SUBSURFACE CHARACTERIZATION AND AQUIFER MAPPING IN ZAMBUK AND ENVIRONS GOMBE STATE VIA ELECTRICAL RESISTIVITY METHOD

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ABSTRACT

This study presents the results of a geophysical investigation aimed at evaluating groundwater potential in a selected area using Vertical Electrical Sounding (VES) techniques. A total of ten VES points was analyzed, revealing that H and K curve types constitute 60% of the subsurface profiles, indicating a relatively uniform stratigraphy favorable for hydrogeological assessment. The interpretation of resistivity data in relation to lithological units enabled the identification of suitable groundwater-bearing formations. Sandstone layers, with resistivity values ranging from 100 to 1000Ωm, emerged as the most promising aquifers due to their moderate to high porosity and permeability. VES1, VES3, VES4, VES6, VES8, and VES10 were classified as moderate-yield sites, while VES5 and VES9 were identified as high-yield locations, though the compacted sandstone at VES5 suggests limited porosity. Low-resistivity zones (<100 Ωm) at VES2 and VES7 correspond to clay and shale formations that act as aquitards, making them unsuitable for groundwater development. An iso-resistivity map generated at an electrode spacing of AB/2 = 80 m delineated three distinct zones-high, moderate, and low resistivity-aligned with regional hydrogeological structures. These findings provide critical insights for informed groundwater exploration and sustainable borehole siting in the study area.

Keywords: Groundwater, WinResist, Aquifer, Gombe, Zambuk

1 INTRODUCTION

Water is a fundamental resource for human survival and development. It is essential for various daily activities such as drinking, cooking, washing, and industrial processes [1, 2] Among available water sources, groundwater plays a critical role due to its relatively large storage capacity, availability, and resistance to surface contamination. Globally, it remains a major source of clean and safe water for domestic, agricultural, and industrial uses [3]. The characteristics of an aquifer significantly influence the movement and availability of groundwater, making it imperative to employ effective methods for aquifer evaluation and groundwater exploration. Geophysical methods, particularly the Vertical Electrical Sounding (VES) technique, have proven to be efficient and reliable in subsurface investigations, including groundwater studies [4, 5]. VES, a form of electrical resistivity survey, enables the determination of resistivity variation with depth, making it ideal for mapping subsurface lithologies and delineating aquifer systems. It has been widely used and recommended for hydro-geophysical investigations, especially in sedimentary terrains like those found in the Benue Trough [6]. The success of groundwater development projects relies heavily on accurate characterization of aquifer parameters and the identification of suitable locations for borehole drilling [7]. In Zambuk, located in Yamaltu Deba Local Government Area of Gombe State, the pressure on water resources is mounting due to rapid population growth, expanding agricultural activities, and changing climatic conditions [8]. Despite the potential of groundwater resources in northeastern Nigeria, many communities in Zambuk still suffer from water scarcity. The frequent failure of boreholes is largely due to poor siting practices, insufficient geological data, and the use of outdated or unscientific methods [9, 10]. Reliance on traditional approaches has resulted in low borehole success rates, financial waste, and unreliable water supply systems. Additionally, the absence of comprehensive hydro-geoelectrical studies has left groundwater resources in the area underutilized and poorly managed [11]. To overcome these limitations, this study leverages the VES technique to delineate subsurface lithologies, characterize aquifer properties, and identify high-potential groundwater zones. The ultimate goal is to provide a scientific framework for sustainable groundwater development in Zambuk and its surrounding communities. The study aims to improve the efficiency of groundwater exploration in Zambuk by employing geo-electrical resistivity methods to locate viable aquifer systems. Specifically, it seeks to delineate subsurface lithologies and aquifer systems in Zambuk using VES; identify and characterize water-bearing zones based on resistivity values and lithologic correlations; and recommend suitable locations for borehole drilling to ensure sustainable groundwater development. The research focuses on investigating groundwater resources in Zambuk using geoelectrical resistivity methods. It includes conducting VES at selected locations, interpreting resistivity data to identify aquifer zones and correlate them with lithologic logs, and generating iso-resistivity maps to visualize subsurface resistivity variations. However, the study is constrained by the probing depth limited to a maximum electrode spacing of AB/2 = 100 m [12] and the accuracy of lithologic interpretation relies on the availability of borehole logs. Furthermore, this study does not cover geochemical analysis of groundwater quality, which is essential for evaluating potability. This study is significant as it provides a scientific and cost-effective approach to groundwater exploration in Zambuk, reducing the risk of borehole failure and promoting cost-effective drilling operations [10]. The findings will contribute to the sustainable management of groundwater resources in the study area, benefiting local communities, farmers, and policymakers [13]. The study also enriches the scientific literature on hydro-geoelectrical investigations within the Benue Trough, especially in less-studied areas like Zambuk [14]. By identifying productive aquifer zones, this research supports the achievement of Sustainable Development Goal (SDG) 6: ensuring access to clean water and sanitation for all [15].

2 THE STUDY AREA

The study area, Zambuk, is located in Yamaltu Deba Local Government Area of Gombe State, northeastern Nigeria, within the coordinates of approximately 10°18' N to 10°21' N latitude and 11°20' E to 11°23' E longitude (Figure). It falls within the Benue Trough, a prominent sedimentary basin in Nigeria, and is underlain by the Bima Formation, known for its groundwater-bearing sandstone units [14]. The topography of Zambuk is gently undulating, with elevations ranging from 400 to 600 meters above sea level, and it is bordered by the Gombe Hills to the west, which influence local drainage patterns and facilitate groundwater recharge [10]. The area experiences a tropical savanna climate with two distinct seasons: a wet season from April to October, bringing 800–1000 mm of rainfall annually, and a dry season from November to March characterized by high temperatures and low humidity [8]. Surface water resources are limited to seasonal streams that often dry up during the long dry season, making groundwater the primary source of water for domestic and agricultural use. The Bima Formation, with its permeable sandstone layers, serves as the main aquifer, offering substantial groundwater storage and transmission potential [10].

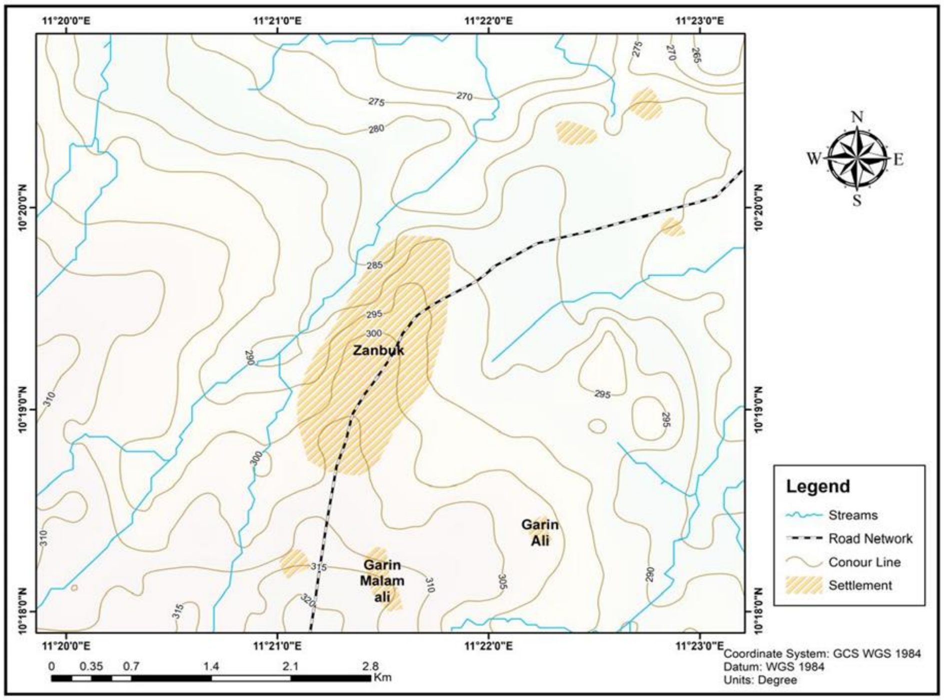

Figure 1. Topographic Map of the study area

3 METHODOLOGY

3.1 Field Methods

The field methodology involved the strategic selection of ten Vertical Electrical Sounding (VES) points across Zambuk, Yamaltu Deba LGA, spaced approximately 1 to 2km apart to capture subsurface variations while ensuring accessibility and data quality. Each point was georeferenced using a handheld GPS and selected based on geological significance-primarily the Bima Sandstone and alluvial deposits-along with logistical ease and minimal interference. An Ohmega Terrameter was used for resistivity measurements, chosen for its high input impedance (>20 MΩ), automatic current adjustment (1–250 mA), and data logging capabilities [12]. The device injected direct current pulses into the ground and measured the resulting voltage difference using current and potential electrodes. Field setup involved AB/2 spacings of up to 100 m, with 20 readings per VES point, and electrode adjustments at 10 m and 45 m to ensure accuracy and data continuity [15]. Essential field tools included a reliable power source and notebooks for recording observations, making the methodology robust for identifying productive aquifer zones and guiding sustainable groundwater development.

3.2 Data Interpretation

Data interpretation was carried out using both manual and computer-aided techniques to analyze the apparent resistivity values obtained from the VES survey. Initially, partial curve matching was employed, which involved comparing the field curves to standard theoretical master curves to estimate subsurface resistivities and layer thicknesses [16]. This method facilitated the identification of typical curve types such as H-type and K-type, and the interpretations were cross-validated using available borehole logs from nearby sites [9]. For greater accuracy, the WinResist software was used to perform one-dimensional (1D) inversion of the resistivity data, automatically adjusting model parameters to achieve a root-mean-square (RMS) error of less than 10% and generating a layered-earth model that detailed the resistivity and thickness of each subsurface layer. Lithological interpretation was performed by correlating resistivity values with known geological units, supported by borehole logs from Zircon Consult Limited. Standard resistivity ranges were applied to infer lithologies: clay and shale (1–100Ωm), topsoil (10–1000Ωm), clayey sand (10–400Ωm), sandy clay (10–100Ωm), sandstone (100–1000Ωm), and compacted sandstone (>1000Ωm) [14]. This integrated approach enabled reliable characterization of the subsurface and identification of productive aquifer zones.

4 RESULTS AND DISCUSSION

The results of the 10 Vertical Electrical Soundings (VES) conducted in Zambuk, Y/Deba, Gombe State, reveal subsurface layers with distinct resistivity and thickness variations (Table 1). In the study area, H and K curve types constitute 60% of the total curves obtained, and locations suitable for potential groundwater exploration include VES1, VES3, VES4, VES6, VES8, and VES10 due to their moderate to low resistivity values. The aquifer units in these locations predominantly consist of sandstone at VES1 and VES3, moderately medium sandstone at VES6 and VES10, and moderately silty sand at VES8. These formations are favorable for groundwater exploration because they exhibit moderate yield with moderate to high porosity and permeability [17]. Conversely, VES5 and VES9 show high resistivity values with aquifers dominated by compacted or weathered sandstone, indicating limited groundwater storage potential. Areas with low resistivity, especially around VES2 and VES7, suggest the presence of shale or clay layers that act as aquitards due to their low permeability, making them unsuitable for drilling. At a probing depth of AB/2 = 100 meters, the study area comprises three to four-layer earth models with varying resistivity ranges. The resistivity ranges associated with key lithological units provide further insight into their groundwater-bearing potential. Clay and shale units typically exhibit low resistivity values ranging from 1 to 100 Ωm due to their low permeability and high-water retention; for example, VES2 Layer 3 recorded a resistivity of 5.9 Ωm. These formations generally act as aquitards, restricting groundwater movement. Sandy clay, with resistivity values between 10 and 100 Ωm (e.g., VES3 Layer 2: 12.2Ωm), shows moderate permeability and high porosity, allowing it to function as an aquifer but with limited groundwater yield. Sandstone, characterized by resistivity values from 100 to 1000 Ωm (VES4 Layer 3: 207.2Ωm), is highly valued as an aquifer material due to its moderate to high porosity and permeability, supporting efficient groundwater flow [16, 18]. In contrast, compacted sandstone, with resistivity exceeding 1000Ωm (e.g., VES5 Layer 3: 6145.3Ωm), indicates low porosity and permeability, making it less favourable for groundwater extraction compared to unconsolidated sandstone layers. These resistivity-lithology relationships are critical for identifying and prioritizing productive groundwater zones [19]. An iso-resistivity map generated at an electrode spacing of AB/2 = 80 m (probing to a depth of approximately 40 m) reveals three distinct resistivity zones that correspond to key aquifer characteristics in the study area (Figure 2). The High-Resistivity Zone, located in the northwestern part of the area, shows resistivity values ranging from 500 to 6,145Ωm and corresponds to sandstone and compacted sandstone aquifers identified at VES4 and VES9. While sandstone aquifers in this zone exhibit high porosity and permeability, facilitating significant groundwater discharge [20], compacted sandstone formations yield lower quantities of groundwater due to reduced porosity and permeability. The Moderate-Resistivity Zone, observed in the central part of the study area, has resistivity values between 100 and 500Ωm and includes points such as VES3 and VES6, where lithologies are dominated by sandy clay or siltstone. These materials possess moderate permeability and may function as leaky aquifers, allowing limited groundwater movement and supply. Finally, the Low-Resistivity Zone is found in the southeastern part of the area and is characterized by resistivity values below 50Ωm. It includes VES2 and VES7 and is dominated by clay and shale layers, which are typically low-permeability formations acting as aquitards, impeding vertical groundwater movement and offering minimal potential for groundwater extraction. These zones correspond well with the geological structure of the Bima Formation and align with known regional groundwater flow patterns [14, 21]. Based on the interpretation of VES data and resistivity-lithology relationships, high-yield borehole sites are recommended at VES5, characterized by high-resistivity sandstone (~4,500–6,500Ωm) suitable for community or small-town boreholes, and VES9, with moderate-resistivity sandstone (~450–2,000Ωm), ideal for high-yield community water supply. Moderate-yield sites include VES1, VES3, VES4, VES6, VES8, and VES10, which contain sandy clay or siltstone layers (~40–200Ωm) suitable for shallow wells and community boreholes. Sites to avoid are VES2 and VES7, with low-resistivity clay or shale layers (<100Ωm), which are unsuitable for drilling due to their low permeability and aquitard characteristics.

Table 1. Inferred Lithologies and aquifer characterization of the study area

VES no.	Coordinate	Layer no.	Resistivity (Ωm)	Thickness (m)	Infered lithology	Curve type	Aquifer characterization
VES 1	N 10°18´11´´	1	41.2	1.0	Top Soil	K	Sandstone
	E 11°21´37´´	2	55.8	1.4	Shale		
		3	50.6	16.3	Sandstone		
		4	22.9		Shale/Sandstone		
VES 2	N 10°18´25.6´´	1	9.2	0.8	Sandy Top Soil	KA	Shaly Sandstone
	E 11°22´8´´	2	45.8	2.3	Shale		
		3	5.9	9.4	Sandstone/Shale		
		4	107.0		Shale		
VES 3	N 10°18´03´´	1	50.0	2.7	Top Soil	H	Sandstone
	E 11°22´53´´	2	12.2	6.7	Shale		
		3	43.0	24.7	Sandstone		
		4	7.8		Shale/Sandstone		
VES 4	N 10°18´41´´	1	5.0	8.2	Top Soil	A	High (sandstone aquifer)
	E 11°22´49´´	2	23.9	44.2	Shale		
		3	207.2		Sandstone		
VES 5	N 10°19´18´´	1	31.2	11.9	Clayey Sand	A	Low (compacted sandstone)
	E 11°21´41´´	2	37.1	29.9	Top Shale		
		3	6145.3		Very Fine-Grained Sandstone		
VES 6	N 10°19´43´´	1	825.9	0.5	Sandy Top Soil	H	Moderate (medium sandstone)
	E 11°22´32´´	2	47.3	1.5	Shale		
		3	152.5	23.9	Shale/Sandstone		
		4	177.1		Sandstone		
VES 7	N 10°20´33´´	1	6.0	13.8	Sandy Top Soil	K	Very Coarse Sandstone
	E 11°22´49´´	2	77.9	37.6	Shale		
		3	13.3		Medium Grained Sandstone		
VES 8	N 10°20´53.4´´	1	86.2	11.16	Sandy Top Soil	K	Moderate (silty sand)
	E 11°22´13´´	2	196.7	31.1	Shale		
		3	99.6		Sandstone		
VES 9	N 10°20´51.7´´	1	34.3	0.6	Sandy Top Soil	KA	High (sandstone aquifer)
	E 11°21´34´´	2	383.1	2.2	Shale		
		3	35.7	6.9	Shale/Sandstone		
		4	462.3		Sandstone		
VES 10	N 10°20´07´´	1	34.1	21.1	Sandy Top Soil	H	Moderate (weathered sandstone)
	E 11°22´11.8´´	2	14.3	38.1	Shale		
		3	67.9		Sandstone		

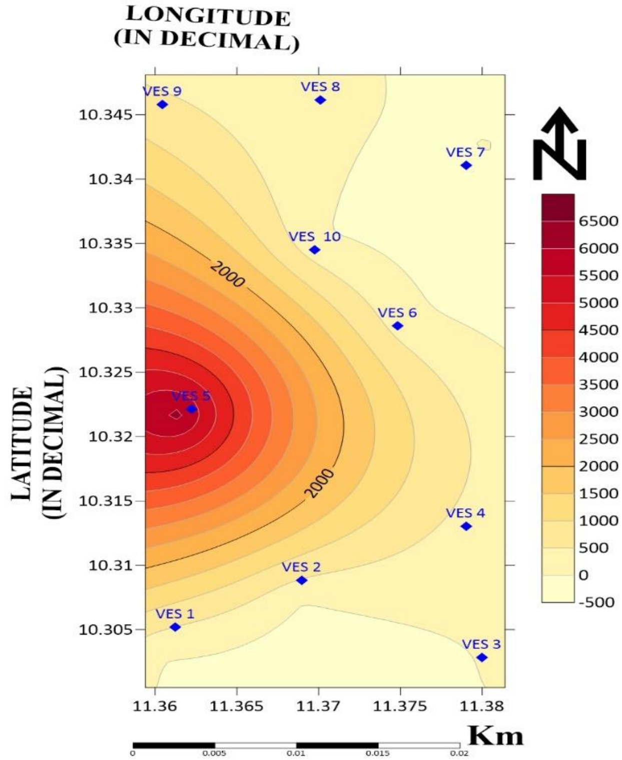

Figure 2. Iso-Resistivity map of the study area

5 CONCLUSIONS

The geophysical investigation using Vertical Electrical Sounding (VES) has successfully delineated the subsurface lithology and assessed the groundwater potential of the study area. The predominance of H and K curve types, constituting 60% of the total curves, indicates a consistent subsurface layering favorable for hydrogeological analysis. Analysis of resistivity values in relation to lithological units has shown that sandstone formations, particularly those with resistivity values between 100 and 1000Ωm, represent the most promising aquifers due to their moderate to high porosity and permeability. Locations such as VES1, VES3, VES4, VES6, VES8, and VES10 are identified as moderate-yield sites, while VES5 and VES9 offer high-yield potential, albeit with caution due to compacted sandstone at VES5. In contrast, VES2 and VES7, which show very low resistivity values, are associated with clay and shale units that act as aquitards, making them unsuitable for groundwater development. The iso-resistivity mapping further reinforces these findings, delineating high, moderate, and low resistivity zones corresponding to sandstone aquifers, sandy clay layers, and clay/shale formations, respectively. These results provide a reliable basis for groundwater exploration and borehole siting in the study area, contributing to more efficient and sustainable water resource management.

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