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Groundwater Exploration in Afi Mountain (Obudu Plateau), South Eastern Nigeria: Integrating Vertical Electrical Sounding (VES), Bore Hole drilling and Pump Testing

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Abstract: *Groundwater development in crystalline basement terrains is often constrained by complex subsurface geology, where groundwater occurrence is controlled by weathered and fractured basement units. This study evaluated the effectiveness of Vertical Electrical Sounding (VES) for groundwater exploration in the Afi Mountain area, Boki Local Government Area, Cross River State, Nigeria, through integration with borehole drilling and pump testing. A total of 41 VES stations were conducted and interpreted using Zoody and WinResist software to delineate aquifer horizons and recommend drilling depths. Based on the VES results, 41 boreholes were drilled using the rotary air-compression method, followed by pumping tests conducted between 2 and 16 July 2017. Pumping test data were analysed using Aquifer Test Pro Version 2011.1 to determine static water level (SWL), drawdown, borehole yield, and pump installation depths. The interpreted geoelectric sections identified weathered regolith with resistivity values of approximately 200–300 Ωm and fractured basement aquifers with resistivity values of 300–600 Ωm, while fresh basement generally exceeded 600 Ωm. Recommended VES drilling depths ranged from 30 to 65 m, whereas actual drilled depths ranged from 35 to 70 m. Comparison of VES predictions with drilling records showed that 30 of the 41 boreholes (73.2%) exhibited excellent agreement, with depth deviations of 1–5 m, while 11 boreholes (26.8%) showed poorer agreement, with deviations of 5–10 m. Static water levels ranged from 3.62 to 20.78 m, borehole installation depths from 30.6 to 68 m, and recommended pump capacities from 0.5 to 1.5 hp. Pumping tests revealed that 30 boreholes produced sustainable yields ranging from 0.71 to 1.50 L s^{-1}, whereas 11 boreholes recorded low yields of 0.0074–0.35 L s^{-1} and were classified as unsuccessful despite intercepting groundwater. The results demonstrate that VES is a reliable technique for locating groundwater-bearing zones within crystalline basement terrains and significantly improves drilling success. However, the occurrence of low-yield boreholes despite successful aquifer interception confirms that geophysical interpretation alone cannot adequately predict aquifer productivity. The study therefore emphasizes that pump testing remains indispensable for verifying hydraulic performance and ensuring sustainable groundwater development in basement complex environments*.

Keywords: *Vertical Electrical Sounding (VES); Groundwater; Aquifer; Borehole Drilling; Pump Testing; Zoody Software.*

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1.0 Introduction

Groundwater constitutes one of the most reliable sources of freshwater for domestic, agricultural, and industrial purposes worldwide, particularly in regions where surface water resources are either inadequate or highly seasonal. Approximately half of the world's population depends directly on groundwater for drinking water, making its sustainable exploration and management essential for socioeconomic development and environmental sustainability. In crystalline basement terrains, however, groundwater occurrence is generally restricted to weathered regolith and fractured bedrock because the fresh basement rocks possess negligible primary porosity and permeability. Consequently, groundwater exploration in these geological environments is often difficult, requiring integrated hydrogeophysical techniques to accurately delineate productive aquifers and minimize borehole failure. Recent studies have demonstrated that Vertical Electrical Sounding (VES) remains one of the most widely applied and cost-effective geophysical methods for groundwater exploration because it provides valuable information on subsurface lithology, aquifer thickness, weathered zones, fracture systems, and depth to bedrock. Furthermore, geoelectrical parameters derived from VES have shown strong relationships with hydraulic properties such as transmissivity and hydraulic conductivity, thereby improving preliminary aquifer characterization before drilling (de Almeida et al., 2021).

The Afi Mountains of Boki Local Government Area, Cross River State, Nigeria, represent one of the most environmentally challenging terrains for groundwater development in southeastern Nigeria. The area occupies approximately 1,458 km² and consists of rugged mountainous landscapes characterized by steep slopes, deeply incised valleys, and highly variable elevations. Communities within the area experience persistent shortages of potable water because surface water sources are largely seasonal, while many shallow hand-dug wells and conventionally drilled boreholes fail during the dry season. These failures are largely attributed to the heterogeneous nature of basement aquifers, variable weathering thickness, localized fracture systems, and the absence of detailed hydrogeophysical investigations prior to drilling. Consequently, identifying productive groundwater zones remains a major challenge for sustainable rural water supply.

Over the past three decades, numerous studies have demonstrated the effectiveness of VES for groundwater exploration in basement complex terrains. Okereke et al. (1998) investigated groundwater potential across Cross River State at a regional scale, while Edet (1994) and Odigi and Okonny (1987) delineated groundwater-producing zones within the Oban Massif and Obudu Plateau, which encompass parts of the present study area. More recent investigations have further confirmed the reliability of VES for identifying weathered and fractured basement aquifers. For example, Abdullahi et al. (2015) successfully delineated groundwater-bearing weathered and fractured basement zones in Kano State using VES, while Ubaidullah et al. (2021) identified productive aquifers in Katsina State through geoelectrical interpretation of weathered and fractured basement layers. Similarly, Nwankwoala et al. (2022) demonstrated the effectiveness of VES in characterizing subsurface lithology and groundwater-bearing formations in Rivers State.

Recent advances have increasingly emphasized integrating VES with complementary hydrogeological techniques to improve groundwater exploration accuracy. Ugbor and Nnadi (2020) combined VES with spontaneous potential logging and borehole data to distinguish clay-rich formations from productive aquifers, thereby improving borehole siting accuracy. Likewise, Oyegoke et al. (2020) demonstrated that combining VES with borehole performance evaluation provides more reliable groundwater assessments than geophysical interpretation alone. More recent studies have integrated VES with pumping test analysis, Dar Zarrouk parameters, GIS, magnetic surveys, electrical resistivity tomography (ERT), and magnetotelluric methods to enhance aquifer characterization and groundwater potential mapping (Sani & Aliyu, 2026; Usman Baba et al., 2026; Feyisa et al., 2026; Falade et al., 2025; Adebisi et al., 2026; El Makrini et al., 2022). These integrated approaches significantly improve the identification of groundwater-bearing structures and reduce uncertainty associated with drilling in heterogeneous basement terrains.

Despite these advances, an important knowledge gap remains within the Afi Mountain region. Previous investigations have primarily focused on regional groundwater potential mapping or geophysical delineation of aquifer zones without quantitatively evaluating the predictive accuracy of VES by comparing interpreted aquifer depths with actual drilling depths and borehole pumping performance. Consequently, there is limited empirical evidence regarding the reliability of VES as a decision-support tool for borehole siting in the rugged basement complex terrain of southeastern Nigeria. Furthermore, relatively few studies have systematically assessed whether successful geophysical predictions necessarily translate into hydraulically productive boreholes after drilling.

Therefore, the aim of this study is to evaluate the effectiveness and predictive reliability of Vertical Electrical Sounding (VES) for groundwater exploration in the environmentally challenging Afi Mountain area by integrating VES interpretation, borehole drilling records, and pumping test analysis. Specifically, the study compares interpreted aquifer depths with actual drilling depths, evaluates the correlation between geophysical predictions and borehole yields, and assesses the suitability of VES for improving groundwater exploration success in crystalline basement terrains.

The significance of this study lies in its integrated evaluation of geophysical and hydrogeological techniques for groundwater development in complex basement environments. The findings will improve understanding of the relationship between VES-derived aquifer interpretations and actual borehole performance, thereby reducing uncertainty and financial risks associated with groundwater exploration. The study also provides practical guidance for groundwater consultants, hydrogeologists, engineers, government agencies, and rural water supply programmes responsible for borehole development in similar basement complex terrains across Nigeria and other parts of sub-Saharan Africa. Ultimately, the results contribute to more sustainable groundwater resource management and improved access to potable water in environmentally challenging regions.

1.1 Location and Geological Setting

The study area is located in southeastern Nigeria, West Africa (Fig. 1), between latitudes

5°57′N and 6°36′N and longitudes 8°42′E and 9°21′E. The terrain exhibits considerable topographic variation, with elevations ranging from approximately 13 m to 1,344 m above mean sea level (Fig. 1a). The landscape comprises extensive low-lying plains interspersed with rugged highlands dominated by the Afi Mountains (Obudu Plateau) (Fig. 1b), which constitute one of the most prominent physiographic features in the region. Geologically, the area lies within the Precambrian Basement Complex of southeastern Nigeria and is underlain predominantly by granite gneiss, migmatite, and porphyritic granite. These lithological units are widely distributed within the Migmatite–Gneiss Complex as described by Ajibade et al. (1987) and form part of the Pan-African Older Granite suite, emplaced during the Pan-African orogeny (Ekwueme, 1981, 1998; Umeji & Fitch, 1988; Ofoegbu, 1990; Ekwueme & Kröner, 2006). The crystalline basement rocks have undergone varying degrees of weathering and fracturing, resulting in the development of a relatively thick regolith that constitutes the principal groundwater reservoir within the area.

Sedimentary rocks also occur locally within the study area and consist mainly of sandstone and mudstone belonging to the Albian Asu River Group. These sedimentary units occur principally along the margins of the basement terrain and contribute to the geological complexity of the area. The coexistence of crystalline basement rocks and sedimentary formations, coupled with pronounced topographic relief, exerts a significant influence on groundwater occurrence, storage, and movement, thereby making the area particularly suitable for integrated hydrogeophysical investigations.

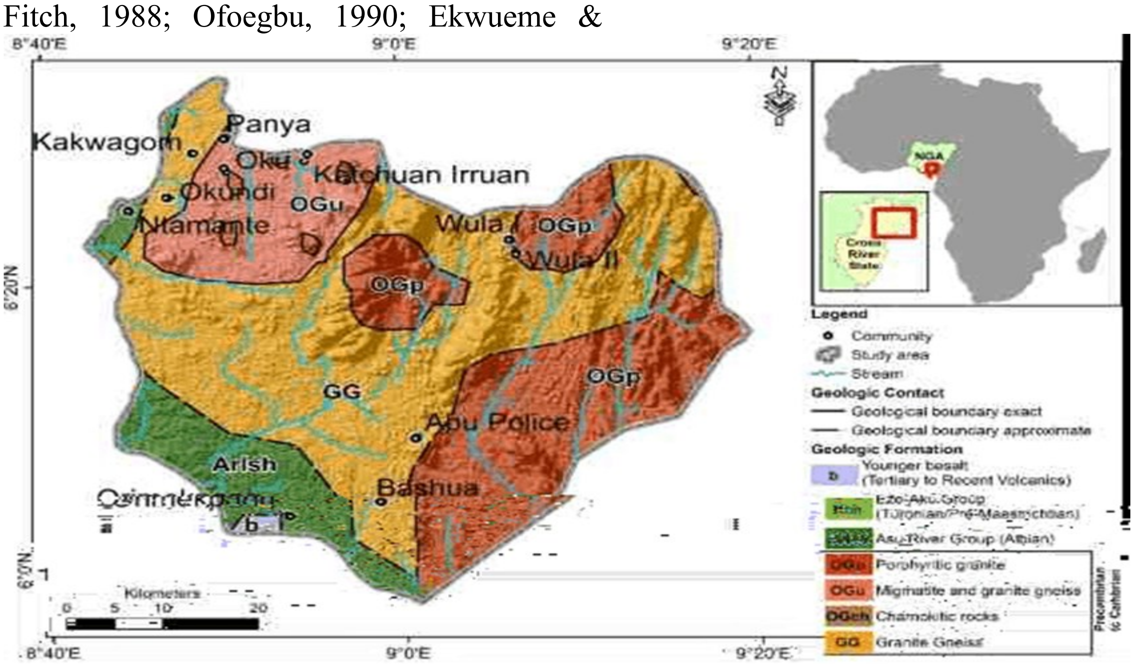

Fig. 1: Map of the study area showing (a) topography (b) Geomophology (c) Geology (NGSA, 2010)

2.0 Materials and Methods

The major equipment used in this study included the ABEM Terrameter SAS 1000 for acquiring Vertical Electrical Sounding (VES) data, an Abu Drill Tech rotary drilling rig for borehole construction, a 3500 W power generator for powering the submersible pump during pumping tests, two Global Positioning System (GPS) receivers for recording borehole and survey coordinates, and a Sonist Dip Meter Model 102 for measuring static and dynamic water levels during pumping tests. Data processing and interpretation were carried out using Zohdy software for VES interpretation, AquiferTest Pro Version 2011.1 for pumping test analysis, Microsoft Excel 2016 for data processing, Golden Software Surfer 18.1 for spatial interpolation and contour generation, Golden Software Strater 5 for borehole log preparation, and ArcGIS 10.8 for map production.

The investigation comprised three major stages: Vertical Electrical Sounding (VES), borehole drilling, and borehole pumping tests. Vertical Electrical Sounding was conducted to characterize subsurface lithological units and identify potential aquifer zones prior to drilling. Boreholes were subsequently drilled at selected VES locations, after which pumping tests were performed to evaluate aquifer productivity and determine hydraulic characteristics. This integrated approach enabled comparison between geophysical predictions and hydrogeological observations.

2.1 Vertical Electrical Sounding (VES)

Vertical Electrical Sounding (VES) was employed to investigate the subsurface electrical resistivity distribution and delineate potential groundwater-bearing formations. The method is based on the variation of apparent resistivity with increasing electrode spacing, allowing the characterization of subsurface layering (Gish & Rooney, 1995). Measurements were conducted using the Schlumberger electrode configuration, in which the current electrodes were progressively expanded while the potential electrodes remained relatively close to the survey centre (Dahlin, 2001).

The VES technique is widely applied in groundwater exploration because it enables the determination of layer resistivity, thickness, depth to bedrock, and the identification of weathered and fractured basement zones that commonly serve as aquifers. It has also been successfully used for distinguishing freshwater from saline-water interfaces in suitable hydrogeological environments (Archie, 1942; Choudhury et al., 2001; El-Waheidi et al., 1992; Slater, 2007).

2.2 Borehole Drilling

Following the interpretation of the VES data, boreholes were drilled at selected locations using an Abu Drill Tech rotary air-compression drilling rig equipped with 5-inch steel casing and diamond drill bits. Rotary air drilling was selected because of its suitability for crystalline basement terrains where groundwater is generally associated with weathered regolith and fractured bedrock. A total of forty-one (41) boreholes were drilled based on the geophysical recommendations.

During drilling, lithological information, drilling depth, water strikes, casing depth, and other relevant drilling parameters were recorded to facilitate comparison between interpreted geophysical data and actual subsurface conditions.

2.3 Pumping Test Analysis

Pumping tests were conducted immediately after borehole completion to evaluate aquifer performance and determine hydraulic properties. The tests involved pumping each borehole at a controlled discharge rate while monitoring changes in water level over time. Static and dynamic water levels were measured using a Sonist Dip Meter Model 102.

The pumping test data were analysed using AquiferTest Pro Version 2011.1 to determine hydraulic parameters including transmissivity, specific capacity, pumping rate, and static water level. These parameters were used to evaluate borehole productivity and aquifer characteristics (Paasche et al., 2006; Seifert et al., 2020).

2.4 Data Acquisition and Analysis

Vertical Electrical Sounding data were acquired using the ABEM SAS 1000 Terrameter with the Schlumberger electrode array. A total of forty-one (41) sounding stations were established across the selected communities. The maximum current electrode spacing was AB/2 = 150 m, while the maximum potential electrode spacing was MN/2 = 20 m. These electrode spacings were considered suitable for investigating the relatively shallow weathered and fractured aquifer systems characteristic of crystalline basement terrains (Algaydi et al., 2019).

The field measurements were processed and interpreted using Zohdy software, which generated one-dimensional geoelectrical models and layer parameters including resistivity, thickness, and depth to subsurface interfaces. These interpreted results were subsequently used to identify potential groundwater-bearing zones and recommend drilling depths.

Following borehole completion, drilling records and pumping test data were compiled and analysed to evaluate aquifer characteristics and assess the relationship between interpreted geoelectrical parameters and observed hydrogeological conditions.

3.0 Results and Discussion

3.1 Vertical Electrical Sounding (VES) Interpretation

A total of forty-one (41) Vertical Electrical Sounding (VES) surveys were completed across the selected communities in the Afi Mountain area using the Schlumberger electrode configuration. The acquired field data were interpreted using Zohdy Software, which generated modeled VES curves, resistivity-depth models, and geoelectric sections for each sounding location. Representative modeled VES sections for Abo-Police, Bashua, and Katchuan–Okubushuyu are presented in Figs. 2–4, while representative resistivity inversion plots are shown in Figs. 5–10. The interpreted geoelectric models were subsequently used to identify groundwater-bearing horizons and recommend drilling depths for the forty-one borehole locations.

The geoelectric interpretation revealed that the subsurface within the study area is composed predominantly of three to five geoelectric layers, corresponding to topsoil or overburden, weathered basement (regolith), fractured basement, and fresh crystalline basement. The lithological succession varies slightly from one location to another depending on the degree of weathering and fracture development, which are the principal controls on groundwater occurrence in basement complex terrains.

The interpreted resistivity values show clear distinctions between the different lithological units. Generally, moderate resistivity values between approximately 200 and 300 Ωm represent saturated weathered regolith, while fractured aquiferous basement zones exhibit resistivity values ranging from approximately 300 to 600 Ωm. In contrast, fresh basement rocks are characterized by resistivity values exceeding 600 Ωm, reflecting their compact nature and low groundwater storage potential. These interpretations agree with the hydrogeological characteristics of crystalline basement aquifers, where groundwater is stored mainly within weathered materials and interconnected fractures rather than within the fresh basement itself.

The representative VES models further illustrate these lithological variations. At Abo 01, the interpreted section comprises a clayey sand overburden with a resistivity of 59.3 Ωm extending to a depth of 1.04 m, underlain by saturated regolith with resistivity values ranging from 292.6 to 399 Ωm extending to approximately 33.1 m, indicating favourable groundwater conditions (Table 1). Conversely, Abo 02 is characterized by a highly resistive overburden (6755 Ωm) to a depth of 3.11 m, underlain by weathered basement (409 Ωm) and a fractured aquiferous zone with resistivity values between 275 and 280 Ωm, extending beyond 33.1 m, indicating that groundwater is predominantly stored within fractured crystalline rocks.

Similarly, the interpreted VES model at Bashua 01 consists of a sandy clay overburden (25.4 Ωm) extending to 4.9 m, followed by saturated regolith with resistivity values of 118.5–292.4 Ωm reaching approximately 49.6 m, before terminating in weathered basement with a resistivity of 481 Ωm. In contrast, Bashua 02 exhibits a resistive overburden (1378 Ωm) overlying basement rocks, while the principal groundwater-bearing unit occurs within a fractured aquiferous zone having resistivity values of 209–278.2 Ωm extending beyond 44.6 m. These relatively low to moderate resistivity values indicate significant groundwater saturation within the fractured basement.

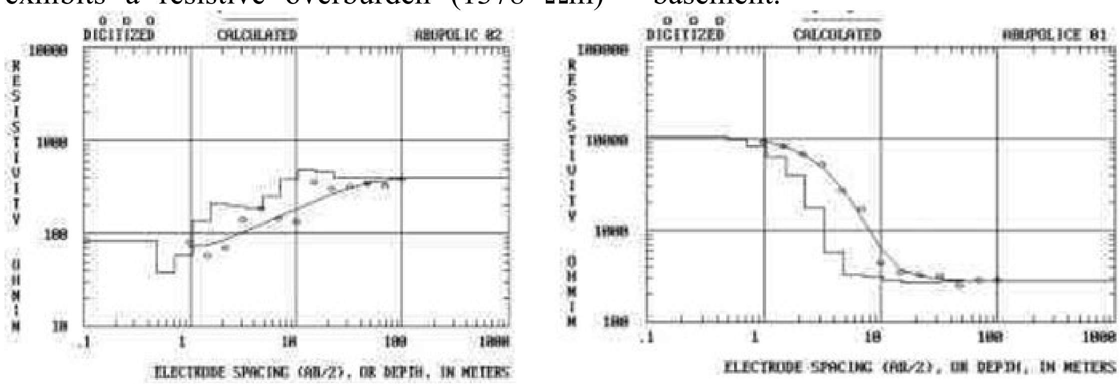

Fig. 2: Modelled VES along Abo -Police

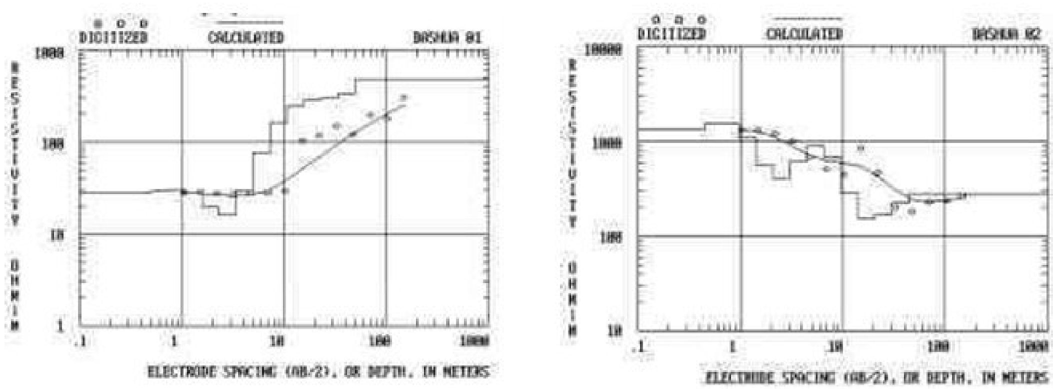

Fig. 3: Modelled VES along Bashua

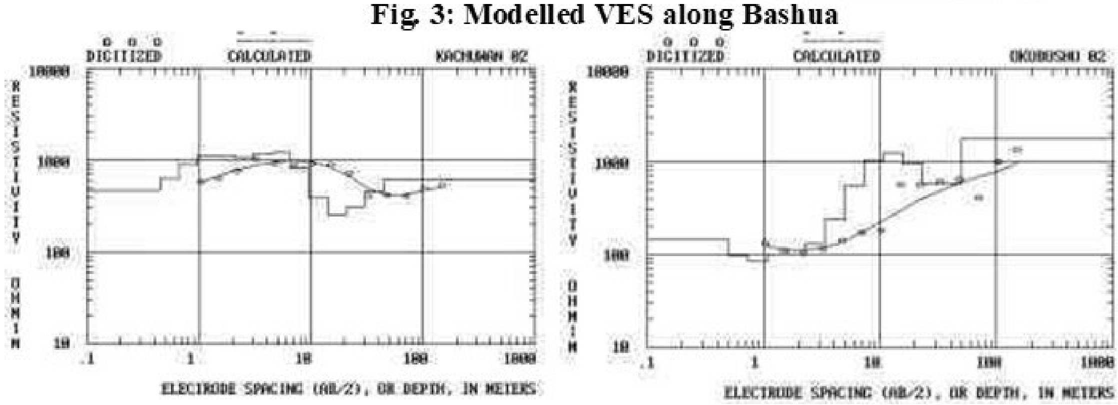

Fig. 4: Modelled VES along Katchuan and Okubushu

Table 1: Geoelectric models and lithological interpretation derived from Zohdy Software

Location	Resistivity Ωm	Depth(m)	Lithologic Description
ABO 01	59.3	1.04	Clayey SAND Overburden
	292.6	4.86	Saturated Regolith
	394.6	33.1	Saturated Regolith
	399	-	Saturated Regolith
ABO 02	6755	3.11	Resistive Overburden
	409	10.4	Weathered Basement
	275	33.1	Fractured Aquiferous zone
	280	-	Fractured Aquiferous zone
BASHUA 01	25.4	4.9	Sandy CLAY overburden
	118.5	10.7	Saturated Regolith
	292.4	49.6	Saturated Regolith
	481	-	Weathered basement
BASHUA 02	1378	1.41	Resistive overburden
	639.2	9.6	Basement
	209	44.6	Fractured Aquiferous zone
	278.2	-	Fractured Aquiferous zone
KATCHUAN	950	9.6	Resistive overburden
IRRUAN	350	44.6	Fractured Aquiferous zone
	618	-	Basement
OKUBUSHUYU	111.2	3.3	Overburden
	942.7	7.2	Basement
	606	23.0	Fractured basement
	577	49.0	Fractured Aquiferous zone
	1758	-	Fresh Basement

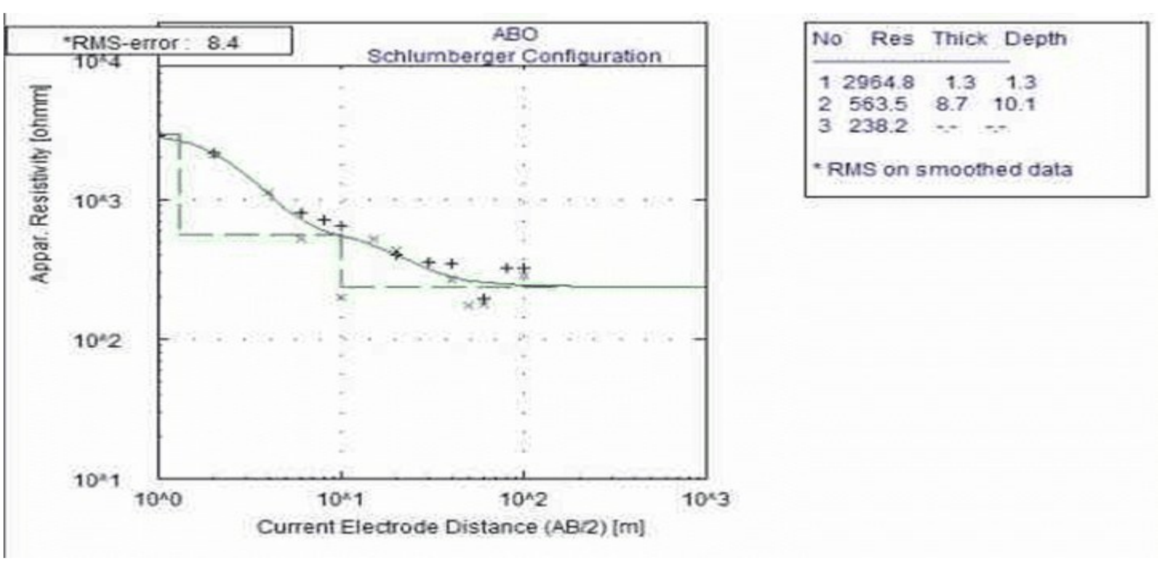

Fig. 5: Resistivity plot for Abo 01

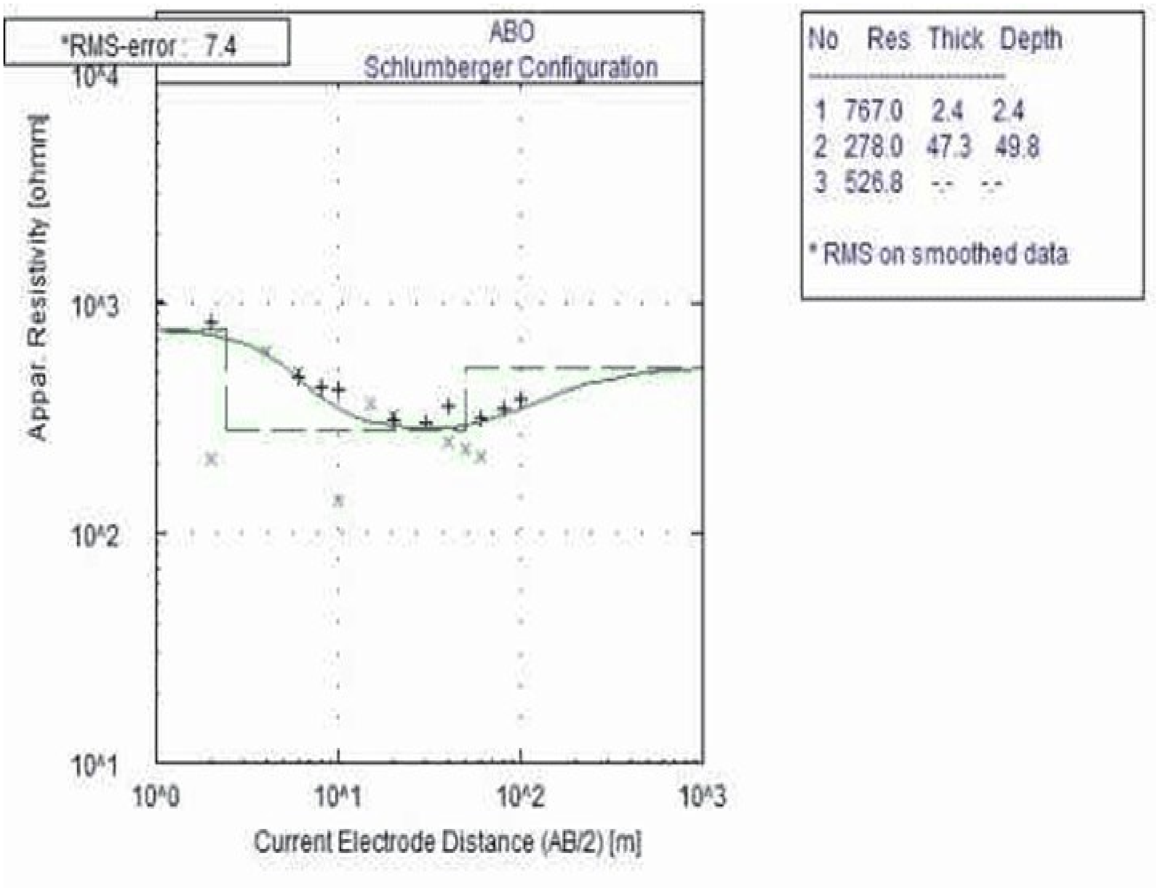

Fig. 6: Resistivity plot for Abo 01

The VES interpretation at Katchuan Irruan indicates a resistive overburden of 950 Ωm extending to 9.6 m, underlain by a fractured aquiferous unit with a resistivity of 350 Ωm extending to approximately 44.6 m, before terminating in competent basement (618 Ωm). Likewise, Okubushuyu exhibits a relatively low-resistivity overburden (111.2 Ωm) to 3.3 m, followed by basement rocks (942.7 Ωm), fractured basement (606 Ωm), and a productive fractured aquiferous zone with a resistivity of 577 Ωm extending to approximately 49.0 m, underlain by fresh basement having a resistivity of 1758 Ωm. These models demonstrate the variability of weathering and fracture development across the study area and confirm that groundwater occurrence is controlled primarily by fractured and weathered basement rocks.

To verify the reliability of the Zohdy interpretation, the VES data were also interpreted using WinResist Software, and the resulting geoelectric models are presented in Table 2. Although slight differences exist in the computed resistivity values and layer thicknesses between the two software packages, both inversion techniques consistently identified the same principal lithological units and groundwater-bearing horizons. For example, the fractured aquifer identified at Abo 01 by Zohdy corresponds to the saturated fractured basement identified by WinResist, while both software packages similarly delineated productive fractured basement zones at Bashua, Katchuan Irruan, and Okubushuyu. The close agreement between the two inversion methods demonstrates the robustness of the geophysical interpretation and increases confidence in the selection of drilling targets

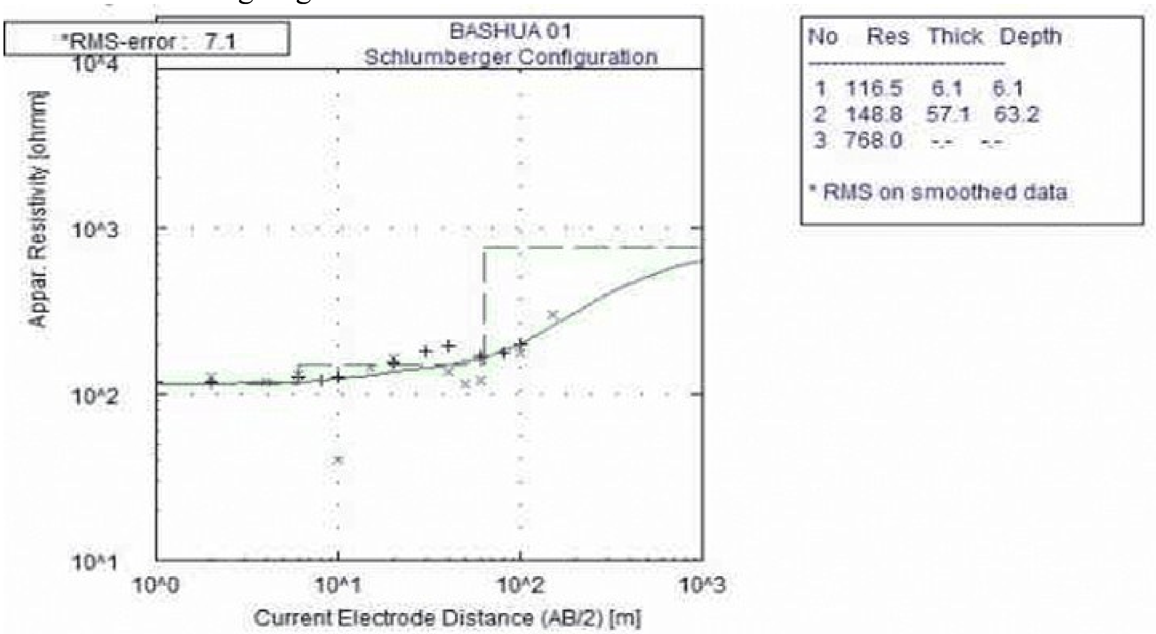

Fig. 7: Resistivity plot for Bashua 01

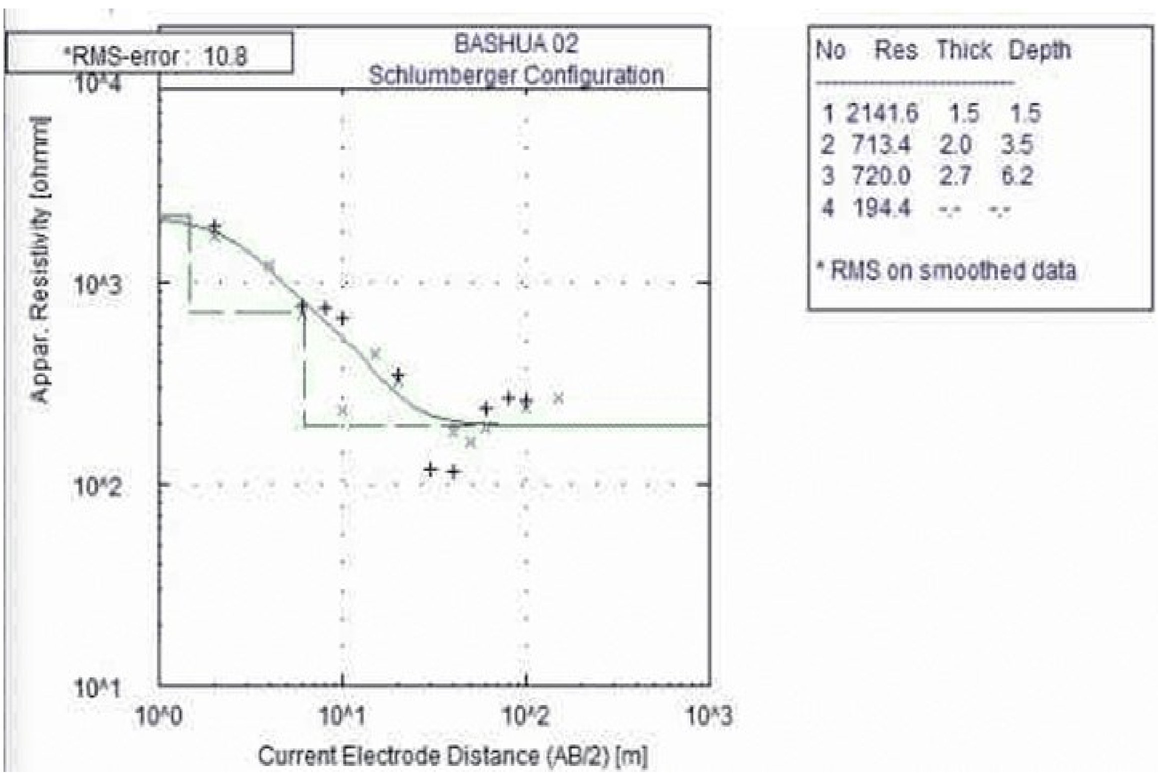

Fig. 8: Resistivity plot for Bashua 02

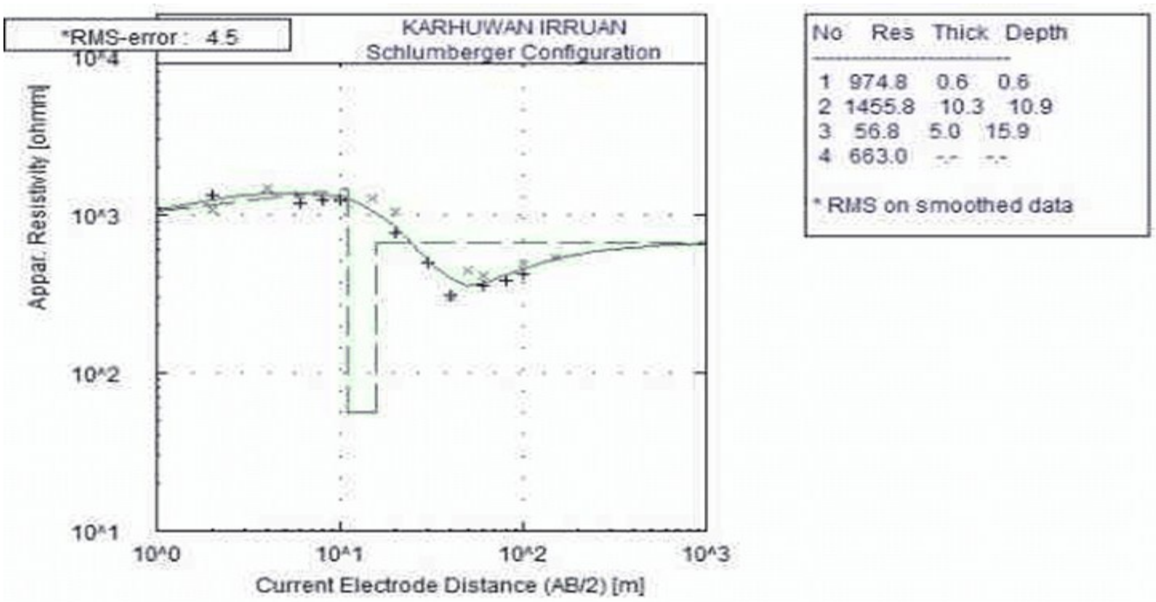

Fig. 9:Resistivity plot for Katchuan Irruank 02

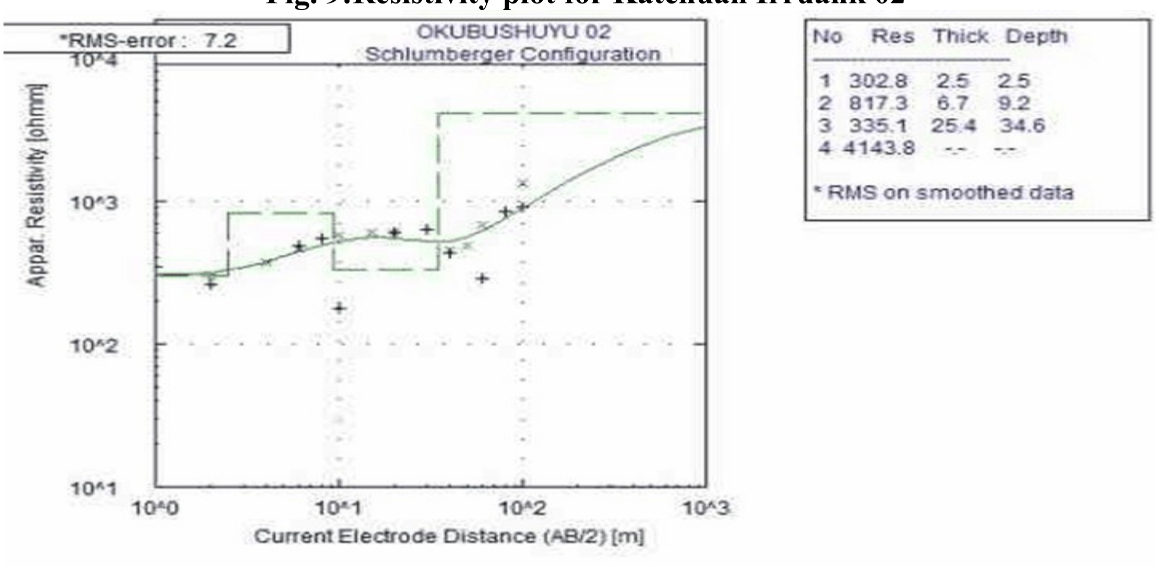

Fig. 10:Resistivity plot for Okubushiyu 02

Table 2: Geoelectric models and lithological interpretation derived from WinResist Software

Location	Resistivity Ωm	Depth(m)	Lithologic Description
ABO 01	2964.8	1.3	Resistive Top overburden
	563.5	10.1	Weathered basement
	238.2	-	Saturated fractured basement
ABO 02	767.0	2.4	Resistive Top overburden
	278.0	49.0	Saturated Regolith
	526.8	-	Weathered Basement

BASHUA 01	116.5	6.1	Sandy Overburden
	148.8	63.2	Saturated Sand
	768	-	Basement
BASHUA 02	2141.6	1.5	Resistive Overburden
	713.4	3.5	Slightly Weathered Basement
	720.0	6.2	Slightly Weathered Basement
	194.4	-	Saturated fractured basement
KATCHUAN IRRUAN	974.8	0.6	Resistive Top overburden
	1455.8	10.9	Basement
	56.8	15.9	Saturated Fractured Basement
	663.0	-	Weathered Basement
OKUBUSHUY0 02	302.8	2.5	Sandy Overburden
	817.3	9.2	Slightly Weathered Basement
	335.1	34.6	Saturated fractured basement
	4143.8	-	Fresh Basement

The interpreted VES aquifer depths for all forty-one boreholes were subsequently contoured to generate the spatial distribution of static groundwater levels, basal aquifer depths, and aquifer thicknesses across the study area (Fig. 11a–c). A clear relationship was observed between topography and aquifer occurrence. Communities located at higher elevations in eastern Boki, including Wula and Orimekpang, with elevations ranging from 154 to 171 m, generally exhibited deeper aquifer occurrences, with recommended VES depths ranging between 50 and 70 m. Conversely, communities within western Boki, including Okundi and Kakwagom, with elevations ranging from 111 to 140 m, were characterized by shallower aquifer depths of approximately 40–50 m. This relationship suggests that groundwater occurrence is strongly influenced by topographic relief and basement weathering patterns.

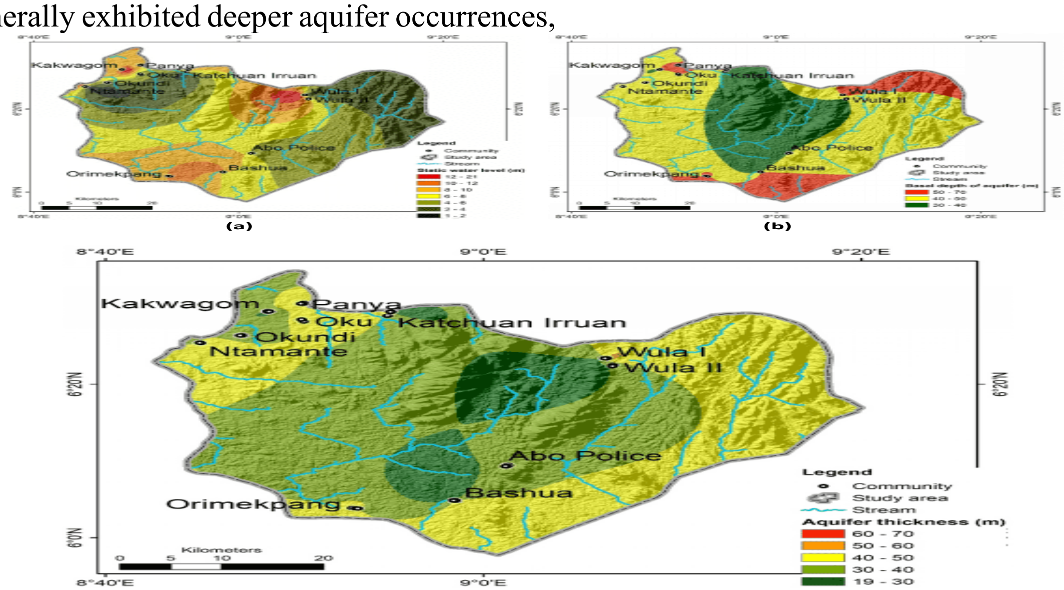

Fig. 11: Spatial distribution of (a) static water level, (b) basal aquifer depth, and (c) aquifer thickness.

The spatial distribution of aquifer thickness further indicates that the thickest aquifer zones occur at Oku, Bashua, and Orimekpang, whereas relatively thin aquifers characterize Katchuan Irruan and Abo-Police, as illustrated by the fence diagram (Fig. 12). These variations are attributed to differences in weathering intensity, fracture development, and basement morphology across the study area.

Considering the entire findings, the VES investigation successfully delineated the principal groundwater-bearing zones within the Afi Mountain area and provided reliable estimates of drilling depths ranging from 30 to 65 m. The interpreted aquifer horizons correspond predominantly to weathered regolith and fractured crystalline basement, confirming that groundwater occurrence within the study area is controlled by secondary porosity and permeability developed through weathering and structural fracturing. The reliability of these interpretations was subsequently evaluated through borehole drilling and pump testing, which are discussed in the following sections.

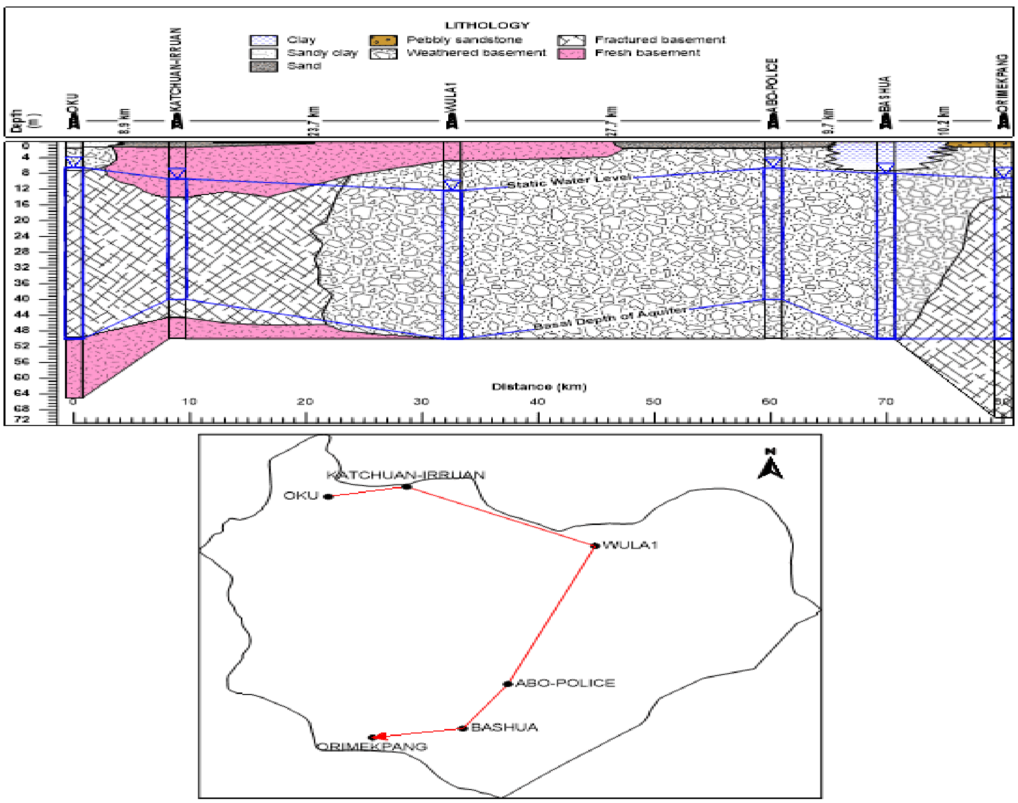

Fig. 12: Fence diagram of drilled Boreholes from Western to Eastern Boki (Inset) showing sub-surface interconnected aquifers

3.2 Borehole Drilling Results and Correlation with VES Interpretation

Following the interpretation of the Vertical Electrical Sounding (VES) data, forty-one (41) boreholes were drilled between 20 April and 13 May 2010 using the Abu Drill Tech rotary air compression drilling rig. The drilling programme was designed to verify the geophysical interpretation and intercept the groundwater-bearing horizons identified from the VES investigations. The drilling results generally confirmed the subsurface lithological sequence interpreted from the VES data. Across the study area, the boreholes penetrated a sequence comprising topsoil or overburden, weathered regolith, fractured basement, and fresh crystalline basement. Groundwater was encountered predominantly within the weathered regolith and fractured basement horizons, confirming that these units constitute the principal aquifers within the crystalline basement complex of the Afi Mountain area.

The recommended VES drilling depths ranged from 30 to 65 m, whereas the actual drilled borehole depths ranged from 35 to 70 m (Table 3). The slight differences between the recommended and actual drilling depths reflect field adjustments made during drilling to ensure complete penetration of the productive aquifer horizons. In most cases, drilling continued slightly beyond the interpreted aquifer to provide sufficient sump space for sediment accumulation and to allow proper installation of the borehole screens and pumps. Comparison of the interpreted VES aquifer depths with the actual drilling depths indicates a high degree of agreement between the geophysical interpretation and the drilling results. The comparison was evaluated using depth deviation criteria in which deviations of less than 5 m were classified as excellent, whereas deviations between 5 and 10 m were classified as poor. These criteria provide an objective assessment of the predictive capability of the VES method in locating groundwater-bearing formations.

Table 3: Comparison between VES recommended drilling depths and actual drilled borehole depths

Town	VES Location	VES Remmended drilling depth (m)	Actual drilling depth (m)	Accuracy deviations level Excellent 1-5m and poor 5-10m	Screen setting (m) Single/Double	Yield (L/S)	Extend success rate of VES method
Okundi	1	50	50	Excellent	20-25/30-40	1.13	Success
	2	50	60	Poor	35-40/50-55	0.35	Fail
	3	50	45	Excellent	15-45	1.43	Success
	4	50	55	Excellent	10-15/45-50	0.75	Success
Okundi New	1	40	55	Poor	30-40/45-50	0.179	Fail
Market	2	40	60	Poor	45-60	0.0027	Fail
	3	40	40	Excellent	20-40	0.69	Success
	4	40	45	Excellent	25-45	0.94	Success
	5	40	40	Excellent	20-35	1.02	Success
Natamante	1	50	55	Excellent	35-55	0.71	Success
	2	50	65	Excellent	20-25/50-60	0.71	Success
	3	50	50	Excellent	30-50	0.86	“
	4	50	55	Excellent	40-50	1.12	“
Kakwagom	1	40	40	Excellent	20-35	1.08	“
	2	60	65	Excellent	30-45	0.66	Fail
	3	45	40	Excellent	20-40	1.0	“
	4	50	40	Poor	20-40	1.02	Success
Abu	1	40	50	Poor	35-45	0.74	Fail
Ogbanyante	2	40	35	Excellent	25-35	0.93	Success

	3	40	45	Excellent	35-45	1.31	“
	4	40	45	Excellent	35-45	1.04	“
Wula II	1	40	35	Excellent	15-35	1.5	Success
	2	40	40	Excellent	20-35	1.08	“
Bashua	1	50	50	Excellent	15-20/35-45	1.0	Success
	2	50	40	Poor	25-40	1.14	Fail
	3	30	45	Poor	25-45	0.99	Fail
	4	40	45	Excellent	25-45	1.08	Success
Katchan	1	40	70	Poor	55-68	0.011	Fail
Irruan	2	40	45	Excellent	25-45	0.0074	Success
	3	50	50	Excellent	30-45	1.07	Success
	4	65	70	Excellent	55-68	1.07	Success
Wula I	1	55	60	Excellent	40-58	1.02	Method
	2	50	50	Excellent	30-45	1.36	Success
	3	45	45	Excellent	30-45	0.003	Success
Orimekpang	1	50	70	Poor	50-65	0.0169	Fail
	2	70	70	Excellent	50-65	0.024	Success
	3	65	70	Poor	50-65	0.0802	Success
	4	50	70	Poor	50-65	0.098	Fail
Oku	1	65	70	Excellent	60-65	0.203	Success
	2	50	45	Poor	25-45	0.0134	Fail
	3	60	65	Excellent	45-65	0.144	Success

ssdddThe comparison revealed that 30 of the 41 boreholes (73.2%) exhibited excellent agreement between the VES-predicted aquifer depth and the actual drilling depth, while 11 boreholes (26.8%) showed poor agreement. Communities such as Ntamante recorded excellent agreement for all four boreholes, indicating consistent hydrogeological conditions and reliable geophysical interpretation. Similarly, most boreholes at Kakwagom, Abo Ogbagante, Wula II, and Wula I also exhibited excellent correlations between the interpreted and drilled aquifer depths.

Conversely, relatively poor correlations were observed in some boreholes within Okundi New Market, Bashua, Katchuan Irruan, Orimekpang, and Oku, where actual drilling depths differed from the VES recommendations by more than 5 m. These discrepancies are attributed primarily to the heterogeneous nature of crystalline basement terrains, where rapid lateral variations in weathering thickness, fracture distribution, and basement relief may not be fully resolved by one-dimensional electrical sounding techniques. Similar limitations of VES in structurally complex basement terrains have been reported by El-Waheidi et al. (1992), Okereke et al. (1998), and Yadav and Abolfazli (1998).

Despite these local discrepancies, all forty-one boreholes successfully intercepted groundwater-bearing formations, demonstrating the effectiveness of the VES technique in identifying favourable drilling locations. However, successful interception of groundwater during drilling did not necessarily correspond to high-yielding boreholes, emphasizing that lithological confirmation alone cannot adequately assess aquifer productivity. The hydraulic characteristics of the aquifers required further evaluation through pumping tests.

The drilling records further indicate considerable variation in total drilled depths, static water levels, borehole installation depths, and recommended pump capacities across the study area (Table 4). Borehole elevations ranged from approximately 111 to 177 m above sea level, reflecting the rugged topography of the Afi Mountain region. Correspondingly, the

estimated VES aquifer depths varied between 40 and 70 m, with higher elevation communities such as Wula, Oku, and Orimekpang generally requiring deeper drilling than lower elevation
communities such as Okundi and Kakwagom.
Static water levels (SWL) measured after drilling ranged from 3.62 m at Oku to 20.78 m at Kakwagom, indicating considerable spatial variability in groundwater levels across the study area. Borehole installation depths generally ranged from 30.6 to 68 m, closely corresponding to the interpreted aquifer intervals identified during the VES survey. Recommended pump capacities varied between 0.5 hp and 1.5 hp, depending on borehole depth and anticipated groundwater yield

Table 4: Summary of VES interpretation, drilling depths, static water levels, borehole installation depths, and recommended pump sizes.

Location	Borehole No	Elevation (m)	VES acquiferous Range depth (m)	SWL (m)	Total Drilled Depth (m)	Borehole installation (m)	Remmend. pump size
Okundi (Panya)	1	136	50	8.27	50	48	1.0
	2	114	50	7.3	60	58	0.5
	3	111	50	8.9	45	43	1.5
	4	149	50	6.45	55	53	1.5
New Market	1	121	40	3.65	55	47	1.0
	2	125	40	5.36	60	57	1.0
	3	124	40	5.70	40	37	1.0
	4	126	40	4.63	45	38	0.5
	5	124	40	5.60	40	38	1.0
Ntamante	1	121	50	11.1	55	51	1.0
	2	126	50	10.33	65	51	1.0
	3	132	50	10.04	50	47	1.0
	4	125	50	11.09	55	52	1.0
Kakwagom	1	128	40	9.2	40	37	1.5
	2	125	60	9.29	65	62	1.0
	3	142	45	9.63	40	38	1.0
	4	132	50	20.78	40	38	1.5
Abo Ogbagante	1	125	40	6.64	50	46	1.0
	2	125	40	7.74	35	30.6	1.0
	3	121	40	6.70	45	42.0	1.0
	4	113	40	5.60	45	43.0	1.0
Wula II	1	171	40	7.98	35	32.0	1.0
	2	159	40	8.53	35	32.0	1.0
Bashua	1	117	50	10.7	50	46	1.0
	2	117	50	7.98	40	32	1.0
	3	127	30	8.62	45	38	0.5
	4	127	40	8.62	45	42	1.0
Katchuan	1	117	40	11.4	70	68	1.0
Irruan	2	138	40	14.5	45	43	1.0
	3	129	50	9.35	50	48	1.5
	4	129	65	10.32	70	67	0.5
Wulla I	1	177	55	14.46	60	54	0.5
	2	169	50	12.28	50	47	1.5
	3	124	45	11.39	45	43	1.5

Orimetupang	1	117	50	9.74	70	65	0.5
	2	115	70	12.14	70	65	0.5
	3	117	65	11.12	70	65	0.5
	4	154	50	9.15	70	68	0.5
Oku	1	117	50	5.78	70	67	0.5
	2	115	50	3.62	45	42	0.5
	3	115	50	6.47	65	62	0.5

hhhThe close agreement observed between the interpreted VES aquifer depths and the actual drilling records confirms the reliability of electrical resistivity sounding as an effective groundwater exploration tool within crystalline basement terrains. Nevertheless, the occurrence of several boreholes with poor depth correlation highlights the influence of localized geological heterogeneity on geophysical interpretation. Consequently, while VES provides valuable guidance for borehole siting, drilling verification remains essential for confirming lithological conditions before borehole completion. The ultimate assessment of groundwater potential, however, depends on the hydraulic performance of the aquifer, which was evaluated through comprehensive borehole pump testing conducted on all forty-one boreholes. The results of the pumping tests are presented and discussed in the following section.

3.3 Borehole Pump Testing Results and Hydraulic Characteristics

Following completion of the drilling programme, borehole pump testing was conducted on all forty-one (41) boreholes between 2 July and 16 July 2017 to evaluate the hydraulic performance of the aquifers intercepted during drilling. The pump tests were designed to determine the sustainable groundwater yields and assess the suitability of the boreholes for domestic water supply. The tests were carried out using a Sonist Model 102 water level sounder for measuring static and dynamic water levels, a 3500 W generator to power the submersible pumps, riser pipes, clamps, stopwatches, and 0.5, 1.0 and 1.5 hp submersible pumps. The pump test data were analysed using Aquifer Test Pro Version 2011.1, from which hydraulic parameters including static water level (SWL), drawdown, pumping duration, dynamic water level, recovery time, borehole yield, total drilled depth, and pump installation depth were determined.

The estimated VES aquifer depths obtained prior to drilling were subsequently compared with the measured hydraulic characteristics of each borehole to evaluate the effectiveness of the VES technique in predicting productive groundwater zones. The complete drilling and pumping test results are summarized in Tables 4, 5a and 5b.

Table 5a. Borehole data analysis (Part I)

Small/Urban Town	Borehole No.	BH Type	Drilled Depth (m)	SWL (m)	Casing Diameter (mm)	Pump Capacity (hp)	Pump Setting Depth (m)
ABU POLICE	No. 1	PVC	45	5.60	140	1.0	43.0
	No. 2	PVC	45	4.20	140	1.0	42.0
	No. 3	PVC	35	7.74	140	1.0	30.6
	No. 4	PVC	50	6.64	140	1.0	46.0
BASHUA	No. 1	PVC	40	7.98	140	1.0	32.0
	No. 2	PVC	50	7.98	140	1.0	46.0

	No. 3	PVC	45	10.70	140	0.5	42.3
	No. 4	PVC	45	8.62	140	1.0	42.0
KAKWAGOM	No. 1	PVC	40	9.20	140	1.5	37.0
	No. 2	PVC	65	9.29	140	1.0	62.0
	No. 3	PVC	40	9.63	140	1.0	38.0
	No. 4	PVC	40	20.80	140	1.5	38.0
KATCHUAN IRRUAN	No. 1	PVC	70	10.30	140	1.5	67.0
	No. 2	PVC	50	9.35	140	1.5	48.0
	No. 3	PVC	45	14.50	140	1.5	43.0
	No. 4	PVC	70	11.40	140	1.5	68.0
NTAMANTE	No. 1	PVC	55	11.10	140	1.0	51.0
	No. 2	PVC	65	10.30	140	1.0	62.0
	No. 3	PVC	50	10.00	140	1.0	47.0
	No. 4	PVC	50	11.10	140	1.0	52.0
OKU	No. 1	PVC	70	5.75	140	1.0	67.0
	No. 2	PVC	45	3.62	140	1.0	42.0
	No. 3	PVC	65	6.47	140	1.0	62.0
OKUNDI	No. 1	PVC	60	3.65	140	1.0	57.0
	No. 2	PVC	60	5.36	140	1.0	57.0
	No. 3	PVC	45	5.70	140	1.0	42.0
	No. 4	PVC	60	4.68	140	1.0	57.0
	No. 5	PVC	45	4.60	140	1.0	42.0
ORIMEKPANG	No. 1	PVC	70	9.15	140	0.5	56.0
	No. 2	PVC	70	9.74	140	0.5	56.0
	No. 3	PVC	70	12.10	140	0.5	56.0
	No. 4	PVC	70	11.20	140	1.5	65.0
PANYIA	No. 1	PVC	50	8.27	140	1.0	48.0
	No. 2	PVC	50	7.30	140	0.5	58.0
	No. 3	PVC	45	8.90	140	1.5	43.0
	No. 4	PVC	55	6.45	140	1.5	53.0
WULA I	No. 1	PVC	45	11.40	140	1.5	42.6
	No. 2	PVC	50	12.30	140	1.5	47.0
	No. 3	PVC	60	14.50	140	1.0	54.0
WULA II	No. 1	PVC	35	7.98	140	1.0	32.0
	No. 2	PVC	45	8.53	140	1.0	32.0

Table 5b. Borehole data analysis (Part II)

Small/Urban Town	Borehole No.	Hours of Pumping	Yield (L/s)	Dynamic WL (m)	Drawdown (m)	Recovery Time (min)	Status
ABU POLICE	No. 1	80 min	0.74	42.29	36.69	45 min	Success
	No. 2	80 min	0.93	42.15	37.95	25 min	Success
	No. 3	120 min	1.31	19.52	11.78	5 min	Success
	No. 4	70 min	1.04	39.55	33.19	40 min	Success
BASHUA	No. 1	70 min	1.00	17.98	10.23	7 min	Success
	No. 2	80 min	1.14	41.45	33.47	–	Success
	No. 3	10 min	–	–	–	–	Failure

	No. 4	70 min	0.99	41.99	33.37	25 min	Success
KAKWAGOM	No. 1	120 min	1.08	31.39	22.23	70 min	Success
	No. 2	120 min	0.66	45.80	36.51	50 min	Success
	No. 3	120 min	1.00	31.50	21.95	30 min	Success
	No. 4	120 min	1.02	33.33	13.16	20 min	Success
KATCHUAN IRRUAN	No. 1	20 min	0.011	–	50.13	120 min	Success
	No. 2	10 min	0.0074	–	34.79	60 min	Failure
	No. 3	120 min	1.07	41.28	26.78	50 min	Success
	No. 4	120 min	1.07	62.57	51.17	60 min	Success
NTAMANTE	No. 1	120 min	0.71	33.39	22.29	30 min	Success
	No. 2	120 min	0.71	–	44.68	45 min	Success
	No. 3	120 min	0.86	–	34.38	25 min	Success
	No. 4	70 min	1.12	45.93	34.84	70 min	Success
OKU	No. 1	25 min	0.203	–	52.60	60 min	Failure
	No. 2	7 min	0.0134	–	33.96	120 min	Success
	No. 3	18 min	0.144	–	48.08	70 min	Failure
OKUNDI	No. 1	30 min	0.179	–	54.27	120 min	Success
	No. 2	40 min	0.693	–	48.12	120 min	Success
	No. 3	120 min	0.94	12.03	6.33	35 min	Success
	No. 4	12 min	0.027	–	31.70	120 min	Failure
	No. 5	120 min	1.04	22.38	17.78	25 min	Success
ORIMEKPANG	No. 1	30 min	0.0169	–	48.30	60 min	Failure
	No. 2	35 min	0.0240	–	49.40	60 min	Failure
	No. 3	40 min	0.0202	–	50.60	60 min	Failure
	No. 4	35 min	0.0980	–	62.38	60 min	Failure
PANYIA	No. 1	120 min	1.13	34.28	26.04	20 min	Success
	No. 2	120 min	0.35	46.89	39.59	90 min	Success
	No. 3	120 min	1.43	15.19	6.29	35 min	Success
	No. 4	120 min	0.725	53.94	47.49	40 min	Success
WULA I	No. 1	120 min	1.02	29.75	18.36	60 min	Success
	No. 2	120 min	1.36	22.93	10.65	45 min	Success
	No. 3	12 min	0.00033	–	30.86	60 min	Failure
WULA II	No. 1	70 min	1.50	10.60	2.62	4 min	Success
	No. 2	70 min	1.08	41.15	32.62	55 min	Success

The pumping test results demonstrate considerable variation in groundwater productivity across the Afi Mountain area, reflecting differences in aquifer thickness, fracture connectivity, degree of weathering, and groundwater storage capacity. Although all forty-one boreholes intercepted groundwater during drilling, only thirty (30) boreholes produced sustainable yields, whereas eleven (11) boreholes exhibited poor hydraulic performance and were classified as failed or low-yielding wells.

The productive boreholes recorded groundwater yields ranging from 0.71 to 1.50 L/s, with the highest yield (1.50 L/s) obtained from Wula II Borehole No. 1. Other highly productive boreholes include Panyia Borehole No. 3 (1.43 L/s), Wula I Borehole No. 2 (1.36 L/s), Abo-Police Borehole No. 3 (1.31 L/s), Bashua Borehole No. 2 (1.14 L/s), Ntamante Borehole No. 4 (1.12 L/s), and several boreholes at Kakwagom, Katchuan Irruan, Okundi, and Abo-Ogbagante, which consistently yielded approximately 1.0 L/s or greater. These boreholes generally exhibited rapid recovery after pumping and relatively moderate drawdown, indicating favourable aquifer transmissivity and adequate groundwater recharge.

Conversely, the low-yielding boreholes produced yields ranging from 0.0074 to 0.35 L/s, indicating poor aquifer productivity despite successful interception of groundwater during drilling. Extremely low yields were recorded at Katchuan Irruan Borehole No. 2 (0.0074 L/s), Katchuan Irruan Borehole No. 1 (0.011 L/s), Oku Borehole No. 2 (0.0134 L/s), Orimekpang Borehole Nos. 1–4 (0.0169–0.098 L/s), and Oku Boreholes Nos. 1 and 3 (0.203 and 0.144 L/s, respectively). These boreholes were characterized by prolonged recovery periods, excessive drawdown, and limited sustainable discharge, indicating poorly developed fractures or thin weathered aquifers incapable of sustaining prolonged pumping.

Static water levels measured immediately before pumping varied considerably across the study area. The shallowest static water level (3.62 m) occurred at Oku Borehole No. 2, whereas the deepest (20.78 m) was recorded at Kakwagom Borehole No. 4. Most boreholes exhibited static water levels between 5 and 12 m, indicating that groundwater is generally accessible at moderate depths throughout the study area. However, static water level alone did not control borehole productivity, as several boreholes with shallow groundwater levels nevertheless recorded poor yields due to limited aquifer thickness or inadequate fracture development.

Dynamic water levels and drawdown values also varied significantly among the boreholes. Productive boreholes generally recorded moderate drawdown with relatively rapid recovery times ranging from 4 to 70 minutes, whereas several low-yielding boreholes required 60–120 minutes to recover following pumping. For example, Wula II Borehole No. 1, which recorded the highest yield of 1.50 L/s, recovered within 4 minutes, demonstrating excellent aquifer recharge characteristics. In contrast, Katchuan Irruan Borehole No. 2, Oku Borehole No. 2, Okundi Borehole No. 1, and several boreholes at Orimekpang required recovery periods of up to 120 minutes, reflecting poor hydraulic conductivity and limited groundwater replenishment.

The borehole construction data further indicate that 140 mm PVC casing was used for all installations, while pump capacities ranged from 0.5 to 1.5 hp, depending on the expected discharge and total installation depth. Pump installation depths generally ranged between 30.6 and 68.0 m, closely corresponding to the interpreted aquifer depths identified from the VES survey. The consistency between pump setting depths and interpreted aquifer intervals demonstrates that borehole completion was appropriately designed to maximize groundwater abstraction from the productive zones.

Comparison of the pumping test results with the VES interpretation further demonstrates the effectiveness of the integrated exploration approach. Boreholes exhibiting excellent agreement between VES-predicted depths and actual drilling depths generally produced the highest groundwater yields, whereas most boreholes classified as having poor VES-depth correlation also recorded poor hydraulic performance. Overall, 30 boreholes (73.2%) exhibited both excellent VES-drilling agreement and satisfactory groundwater yields, while 11 boreholes (26.8%) showed poor depth correlation accompanied by low yields. This relationship confirms that accurate geophysical interpretation substantially improves the probability of successful groundwater development in basement terrains.

Nevertheless, the occurrence of several low-yielding boreholes despite successful VES predictions illustrates the limitations of relying solely on electrical resistivity data for groundwater development. Electrical resistivity methods primarily identify weathered and fractured zones but cannot fully resolve fracture aperture, fracture connectivity, hydraulic conductivity, or groundwater storage capacity. Consequently, some boreholes intercepted water-bearing fractures that were incapable of sustaining prolonged pumping, resulting in low yields despite apparently favourable geophysical signatures. Similar observations have been reported in crystalline basement aquifers by El-Waheidi et al. (1992), Okereke et al. (1998), Yadav and Abolfazli (1998), and Kussiński and Kelly (1981).

Overall, the pumping test results confirm that pump testing remains an indispensable component of groundwater exploration programmes. While the VES survey proved highly effective in identifying groundwater-bearing formations and guiding drilling operations, only hydraulic testing could determine whether the intercepted aquifers were capable of providing sustainable water supplies. The combined application of Vertical Electrical Sounding, borehole drilling, and pump testing therefore provides a comprehensive and reliable methodology for groundwater exploration and development in environmentally challenging crystalline basement terrains such as the Afi Mountain area.

3.4 Evaluation of VES Accuracy Using Borehole Drilling and Pump Testing

The effectiveness of the Vertical Electrical Sounding (VES) technique for groundwater exploration in the Afi Mountain area was evaluated by comparing the recommended VES drilling depths with the actual drilling depths and the corresponding pump testing results obtained from the forty-one boreholes. The comparison was undertaken to determine the reliability of the VES method in predicting groundwater-bearing zones and to assess its effectiveness in guiding borehole drilling within the crystalline basement terrain. The degree of agreement between the VES interpretation and the drilling records was classified using deviation limits of less than 5 m as excellent and greater than 5–10 m as poor (Table 3).

The results indicate that the VES technique provided reliable estimates of aquifer occurrence throughout the study area. Of the 41 boreholes investigated, 30 boreholes (73.2%) showed excellent agreement between the interpreted VES aquifer depths and the actual drilling depths, whereas 11 boreholes (26.8%) exhibited poor agreement, with deviations exceeding the established tolerance of 5 m. This high percentage of accurate predictions demonstrates that electrical resistivity sounding is an effective method for locating groundwater-bearing weathered and fractured basement zones within the Afi Mountain area.

The distribution of VES accuracy varied among the investigated communities. Ntamante recorded excellent agreement for all four boreholes, with groundwater yields ranging from 0.71 to 1.12 L/s. Similarly, Wula II, Abo-Ogbagante, and most boreholes in Kakwagom and Wula I exhibited close correspondence between the VES-recommended drilling depths and the actual drilling depths, confirming the reliability of the geophysical interpretation.

Conversely, several boreholes in Okundi New Market, Bashua, Katchuan Irruan, Orimekpang, and Oku exhibited poorer agreement between the predicted and actual drilling depths. For instance, Katchuan Irruan Borehole 1 required drilling to 70 m compared with the recommended depth of 40 m, while Orimekpang Boreholes 1, 3, and 4 also showed deviations exceeding 5 m. Similar discrepancies occurred in Okundi New Market, where two boreholes required drilling to depths of 55–60 m instead of the recommended 40 m. These differences reflect the heterogeneous nature of crystalline basement aquifers, where rapid lateral variations in weathering thickness, fracture distribution, and basement topography cannot always be fully resolved by one-dimensional resistivity sounding.

Pump testing further demonstrated a strong relationship between VES accuracy and borehole productivity. Boreholes with excellent agreement between VES interpretation and drilling records generally produced sustainable groundwater yields ranging from 0.71 to 1.50 L/s. Notable examples include Panyia Borehole 3 (1.43 L/s), Wula II Borehole 1 (1.50 L/s), Wula I Borehole 2 (1.36 L/s), and Abo-Ogbagante Borehole 3 (1.31 L/s). These boreholes also exhibited moderate drawdown and relatively rapid recovery following pumping, indicating favourable aquifer transmissivity and storage characteristics.

In contrast, boreholes exhibiting poor agreement between the VES predictions and drilling depths generally recorded low groundwater yields. Katchuan Irruan Borehole 2 yielded only 0.0074 L/s, while Katchuan Irruan Borehole 1 produced 0.011 L/s. Likewise, boreholes at Orimekpang yielded between 0.0169 and 0.098 L/s, whereas Oku recorded yields ranging from 0.0134 to 0.203 L/s. These boreholes were characterized by prolonged recovery times and relatively large drawdown values, indicating poor hydraulic connectivity and low aquifer transmissivity despite the presence of groundwater.

Overall, groundwater was intercepted in all forty-one boreholes, confirming that the VES method successfully identified groundwater-bearing formations throughout the study area. However, the hydraulic performance of the boreholes varied considerably. The eleven low-yielding boreholes demonstrate that identifying groundwater-bearing formations does not necessarily guarantee sustainable groundwater production, particularly where fractures are poorly interconnected or the weathered zone has limited saturated thickness.

The observed discrepancies between VES predictions and borehole performance may be attributed to the inherent complexity of fractured basement aquifers. Although electrical resistivity surveys effectively identify weathered and fractured zones, they cannot directly determine fracture connectivity, aquifer transmissivity, recharge conditions, or groundwater storage capacity. Similar limitations of electrical resistivity techniques in crystalline basement terrains have been reported by El-Waheidi et al. (1992), Okereke et al. (1998), Yadav and Abolfazli (1998), and Kussiński and Kelly (1981).

Overall, the results demonstrate that the integrated application of Vertical Electrical Sounding, borehole drilling, and pump testing substantially improves the reliability of groundwater exploration in basement complex terrains. While the VES technique achieved an overall prediction accuracy of 73.2%, pump testing provided essential hydraulic verification of borehole productivity, confirming that hydraulic testing remains indispensable before groundwater development.

3.5 Hydrogeological Implications for Groundwater Development in the Afi Mountain Area

The integrated interpretation of the Vertical Electrical Sounding (VES), borehole drilling, and pump testing results provides important insights into the hydrogeological characteristics of the crystalline basement underlying the Afi Mountain area. The results indicate that groundwater occurrence is controlled primarily by the thickness of the weathered regolith, the degree of basement fracturing, aquifer thickness, and topographic variation. These factors collectively influence groundwater storage, recharge, and borehole productivity within the study area.

The geoelectrical interpretation (Tables 1 and 2) shows that the most productive groundwater zones occur within moderately weathered regolith and fractured basement rocks, where resistivity values generally range between 200 and 300 Ωm for saturated weathered regolith and 300–600 Ωm for fractured basement aquifers. Fresh basement rocks, characterized by resistivity values exceeding 600 Ωm, generally possess poor groundwater potential because of their negligible primary porosity. These observations agree with previous studies of groundwater occurrence in Precambrian basement terrains (El-Waheidi et al., 1992; Okereke et al., 1998; Yadav & Abolfazli, 1998).

The spatial distribution of groundwater also reflects the influence of topography. Higher-elevation communities such as Wula, Oku, and Orimekpang required deeper drilling depths of 50–70 m, whereas lower-elevation communities including Okundi, Kakwagom, and Abo-Ogbagante generally encountered productive aquifers between 40 and 50 m. This pattern suggests that groundwater recharge occurs mainly in the elevated terrains before flowing through weathered and fractured basement zones toward lower elevations.

The groundwater maps (Fig. 11a–c) show the spatial distribution of static water level, basal aquifer depth, and aquifer thickness across the study area, while the fence diagram (Fig. 12) illustrates the lateral continuity and variation of the aquifer system. The figures reveal relatively thicker aquifer zones beneath Oku, Bashua, and Orimekpang, indicating greater groundwater storage potential, whereas Katchuan Irruan and Abo-Ogbagante possess comparatively thinner aquifers associated with lower groundwater storage capacity. These spatial variations highlight the need for detailed hydrogeophysical investigations before borehole development in crystalline basement terrains.

Although groundwater was encountered in all forty-one drilled boreholes, the pumping test results demonstrate that groundwater occurrence alone does not guarantee sustainable groundwater production. Eleven boreholes recorded low yields despite successfully intersecting groundwater-bearing formations. These failures are attributed primarily to poor fracture connectivity, thin saturated weathered zones, and low hydraulic conductivity within the fractured basement aquifers. Consequently, electrical resistivity surveys should always be complemented by drilling verification and hydraulic testing to accurately assess aquifer productivity.

The overall success rate of 73.2% obtained in this study compares favourably with previous groundwater investigations in Nigerian basement terrains (Edet, 1994; Odigi & Okonny, 1987; Okereke et al., 1998). The findings confirm that integrating VES, borehole drilling, and pump testing provides a robust and reliable framework for groundwater exploration, reduces drilling uncertainty, and enhances the sustainable development of groundwater resources in environmentally challenging crystalline basement environments.

3.6 Summary of Major Findings

The integrated application of **Vertical** Electrical Sounding (VES), borehole drilling, and borehole pump testing provided a comprehensive assessment of groundwater occurrence, aquifer characteristics, and borehole productivity within the environmentally challenging crystalline basement terrain of the Afi Mountain area, Boki Local Government Area, Cross River State. The results demonstrate that the combined hydrogeophysical and hydrogeological approach significantly improved groundwater exploration success by providing reliable estimates of aquifer depth prior to drilling and subsequently validating groundwater productivity through hydraulic testing.

The VES investigation successfully delineated the principal subsurface lithological units, consisting of topsoil or overburden, weathered regolith, fractured basement, and fresh basement rocks. The interpreted resistivity values clearly distinguished these lithological units, with moderate resistivity values (200–300 Ωm) corresponding to saturated weathered regolith, 300–600 Ωm representing fractured basement aquifers, and values greater than 600 Ωm indicating competent fresh basement. The interpreted aquifer depths ranged from 30 to 65 m, providing the basis for locating the forty-one boreholes drilled during the investigation.

Comparison between the VES interpretations and the actual drilling records demonstrated a high degree of agreement. Of the forty-one boreholes, thirty (73.2%) exhibited excellent correspondence between the predicted aquifer depths and the drilled depths, while eleven (26.8%) showed poorer agreement with depth deviations exceeding 5 m. These results indicate that the VES technique provided reliable predictions of groundwater occurrence despite the complex geological conditions associated with the crystalline basement terrain.

Borehole drilling confirmed that groundwater occurs predominantly within the weathered regolith and fractured crystalline basement, validating the geophysical interpretation. The drilling records further demonstrated considerable spatial variability in aquifer thickness and depth, reflecting differences in basement weathering, fracture development, and topographic relief across the study area. Higher elevation communities generally required deeper boreholes than the lower-lying western communities, indicating the influence of topography on groundwater occurrence.

The pumping test results further demonstrated that successful interception of groundwater during drilling does not necessarily guarantee sustainable groundwater production. Although groundwater was encountered in all forty-one boreholes, only thirty boreholes produced sustainable yields, whereas eleven boreholes recorded very low groundwater yields ranging from approximately 0.0074 to 0.35 L/s. In contrast, productive boreholes yielded between 0.71 and 1.50 L/s, with the highest discharge recorded at Wula II. The low-yielding boreholes were generally associated with poor fracture connectivity, limited aquifer thickness, and reduced hydraulic conductivity despite the presence of groundwater-bearing formations.

The comparison between the VES predictions, drilling records, and pumping test results demonstrates that boreholes exhibiting excellent agreement between interpreted and drilled aquifer depths generally produced higher groundwater yields, whereas many of the boreholes with poor VES correlation also exhibited poor hydraulic performance. This relationship confirms that accurate geophysical interpretation substantially increases the probability of drilling productive groundwater wells, although hydraulic testing remains essential for confirming long-term borehole performance.

The study further established that groundwater occurrence within the Afi Mountain area is strongly controlled by secondary porosity developed through weathering and fracturing of the crystalline basement rocks. Consequently, the distribution of groundwater is highly heterogeneous, with significant variations in aquifer thickness, hydraulic characteristics, and borehole productivity occurring over relatively short distances. These findings emphasize the limitations of relying solely on geological observations or drilling experience for groundwater exploration in basement terrains.

Overall, the investigation demonstrates that the integration of Vertical Electrical Sounding, borehole drilling, and pump testing provides a reliable and scientifically robust methodology for groundwater exploration in crystalline basement environments. While the VES technique proved highly effective for identifying groundwater-bearing zones and selecting drilling locations, the pump testing programme was indispensable for evaluating aquifer productivity and distinguishing productive boreholes from low-yielding wells. The combined approach therefore minimizes exploration uncertainty, improves borehole success rates, and provides a sound basis for sustainable groundwater development within the Afi Mountain region and other environmentally challenging basement complex terrains.

The findings of this study contribute valuable hydrogeological information for groundwater resource planning in Cross River State and provide a practical framework for future groundwater exploration programmes in similar Precambrian basement terrains throughout Nigeria and other parts of sub-Saharan Africa. These results underscore the necessity of integrating geophysical investigation with drilling verification and hydraulic testing to ensure the successful development of reliable and sustainable groundwater supplies.

4.0 Conclusion

This study successfully evaluated the effectiveness of Vertical Electrical Sounding (VES), borehole drilling, and pump testing for groundwater exploration within the environmentally challenging crystalline basement terrain of the Afi Mountains, Boki Local Government Area, South-Eastern Nigeria. The integrated approach proved reliable in delineating groundwater-bearing weathered and fractured basement zones and in guiding borehole drilling. The interpreted VES models identified aquifer depths ranging from 30 to 65 m, while actual drilling depths ranged from 35 to 70 m, demonstrating good agreement between geophysical predictions and field observations.

Comparison between VES interpretations and drilling records showed that 30 of the 41 boreholes (73.2%) exhibited excellent depth correlation, whereas 11 boreholes (26.8%) showed poor agreement due to geological heterogeneity and variations in fracture development. Although groundwater was encountered in all drilled boreholes, pumping tests revealed that only 30 boreholes produced sustainable yields ranging from 0.71 to 1.50 L/s, while 11 boreholes recorded low yields between 0.0074 and 0.35 L/s despite successfully intercepting groundwater-bearing formations. These results demonstrate that successful borehole drilling alone does not guarantee sustainable groundwater production.

The study further established that groundwater occurrence is controlled primarily by the thickness of the weathered regolith, the extent of basement fracturing, and local topographic conditions. Consequently, electrical resistivity surveys should be complemented with borehole drilling and hydraulic testing to accurately evaluate aquifer productivity. Overall, the integration of VES, drilling, and pump testing provides a robust and cost-effective methodology for groundwater exploration and development in basement complex terrains. The findings provide valuable baseline information for groundwater resource planning and sustainable rural water supply development in the Afi Mountain region and other similar crystalline basement environments across Nigeria.

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Author Contribution

Dominic Akam Obi conceived the study, supervised field investigations, and contributed to manuscript review. Philip Asuquo Edem conducted data analysis, interpreted results, and drafted the manuscript. Samuel Izama Ugar participated in geophysical surveys and data acquisition. M. I. Morphy assisted with borehole drilling and pump-test evaluation. Selong Unanaonwi Edem contributed to data validation and manuscript editing. Moses Ekene Obasi supported fieldwork, literature review, and final manuscript preparation. All authors read and approved the final manuscript.