritic drainage pattern resulting from the presence of relatively uniform surface materials, forming a branching tree-like arrangement in the area.

The influence of drainage on the groundwater potential map is evident as most of the areas with close drainage have high groundwater potential, while areas with low groundwater potential are characterised by near to far type of drainage.

4. 2. 5. Soil

Soils map for the study area was extracted from the Nigerian soil map. From the extracted soil map, two soil types were identified, namely the Leptosols and Luvisols. These soils play an important role in groundwater accumulation and in the preparation of the groundwater potential map. Highly porous soils are more favorable for groundwater than less porous soils. Leptosols are characterized by a strongly dissected topography and thus easily allow infiltration into groundwater aquifers. In the study area, the leptols are ranked as having the highest groundwater potential. Similarly, the luvisols are a soil with a pedogenetic clay differentiation between a topsoil with a lower and a subsoil with higher clay content.

Meanwhile, luvisols have higher clay content in the subsoil than in the topsoil. Their clay content reduces their ability to conduct water in order to recharge groundwater aquifers. Therefore, they have a lower groundwater potential.

4. 2. 6. Lineament and lineament density

Structural trends such as discontinuity can be detected in many forms, such as faults, joints, bedding planes, or foliation [12], and may be detected in the form of a lineament using remotely sensed data such as conventional aerial photographs and satellite imagery.

The commonest method used to calculate lineament density is based on the number of lineaments per unit area (number/km²), or the total length of lineaments per unit area (numbe/km²), or combining both.

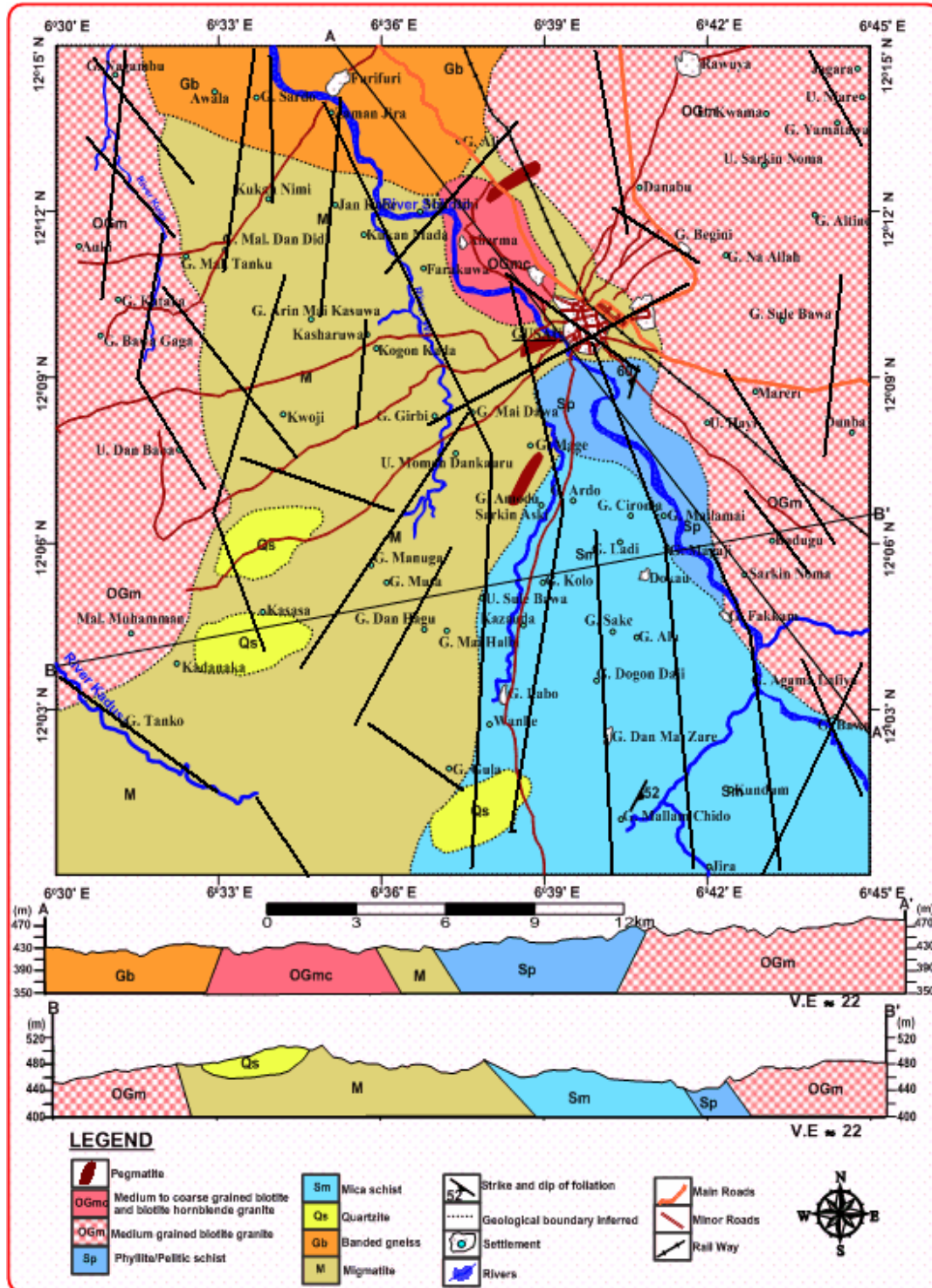


Figure 18. Lineament map of the study area superimposed on the geological map.

Lineaments serve as channels for the percolation of groundwater into the subsurface. Areas of high lineaments are more favorable for groundwater than areas of low lineament density. This is because crystalline rocks constitute 100% of the rock types of the study area, and most of the geologic linear features are assumed to be the zone of fractured rocks, and the position of porous and permeable rocks will greatly enhance well yields.

4. 3. Model Validation

4. 3. 1. Lithologic logs

The borehole at Furfuri (Fig. 18), whose litholog is readily available to serve for control in the interpretation of geoelectric sections (Fig. 4.16), is sited close to VES point 3. This profile was undertaken within the area of high groundwater potential on the crystalline geologic terrain. Four layers were delineated, namely: top soil/laterite, decomposed granite, fractured basement, and fresh basement.

This conforms with the results obtained from the geologic section across P2-P2, consisting of both weathered and fractured basement with a thickness ranging from 3.5 to 18.5 m and a fractured basement resistivity value of 224 ohms. There is, therefore, high groundwater potential in this area.

The profile along P3-P3 was run from low to high groundwater potential and covers areas around Ungwar Gwaza, within Gusau metropolis. Three to four geoelectric layers were also encountered in this zone, namely: top soil, weathered overburden, weathered basement, and the fresh basement.

The lithologic log obtained from the drilled borehole at Ungwar Gwaza revealed that the area has low to high groundwater potential. This conforms with the thin topsoil and weathered overburden, as well as the absence of fracture zones within the formation of the area. The resistivity of the top soil is 297 with a thickness ranging from 0.00 to 1.2, while that of the weathered overburden has a resistivity value of 161 with a thickness ranging from 1.2 to 12 m. Finally, the fresh basement has an infinite resistivity value higher than 600.

4. 3. 2. Groundwater Configuration Map

In areas of higher elevations, such as the southern part of the study area, the static water level is deeper. The depth to the water table is thick at the recharge area (watersheds) and thinner at the discharge areas (river or stream channels). Groundwater recharge is a function of rainfall, vegetation, relief, and characteristics of regolith, among others. Aquifers are usually recharged by infiltration directly from rainfall or by fractures directly connected to a major river or stream. The flow direction is generally from topographically higher areas towards lower-lying areas. It indicates flows that are parallel to the hydraulic gradient and perpendicular to the water table contours. The directions of groundwater flow are shown by arrows on the maps of water table configuration and directions of groundwater flow of the peaks of dry and wet seasons.

4. 4. Discussions of Geophysical Results

Vertical Electrical Sounding aims to determine the different geoelectric layers in the subsurface, the aquifer units and their characteristics, as well as the general hydrogeological condition. Three to five layered-type curves were obtained from the VES points in the study area. They have varying geologic characteristics, showing different degrees of weathering and other secondary porosity in the form of fracturing of the bedrock. Plots of calculated apparent

resistivity in ohm-m against electrode spacing with geologic sections showing resistivity and depth of the subsurface layer, which is presented in Appendix VI. These layers could be grouped as follows:

1st layer – Top soil

2nd layer – Weathered overburden

3rd layer – Weathered basement

4th layer – Fractured basement

5th layer – Fresh basement.

4. 4. 1. Topsoil

This is a surface dry layer of high resistivity that ranges from 183-ohm m to 1213-ohm m. It has a thickness that varies from 0.438 m to 4.09 m. The low resistivity end is diagnostic of sandy clay and clay, while a high resistivity end indicates laterite. However, a very high resistivity value could be an indurated material or a fresh basement.

4. 4. 2. Weathered overburden

The layer immediately below the top soil is the weathered overburden, which also overlies the weathered basement horizon. It is made up of lateritic cover formed as a result of the weathering of geological materials such as weathered granites. The resistivity value ranges from 29.7 to 161 Ωm with thickness varying from 1.62 to 12.3 m.

4. 4. 3. Weathered basement

This layer is thought to be highly decomposed crystalline rock. Rock weathering is the primary process regulating the chemistry of the groundwater [1]. The resistivity value ranges from 182ohm m to 413-ohm m. The thickness varies from 11.1 m to 20.3 m. The layer is highly decomposed by weathering to form sand and clayey sand, depending on the local variation of the mineralogy. However, this layer is believed to be the regolith. A saprolite aquifer is shown to occur at the base of the weathered zone [9].

4. 4. 4. Fractured basement

The resistivity value ranges from 46-ohm m to 224-ohm m. The thickness varies from 4 m to 15 m. In most places, fractured zones occur immediately beneath the weathered basement horizon. The fractured zones are sometimes difficult to detect using geophysics, unless they are of greater thickness. Where the fractured zone is saturated, a high groundwater yield can be obtained from a borehole penetrating such a formation. This is evident considering the high groundwater potential recorded close to VES 3 at Furfuri.

4. 4. 5. Fresh basement

This has a very high resistivity with infinite thickness. But where it is fractured and saturated, the resistivity reduces. It is not a source of groundwater unless fractured. However, when the shape of the VES curves approaches a very steep gradient, it may indicate a fresh basement rock without fractures.

Finally, the geophysical results show that, generally, the Gusau area has a low to high potential for groundwater development, especially in places underlain by granite because of its thick overburden and weathered basement as well as extensive fractures. The occurrence of groundwater in recoverable quantities as well as its circulation in the Precambrian Basement Complex is controlled by geological factors [14].

5. CONCLUSIONS

Demonstrated that physicochemical parameters such as pH, turbidity, and temperature varied among water sources, with some values exceeding recommended drinking-water standards. Field study has shown that the major lithologic units in the study area comprise migmatite, gneiss (banded gneiss), metasediments (mica schists and phyllites), and granites (medium-grained biotite granite and medium-coarse-grained biotite and biotite hornblende granite).

The minor rock types are quartzites, Pegmatites, quartz veins, aplite dykes, as well as quartzofeldspathic intrusions in some localities. Geological structures such as fractures, faults, joints, and foliations are common in the study area. The prominent structural trends of these structures are the N-S, NE/SW, and NW/SE. The trend of foliation in the metasediments (mica schist and phyllite) is in the NE-SW direction. Also, the trend of joint measurements in the granite indicates a NW-SE direction.

The rivers and streams are structurally controlled as observed in the rose diagram, with flow directions coinciding almost with the dominant lineaments, which indicates a predominantly NW-SE direction. These lineaments relate well to the fracture directions of the regional geologic structure in the basement complex [14].

Therefore, the zones of high lineament density have been confirmed to probably be feasible zones for groundwater accumulation based on the results obtained from the groundwater potential map produced. Subsequently, the importance of the weathered zone/fracture aquifers cannot be overemphasized couple with other techniques such as careful application of subsurface geophysics, in conveniently supporting good and productive borehole yields for different purposes.

Recommendation

- 1). It is recommended that a more detailed surface geophysical survey employing the resistivity techniques which entails both Constant Separation Traversing (CST) and Vertical Electrical Sounding (VES), is highly desirable. This is to enable researchers to effectively locate good aquifers with thick overburden and fractures in the basement terrain.
- 2). There is a need for water borehole drillers, including government organizations (Ministries, Departments, and Agencies) that are responsible for water development, to keep records of hydrogeological data such as raw pumping test data, results from physico-chemical analysis, as well as lithologic logs of drilled boreholes, which will assist researchers undertaking groundwater potential assessment of an area.

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