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Geophysical and Hydrogeological Assessment and Characterization of Limestone Aquifers for Sustainable Groundwater Resource Management: A Case Study in Gada L.G.A. Sokoto State, Nigeria

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Abstract

The aim of this study is to conduct a geophysical survey at Gidan Fako to determine the optimal borehole location, drilling depth, drilling method, and estimate the anticipated water yield. The survey employed the Half-Schlumberger array of electrical resistivity method and utilized the SSR resistivity meter for data collection. The collected data was interpreted using the IPI2WIN software, enabling a comprehensive analysis of the subsurface characteristics. The results of the lithological log analysis indicated the presence of limestone aquifers at various depths, including intervals of 25m, 70m, 130m, and 140m. Considering the moderate anticipated water yield, the MUD drilling method was selected as the most suitable technique for the drilling operation. The MUD drilling method offers advantages such as efficient removal of cuttings, improved stability of the borehole, and reduced risk of contamination. The outcomes of this study have significant implications for the local community, as the provision of a reliable water supply source is of utmost importance. Additionally, the study findings will serve as a valuable resource for future hydrogeological investigations in the region, aiding in the development of sustainable water management strategies. Based on the interpreted results, it is recommended to drill the borehole to a depth ranging from 150 to 160 meters to ensure optimal water extraction from the identified aquifer zones. The geophysical survey provides valuable insights for water resource planning, fostering sustainability and informed decision-making.

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1. Introduction

Water is one of the basic necessities of human life. Humans can live without food for 40 days but cannot survive without water for 3 days. Water is crucial for human life and development [1]. Water is an essential natural resource crucial for sustaining life on Earth [1], [2], second only to air. Underground water sources have been recognized as the largest available reservoirs of fresh water [3]. However, The issue of water scarcity in and around northern Nigeria has become increasingly challenging [4]. One contributing factor may be the relatively lower average annual rainfall in the region, which is typically lower compared to the rainforest regions with an average of about 3000 mm per year [5]. Consequently, the recharge of aquifers in the northern region is expected to be lower compared to the southern part of the country. Additionally, the presence of groundwater in an area can also be influenced by various factors such as geology [1], including lithology [1], rock type [1] and structural lineaments [1] as well as soil composition, vegetation cover, drainage patterns, elevation, topography, annual rainfall, slope, and other related factors [2]. These combined factors provide insights into the hydrogeological conditions of a specific area.

Groundwater, as highlighted in [6, 7, 8], is a highly dynamic and renewable natural resource that serves a variety of purposes, including drinking, agricultural, and industrial needs. In the Sokoto Basin, agriculture plays a significant role as a major occupation and the primary consumer of water, both through rain-fed farming and irrigation, particularly during the dry season. Given the unique characteristics of the area, many streams and rivers tend to dry up during this period, making it necessary to rely on groundwater sources to sustain irrigated agriculture. Consequently, the absence of reliable surface water suitable for consumption has led to a heavy reliance on accessible and dependable fresh groundwater sources [6.7.8].

Access to safe and reliable groundwater sources is crucial for communities, especially in arid and semi-arid regions with limited surface water resources. In Nigeria, groundwater accounts for approximately 60% of the country's drinking water supply [9]. However, the availability and quality of groundwater can vary significantly due to factors such as geology, climate, and human activities like agriculture and industry [10; 11]. Ensuring access to clean and safe drinking water is a fundamental human right and a basic necessity for survival. Unfortunately, many regions, including Nigeria, face significant challenges in providing safe drinking water. According to the United Nations (UN), over 2 billion people worldwide lack access to safe drinking water, and approximately 4 billion people experience severe water scarcity for at least one month each year. In Nigeria specifically, around 60 million people lack access to safe drinking water, leading to outbreaks of water-borne diseases like cholera and typhoid fever, which claim numerous lives annually. Improving access to safe drinking water is a critical priority to address these challenges and ensure the well-being of the population.

To address the issue of water scarcity, there is a need to explore alternative sources of water, including groundwater. Groundwater is a reliable and sustainable source of water that can provide a significant amount of water for domestic, agricultural, and industrial purposes. In Nigeria, groundwater resources have not been fully explored, and the available data on groundwater is often incomplete or outdated. The comprehensive exploration and understanding of groundwater resources in Nigeria is still an ongoing process, and there are areas where detailed hydrogeological investigations are yet to be conducted. As a result, the data on groundwater availability, quality, and sustainable yield may be limited or outdated in some regions. This lack of comprehensive data can pose challenges for effective water resource planning and management. It hinders the accurate assessment of groundwater potential, which is essential for identifying optimal drilling locations, estimating water yields, and implementing sustainable water supply projects. To address this issue, there is a need for continued efforts to improve data collection, monitoring, and research on groundwater resources in Nigeria to ensure better understanding and utilization of this vital water source.

Therefore, there is a need for comprehensive geophysical and hydrogeological investigations to determine the quantity, quality, and distribution of groundwater in various locations. Geophysical and hydrogeological investigations are commonly used to assess the potential for groundwater resources in a given area [12]. Geophysical methods such as electrical resistivity tomography (ERT) and vertical electrical sounding (VES) can provide information on the subsurface geology and the presence of aquifers, while hydrogeological techniques such as pumping tests can be used to estimate the yield and sustainability of groundwater sources [13].

This study focuses on the Gidan Fako Immigration Border Patrol in Gada, Gada L.G.A, Sokoto State, which is an area that has been identified as having limited access to safe drinking water [14]. To address the issue of water scarcity in the region, this study aims to conduct a geophysical and hydrogeological investigation of the groundwater resources at Gidan Fako Immigration Border Patrol Gada. The study seeks to identify potential groundwater sources, assess their quality, and determine the sustainable yield of the aquifers in the area. The findings of this study will provide valuable information that can guide the development of new groundwater sources to meet the water needs of the communities living in the area.

2. Materials and Methods

2.1 Location of the Study Area

The study area is located in Gada Local Government Area of Sokoto State, Nigeria. The specific location of the study area is Gidan Fako Immigration Border Patrol, which is situated at latitude 13°00'44.2" N and longitude 4°07'13.6" E (Figure 1).

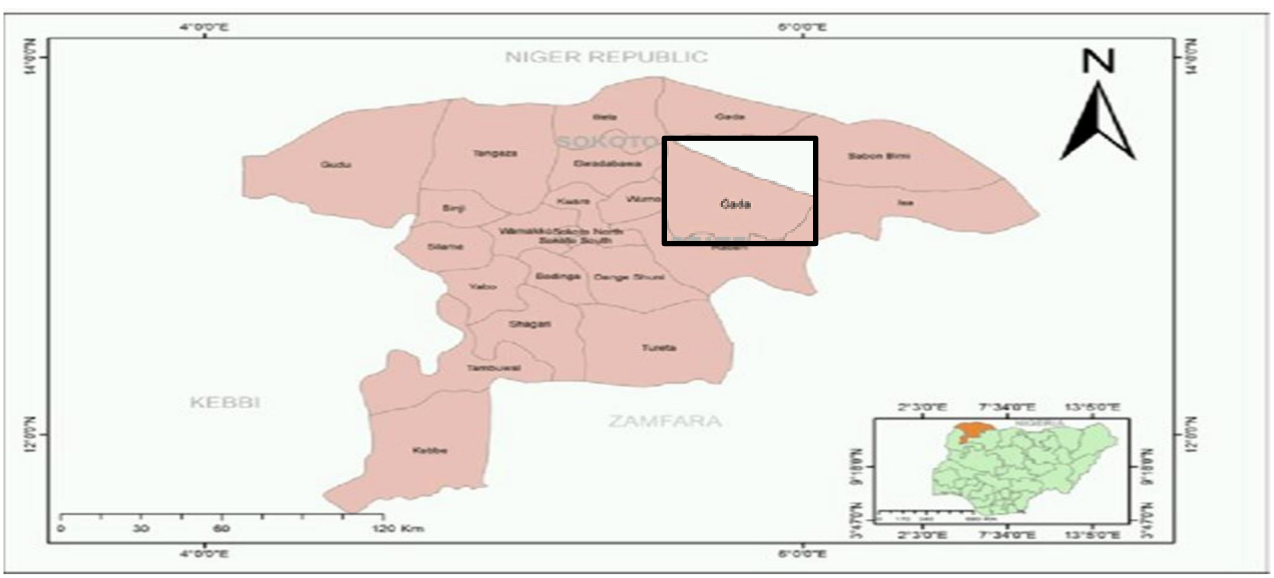

Figure 1: **Geographical location map of Sokoto State showing Gada Local Government Area. Inset shows a general map of Nigeria. Modified after [15]**

Gada is one of the 23 Local Government Area in Sokoto State, Nigeria. Its headquarters are in the town of Gada. It has eleven (11) Political wards namely: Gada, Kyadawa-Holai, Ilah-Dukamaje, Gilbadi, Kaffe, Tsitse, Kadadi, Kadassaka, Kaddi, Kiri and Kwarma respectively. Gada shares a border with the Republic of Niger to the north. It has an area of 1,315 km2 and a population of 248,267 at the 2006 census [15].
The study area is characterized by a semi-arid climate, with a mean annual rainfall of about 500 mm and a mean annual temperature of about 31°C. The study area is approximately 25 km southwest of the Sokoto metropolis and is bordered by the Republic of Niger to the north and Kebbi State to the west. It is located within the Sahel region of Nigeria (Figure 2), which is characterized by a semi-arid climate and low annual rainfall. The region is known for its extensive sand dunes, sand sheets, and occasional rocky outcrops. The Sudano-Sahelian region of Nigeria (Figure 2) extends from the northern limits of the country to the northern boundary of the Northern Guinea Savanna. It traverses Sokoto, Zamfara, Kano, Katsina, Jigawa, Yobe and Borno States. The Sudano-Sahelian region of Nigeria is dominated by the Sokoto Plains to the north-western areas and the Chad Plains to the north-eastern parts. The Sokoto Plains are flat rolling plains on sedimentary rocks with isolated low, flat-topped hill [16].
The area is mainly underlain by basement complex rocks, with occasional occurrence of sedimentary rocks. The topography of the area is undulating, with flat to gently sloping terrain.

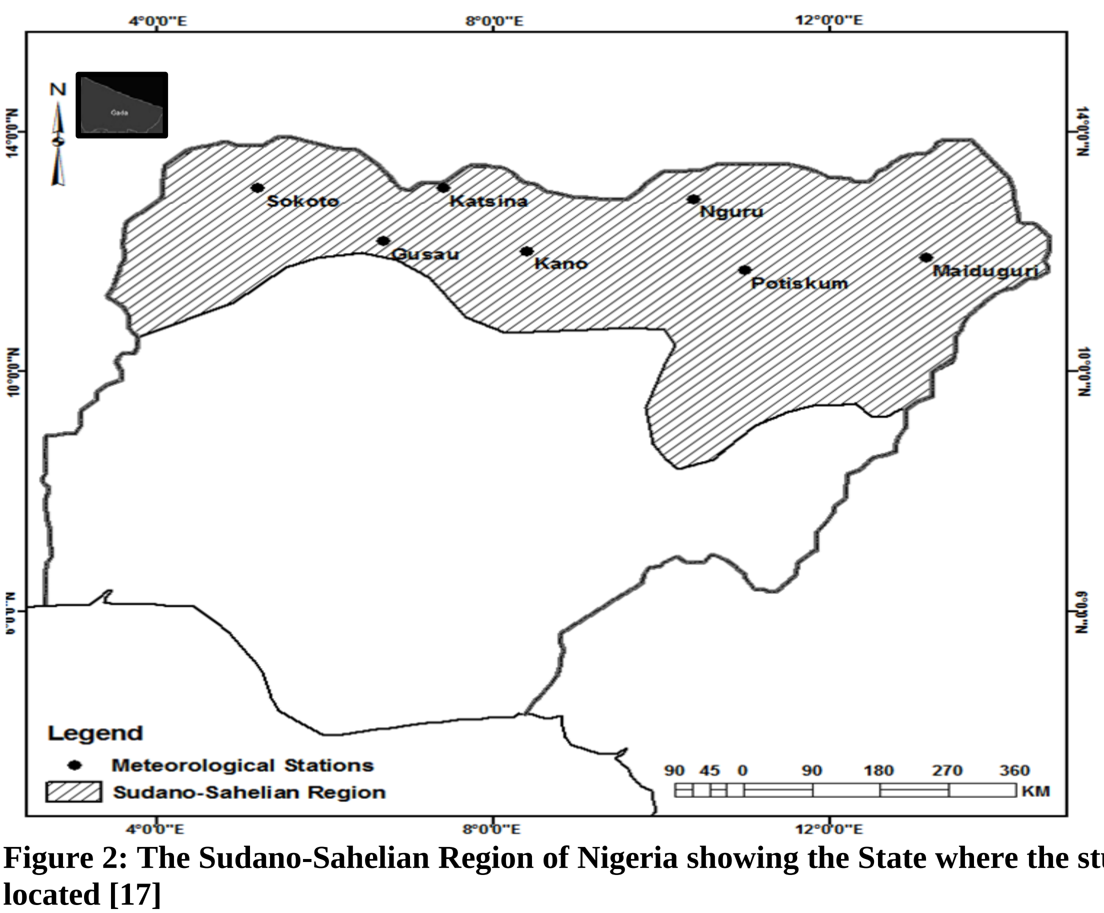

Figure 2: The Sudano-Sahelian Region of Nigeria showing the State where the study area is located [17]

Groundwater is the main source of water supply in the study area, with boreholes being the primary source of groundwater abstraction. However, the availability and accessibility of groundwater are limited due to the arid nature of the region and the occurrence of geological formations that are not favorable for groundwater storage and transmission.

2.2.Geology And Hydrogeology Of The Study Area

Sokoto State is situated within the Illumeden Basin, which is surrounded by the Precambrian basement complex to the east and south [18]. The state itself does not have outcrops of the basement complex but is covered by a series of sedimentary rocks that were deposited over the basement complex (Table 1). These sediments were formed under diverse environmental conditions, ranging from continental to marine events. The sedimentary rocks in Sokoto State can be classified into four major categories.

The first category is the Gundumi Formation, which is the oldest sedimentary rock in the state and directly overlies the basement complex. It primarily consists of sandstones and clays of continental origin. The sandstone portion of the formation is known to contain significant amounts of water and is currently being exploited through boreholes [19].

The second category is the Rima Group, which comprises three distinct marine sediments: the Taloka, Dukamaje, and Wumo Formations. The Taloka Formation is the oldest within the Rima Group and consists of multiple layers of sandstones and shales. The sandstone layers in this formation are known to be highly water-bearing [20]. The Dukamaje Formation, on the other hand, is predominantly shaly and non-aquiferous. The Wumo Formation is characterized by a single layer of sandstone.

The third category of sedimentary rocks in Sokoto State is referred to as the Sokoto Group, which has a marine origin. It consists of two main formations: the Dange and Kalambaina Formations. The Dange Formation primarily comprises clays and shales, while the overlying Kalambaina Formation is composed of limestones. Both formations have aquiferous properties and contribute to groundwater resources in the region [18].

The fourth category of sedimentary rocks in the state is the Gwandu Formation, which is found in the northwestern and southern parts of Sokoto State. This formation is characterized by clays and sandstones and has a high potential for groundwater storage and extraction [19]. Underlying the sedimentary rocks, the basement complex extends to a depth of 500 meters in Sokoto State. It consists of ancient granites, gneisses, migmatites, schists, and other metavolcanic rocks, which are crystalline and impermeable.

The relief of Sokoto State is predominantly low-lying, with an average elevation of 300 meters above sea level known as the Sokoto Plains. [21] Characterized the relief as a monotony of lowland interrupted by isolated flat-topped hills (mesas) and escarpments. The prominent escarpments are found in Dange and Kalambaina, rising up to 488 meters along with the hills. The state is also rich in minerals such as clay, gold, kaolin, gypsum, marble, lignite, feldspar, and limestone. Regarding drainage, Sokoto State is primarily drained by the Rima River and its tributaries. Most of these tributaries originate in the southeastern part of the state and neighboring Kaduna State. The Bunsuru and Gangere Rivers flow in a northerly direction, eventually joining the Rima near Sabon Birni. Conversely, the Sokoto, Zarnfara, and Ka tributaries flow westwards to join the Rima. In their upper reaches, these tributaries flow over the basement complex rocks, with narrow and restricted valleys. However, as they enter the area of young sedimentary rocks, they form broad valleys that facilitate their flow [18].

Table 1: Geological Formations and Their Lithology in Sokoto State

Formation	**Lithology**	**Aquiferous Properties**	**References**
Gundumi Formation	Sandstones and Clays	Yes	Ahmed et al., 2019
Taloka Formation	Sandstones and Shales	Yes	Ibe, 2017
Dukamaje Formation	Shales	No	-
Wumo Formation	Sandstone	Yes	-
Dange Formation	Clays and Shales	Yes	Omosuyi, 2020
Kalambaina Formation	Limestones	Yes	Omosuyi, 2020
Gwandu Formation	Clays and Sandstones	Yes	-
Basement Complex	Granites, Gneisses, Migmatites,	Impermeable	-
	Schists, Metavolcanic Rocks		

Note: Aquiferous properties indicate the formations' ability to store and transmit water.

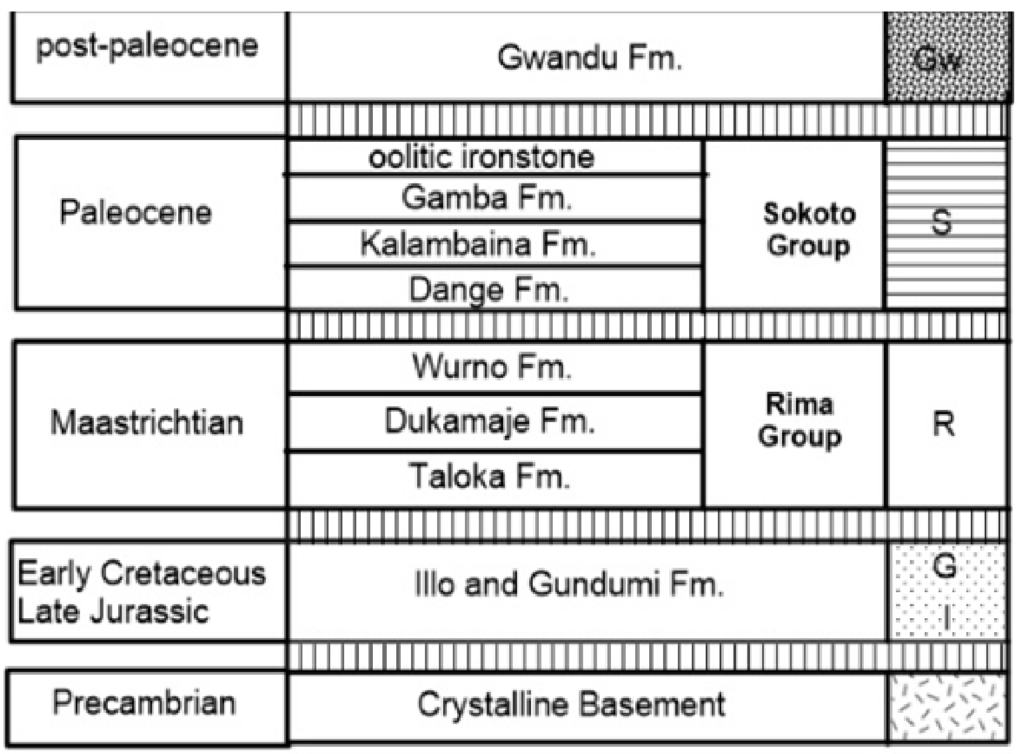

Figure 3: Lithostratigraphical subdivisions of the Sokoto Basin (modified after [22])

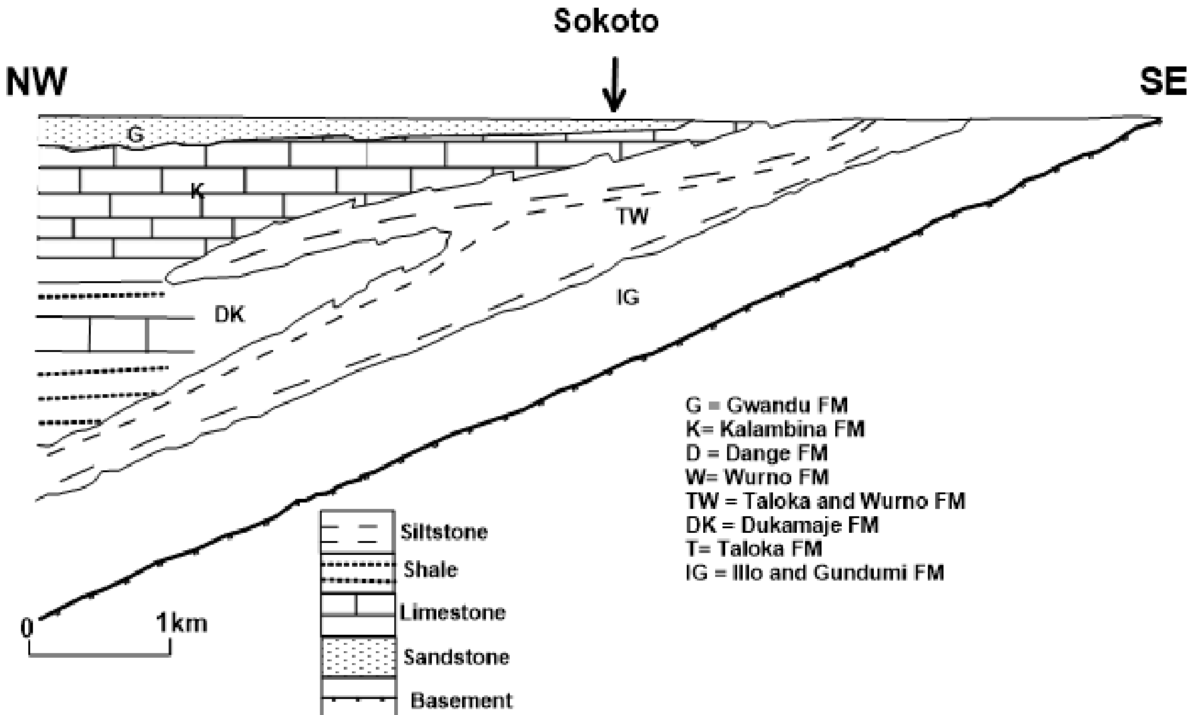

Figure 4: Stratigraphic section through the Sokoto Basin (after [23])

2.3 Methodology

The Half-Schlumberger array of electrical resistivity method and SSR resistivity meter were used for data collection, while the interpretation was done using the IPI2WIN software.

2.3.1 Data Collection Techniques:

Half-Schlumberger Array of Electrical Resistivity Method: The Half-Schlumberger array was employed to collect electrical resistivity data. This method involves the use of electrodes to measure the electrical resistivity of the subsurface at different depths. Two distinct VES measurements (profiles) were conducted at different locations or points within the study area. This approach allows for a comparative analysis of the subsurface resistivity characteristics and can provide insights into the geological and hydrogeological variations between the two locations. VES1 and VES2 (Figure 5 and Figure 6) refer to Vertical Electrical Sounding (VES) profiles or measurements conducted at two different locations or points within the study area. VES is a geophysical method used to investigate the subsurface electrical resistivity distribution and infer geological and hydrogeological properties.

Each VES profile typically involves the following steps:

2.3.1.1 Equipment Setup*:* The equipment used for conducting the VES measurements are resistivity meter, current and potential electrodes, cables, and a field computer or data logger. The electrodes are inserted into the ground at specified locations and depths.

2.3.1.2 Measurement Procedure: A current electrode (current source) was placed at a predetermined depth and a potential electrode (voltage measurement point) was positioned at different locations along a straight line or profile. A known amount of electrical current was injected into the ground through the current electrode, and the resulting voltage was measured between the potential electrode and a reference electrode at the surface. Multiple measurements are typically taken at different electrode spacings to capture a range of subsurface depths.

2.3.2 *SSR Resistivity Meter*: The Self-Potential (SP) and Spontaneous Potential (SP) Resistivity (SSR) resistivity meter was utilized to measure the self-potential (SP) and spontaneous potential (SP) data. This geophysical method involves measuring the natural electrical potential differences in the ground to gain insights into subsurface geological structures and fluid flow. The method is based on the principle that subsurface geological structures and fluid flow can create electrical potentials, which can be measured at the surface. SSR resistivity meter was used to measure and analyze the self-potential and spontaneous potential data during the data collection phase of the study. These measurements can provide valuable information about subsurface geological features and fluid movements, aiding in the interpretation of the hydrogeological conditions of the study area.

***2.3.3 Data Interpretation*:**

IPI2WIN Software: The collected data was interpreted using the IPI2WIN software. This software is widely used for geophysical data interpretation and provides tools and algorithms to process and analyze electrical resistivity data.

3.0 Results and Discussions

VES1

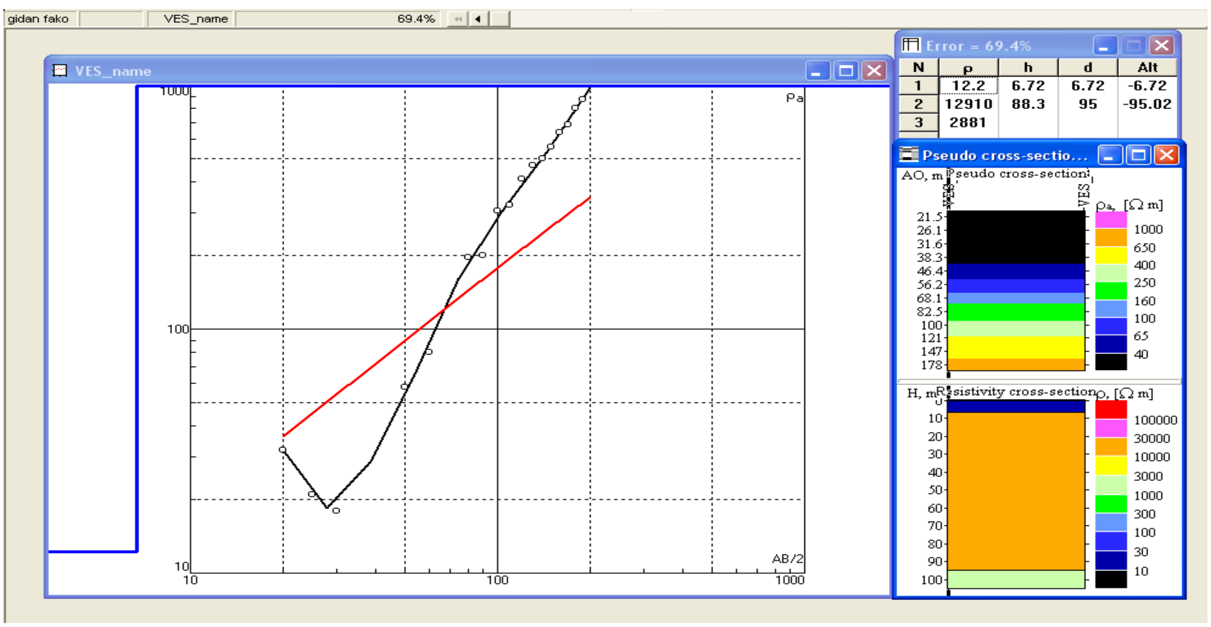

Figure 5: VES1

VES2

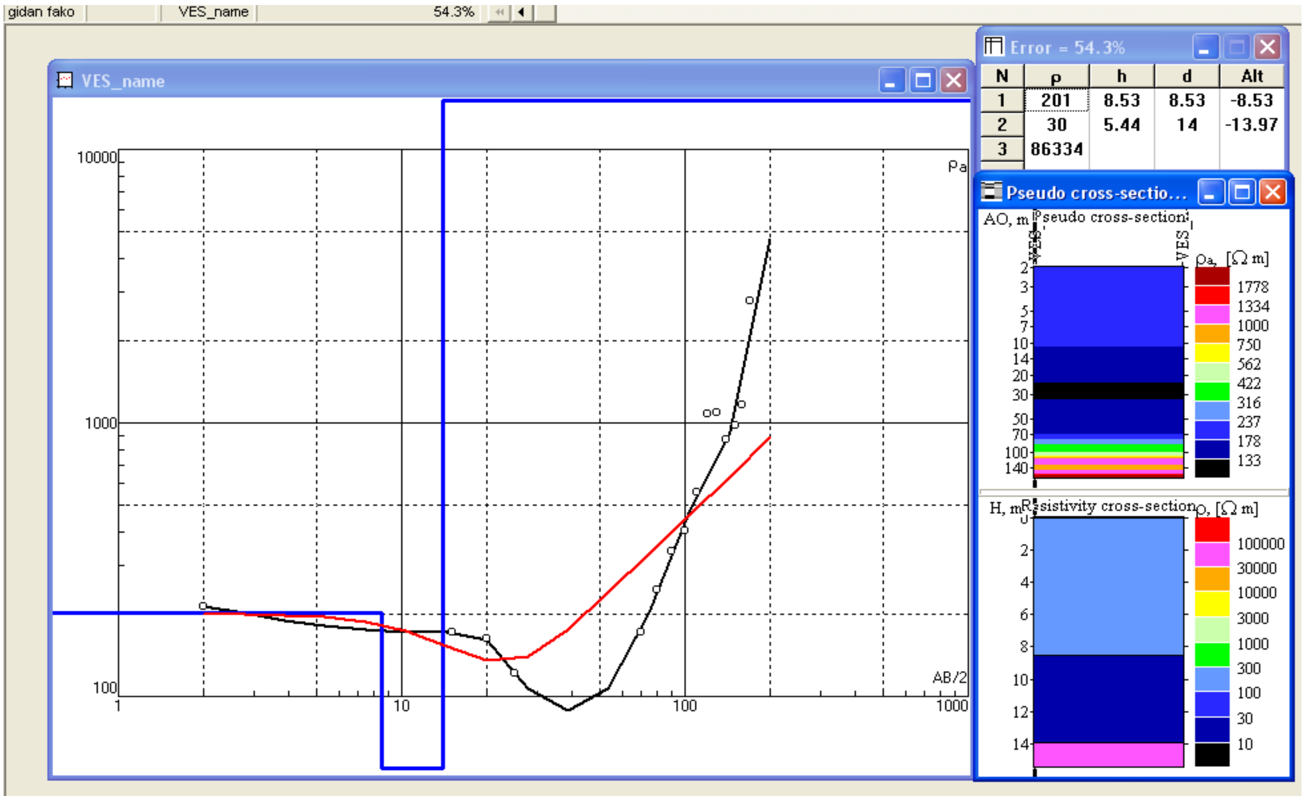

Figure 6: VES2

The results obtained from the data analysis and interpretation of VES 2 (Figure 6) provides valuable insights into the hydrogeological conditions in the study area. The resistivity measurements, along with the lithological log, contribute to understanding the subsurface characteristics and the potential for groundwater resources. The following key findings and their implications are discussed:

3.1 Aquifer Identification: The resistivity measurements indicate the presence of limestone aquifers at various depths within the study area. The resistivity values of 1062 ohm/m and 871 ohm/m observed between 25m and 70m, and 70m and 140m, respectively, are indicative of saturated limestone formations. These aquifers have the potential to store and transmit groundwater. Aquifer identification based on resistivity measurements is a common approach in hydrogeological studies. The resistivity values obtained from the VES 2 survey in the study area provide indications of the presence of limestone aquifers and their potential for groundwater storage and transmission. Limestone is known for its high permeability and ability to store significant amounts of groundwater [24]. The resistivity values of 1062 ohm/m and 871 ohm/m observed between 25m and 70m, and 70m and 140m, respectively, are within the range typically associated with saturated limestone formations [25]. The resistivity of a rock or formation is influenced by its porosity, fluid saturation, and mineral composition. In the case of limestone, the presence of interconnected pore spaces and the permeability of the rock allow for the movement and storage of groundwater [26]. The resistivity measurements reflect the electrical conductivity of the subsurface, which is affected by the presence of groundwater within the limestone aquifers. The identification of limestone aquifers based on resistivity measurements is supported by previous research and studies. Limestone formations are commonly recognized as important aquifer systems due to their unique hydrogeological properties [27]. These aquifers often exhibit high productivity and are relied upon as a source of water supply in many regions [28]. Overall, the resistivity values obtained from the VES 2 survey and their correlation with the presence of limestone formations suggest the presence of saturated limestone aquifers in the study area. These aquifers have the potential to store and transmit groundwater, making them valuable resources for water supply and management.

3.2 Borehole Depth Recommendation: Based on the resistivity data and the presence of limestone aquifers, it is recommended to drill the borehole to a depth of 150-160 meters. This depth is expected to intersect the identified limestone aquifers and increase the chances of accessing an adequate water supply. The recommendation for borehole depth is based on the analysis of resistivity data and the identification of limestone aquifers in the study area. The resistivity values obtained from the VES 2 survey provide valuable insights into the subsurface conditions and the potential for groundwater resources.

The resistivity values between 25m and 70m (1062 ohm/m) and between 70m and 140m (871 ohm/m) indicate the presence of saturated limestone formations, which are potential aquifers capable of storing and transmitting groundwater. Based on this information, a borehole depth of 150-160 meters is recommended. This depth is chosen to intersect the identified limestone aquifers and maximize the chances of accessing an adequate water supply from these formations. However, the termination point of the well should be determined by an experienced site driller or geologist.

3.3 Anticipated Yield and Water Quality*:* The study of groundwater occurrences and its movement has become very important in view of acute shortage of pipe borne water supply and surface water in many places [29]. The presence of limestone aquifers in the study area indicates a moderate anticipated yield of groundwater. Limestone formations are known to have relatively high permeability and storage capacity, allowing them to hold and transmit water. However, it is important to conduct pump-testing to accurately determine the actual water yield from the borehole. Pump-testing involves temporarily pumping water from the borehole at a known rate and monitoring the water level response over time. This test helps evaluate the sustainable pumping rate, which is the rate at which water can be continuously extracted from the aquifer without causing excessive drawdown or depletion. By conducting pump-testing after drilling the borehole, the specific yield of the limestone aquifer can be determined. The specific yield represents the volume of water released from the aquifer per unit volume of the aquifer when it is drained under gravitational conditions. It provides insights into the aquifer's ability to sustain water supply over time.

Additionally, pump-testing allows for the assessment of water quality. The quality of groundwater, including its chemical composition and suitability for different uses, can vary depending on local geology and hydrochemical processes. Pump-testing can help determine the water quality parameters such as pH, electrical conductivity, major and trace element concentrations, and potential contaminants. Evaluating the water quality is crucial to ensure that the groundwater meets the required standards for its intended use, such as drinking water supply or agricultural irrigation. It helps identify any potential issues such as high salinity, presence of contaminants, or other factors that may affect the water's suitability for different applications. Therefore, to accurately assess the anticipated yield and water quality of the limestone aquifers, conducting pump-testing after drilling the borehole is essential. This will provide valuable data to inform decision-making regarding sustainable water extraction rates and the appropriate use of the groundwater resources. It is recommended to follow standard guidelines and consult with hydrogeological experts to design and conduct the pump-testing in a scientifically rigorous manner, ensuring accurate assessment of groundwater yield and quality.

3.4 Lithology Interpretation: According to [30], Geophysical survey is only an indirect method of studying the subsurface. Conditions indicated may differ slightly or even significantly from what actually obtains.

The lithologic table (Table 2) provides valuable information about the subsurface composition and allows for a more detailed interpretation of the lithology in the study area. The lithological interpretation based on the information provided in table 2 is given below:

Depth range: 0-20meters

Resistivity: 361 ohm/m

Inferred Lithology: Top Soil/Lateritic sand

Inference: This layer represents unsaturated material, typically consisting of topsoil and lateritic sand. It is the surface layer and plays a role in water infiltration and surface water interactions.

Depth range: 20-25meters

Resistivity: 92 ohm/m

Inferred Lithology: Limestone

Inference: The resistivity value suggests a limestone layer, which is likely saturated. Limestone is a common aquifer material with high permeability, indicating the potential for groundwater storage within this layer.

Depth range: 25-70meters

Resistivity: 1062 ohm/m

Inferred Lithology: Shale

Inference: The resistivity value corresponds to a shale layer, which is typically unsaturated. Shale has low permeability, restricting the movement and storage of groundwater. It acts as an impermeable layer between the limestone aquifers.

Depth range: 70-140meters

Resistivity: 871 ohm/m

Inferred Lithology: Limestone

Inference: The resistivity value indicates the presence of another saturated limestone layer. This layer holds the potential for groundwater storage and can contribute to the overall aquifer system.

Depth range: >140meters

Resistivity: 2771 ohm/m

Inferred Lithology: Shale

Inference: The resistivity value suggests an unsaturated shale layer. Shale typically has low permeability, limiting its ability to store and transmit significant amounts of groundwater.

The lithological interpretation provided by Table 2 confirms the presence of unsaturated topsoil/lateritic sand layer at the surface and identifies the alternating saturated limestone and unsaturated shale layers at different depths. This information is valuable for understanding the subsurface characteristics and the distribution of potential aquifers in the study area.

Table 2: The lithologic Table

Depth(m)	Resistivity (ohm/m)	Inferred Lithology	Inference
0 – 20	361	Top Soil/Lateritic sand	Unsaturated
20 –25	92	Limestone	Saturated
25-70	1062	Shale	Unsaturated
70-140	871	Limestone	Saturated
>140	2771	Shale	Unsaturated

Limestone aquifers are widely recognized and studied in the field of hydrogeology. Limestone formations are known for their high permeability and storage capacity, making them important sources of groundwater in many regions [24]. The interconnected pore spaces and fractures within limestone allow for the movement and storage of significant amounts of water [31]. In various geological settings, limestone aquifers have been identified as key sources of water supply. Their ability to store and transmit groundwater has made them targets for groundwater exploration and development [32]. Studies have highlighted the importance of understanding the characteristics and behavior of limestone aquifers for sustainable management of water resources [33].

The interpretation of the lithological log in the study area aligns with the general understanding of limestone aquifers. The presence of saturated limestone layers observed at depths of 20-25 meters and 70-140 meters corresponds to the expected behavior of limestone aquifers in terms of water storage and transmission. The identification of limestone aquifers based on the resistivity data and lithological interpretation is consistent with the broader understanding of limestone aquifers in hydrogeology.

Comparing these findings with existing knowledge and literature, the identified limestone aquifers align with the geological characteristics of the region. This study contributes to the understanding of the hydrogeological conditions in the study area and provides valuable information for groundwater resource management and planning. The identified limestone aquifers hold the potential for groundwater storage and supply, emphasizing the importance of sustainable utilization and protection of these resources.

However, it is important to consider certain limitations and uncertainties. The geophysical survey does not directly determine the presence of water, but rather provides information about potential water-bearing formations. The actual water yield can only be determined through pump-testing, which should be conducted after drilling the borehole. Additionally, geophysical logging should be carried out before inserting screens and casings to ensure proper well construction and optimal placement.

The results of this study indicate the presence of limestone aquifers within the study area, suggesting a moderate potential for groundwater resources. Drilling a borehole to a depth of 150-160 meters, using mud drilling as the recommended method, can provide access to these aquifers. Further investigation, including pump-testing and water quality analysis, is necessary to assess the actual water yield and suitability for specific uses. These findings contribute to the understanding of the hydrogeological conditions in the area and can inform decision-making for sustainable water resource management and development.

3.5 Borehole Recommendation:

3.5.1 Drilling Technique: It is recommended to use MUD drilling for the borehole construction in the study area. MUD drilling is a widely used technique in drilling operations, particularly in areas with complex geological formations. This technique involves the circulation of drilling fluids, commonly known as mud, to achieve several objectives:

i. Removal of cuttings: The drilling mud carries the cuttings (rock fragments) to the surface, allowing for continuous drilling and preventing the accumulation of debris in the borehole.
ii. Borehole stabilization: The drilling mud forms a thin layer on the borehole walls, providing stability and preventing collapse or caving of the formation during drilling.
iii. Formation pressure control: The hydrostatic pressure exerted by the drilling mud helps balance and control the formation pressures encountered during drilling, preventing blowouts or influx of fluids from the formation.

3.5.2 Borehole Depth: The recommended depth for the borehole is 150-160 meters. This depth recommendation is based on geological and hydrogeological considerations specific to the study area. These considerations may include:

i. Aquifer depth: The anticipated depth of the targeted aquifer(s) is an important factor in determining the borehole depth. It is essential to intersect the identified limestone aquifers, as they hold the potential for groundwater storage and supply.
ii. Target geological formations: The depth recommendation may also consider the desired intersection with specific geological formations that are known to host aquifers or contain favorable hydrogeological properties.

4 Conclusion

In conclusion, this study has provided valuable insights into the hydrogeological conditions of the study area through the analysis and interpretation of VES 2 data. The key findings and implications can be summarized as follows:

1. *Aquifer Identification*: The resistivity measurements indicate the presence of limestone aquifers at various depths within the study area. These aquifers have the potential to store and transmit groundwater, as evidenced by the resistivity values observed.
2. *Borehole Depth Recommendation:* Based on the resistivity data and the presence of limestone aquifers, it is recommended to drill the borehole to a depth of 150-160 meters. This depth is expected to intersect the identified limestone aquifers and increase the chances of accessing an adequate water supply. This depth recommendation increases the likelihood of accessing an adequate water supply, which is crucial for meeting the water demands of the local community or any potential users in the area. The specific termination point of the well should be determined by an experienced site driller or geologist.
3. *Anticipated Yield and Water Quality*: The presence of limestone aquifers suggests a moderate anticipated yield of groundwater. However, the actual water yield can only be determined through pump-testing. Pump-testing should be conducted after drilling the borehole to assess the sustainable pumping rate and evaluate the quality of the groundwater for various uses. It is important to emphasize that the actual water yield and quality can

only be determined through pump-testing. Pump-testing will provide valuable information about the sustainable pumping rate, which is crucial for designing efficient water extraction systems. Additionally, it will allow for the assessment of water quality parameters, ensuring that the groundwater is suitable for various purposes such as drinking, irrigation, or industrial use.

4. *Lithological Interpretation*: The lithological analysis provides further insights into the subsurface composition. The presence of unsaturated topsoil/lateritic sand layer, saturated limestone layers, and unsaturated shale layers at different depths confirms the expected behavior of the geological formations in the study area. The lithological interpretation adds to the understanding of the subsurface composition and the distribution of different geological formations. This information is vital for groundwater modeling, predicting groundwater flow patterns, and identifying potential areas of recharge and discharge. It also aids in the selection of appropriate drilling techniques and well construction methods to optimize water extraction from the identified aquifers.

The findings of this study align with existing knowledge and literature regarding limestone aquifers and their hydrogeological characteristics. The study contributes to a better understanding of the hydrogeological conditions in the study area, providing important information for groundwater resource management and planning. Overall, the insights gained from this study are valuable for sustainable groundwater management, aiding decision-making processes related to borehole construction, water resource development, and protection of the groundwater in the study area.

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