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An Assessment of Geoelectric Layers for Groundwater Availability in Makurdi Local Government Area, Benue State, Nigeria

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ABSTRACT

This study assesses the geoelectric layering and groundwater availability in Makurdi Local Government Area, Benue State, Nigeria, using the Vertical Electrical Sounding (VES) method. Geoelectrical parameters, including resistivity, layer thickness, and depth, were analyzed across multiple VES stations to evaluate groundwater potential. The results reveal considerable spatial variation in subsurface resistivity values, ranging from 30.7 Ωm to 58,000 Ωm, indicating heterogeneous lithologic conditions that transition from clayey and sandy soils to consolidated bedrock. Hydraulic parameters, including transmissivity and hydraulic conductivity, were estimated from the interpreted geoelectric data to characterize groundwater flow potential. Transmissivity values reached up to 200.196 m²/day, while hydraulic conductivity ranged from 0.000164 to 0.034578 m/day, reflecting varying aquifer capacities across the study area. High groundwater potential was identified at locations such as North Bank Market, whereas restricted groundwater flow conditions were observed around Aper Aku Stadium. The calculated current electrode spacing (AB/2) and apparent resistivity values further elucidate the groundwater flow characteristics of the subsurface layers. Overall, this research provides valuable insights into the hydrogeophysical characteristics and groundwater dynamics of Makurdi, supporting informed groundwater resource management.

Keywords:
Vertical Electrical Sounding (VES);
Groundwater potential;
Hydraulic conductivity.

INTRODUCTION

Groundwater is a vital component of the hydrological cycle and an essential resource for domestic, agricultural, and industrial uses, particularly in regions where surface water is limited or unreliable. In Nigeria, groundwater constitutes a major source of potable water for both rural and urban populations, largely due to the susceptibility of surface water to pollution, seasonal variability, and evaporation losses (Adelana & MacDonald, 2008; MacDonald et al., 2012). Sustainable groundwater development therefore requires accurate delineation of aquifer geometry, hydraulic properties, and spatial distribution, which depend on reliable subsurface investigation techniques.

Geophysical methods have become widely adopted in groundwater exploration because they are non-invasive, cost-effective, and capable of providing continuous subsurface information (Reynolds, 2011). Among these methods, the Vertical Electrical Sounding (VES) technique is one of the most commonly used approaches in hydrogeological investigations due to its sensitivity to variations in subsurface resistivity controlled by lithology, porosity, water saturation, and fluid conductivity (Orellana & Mooney, 1966; Keller & Frischknecht, 1966).

The VES method, typically employing Schlumberger or Wenner electrode configurations, has been successfully applied to delineate geoelectric layers, identify aquifer boundaries, and evaluate groundwater potential in a wide range of geological environments (Zohdy et al., 1974; Telford et al., 1990; Niwas & Singhal, 1981). These configurations allow for deeper penetration and improved resolution of subsurface layering, making them particularly suitable for groundwater exploration.

The electrical resistivity method is based on the principle that different subsurface materials exhibit contrasting resistivity values. Water-saturated and unconsolidated formations generally display low resistivity due to enhanced ionic conduction, whereas consolidated and dry formations show relatively high resistivity values (Freeze & Cherry, 1979). However, clay-rich formations may also exhibit low resistivity despite poor groundwater potential because of surface conduction and bound water effects. This overlap necessitates careful interpretation of resistivity data, often integrated with geological information, to distinguish aquiferous formations from non-productive layers. Furthermore, the estimation of hydraulic parameters such as transmissivity and hydraulic conductivity from resistivity data has been demonstrated to improve the understanding of aquifer characteristics and groundwater flow dynamics (Niwas & Singhal, 1981; Singh et al., 2004).

Makurdi Local Government Area, located within the Benue Trough of central Nigeria, is characterized by a complex sedimentary geology comprising sandstones, shales, and alluvial deposits. These formations exhibit significant heterogeneity in porosity, permeability, and water-bearing capacity. Previous hydrogeological studies in the Benue Trough and surrounding regions have reported considerable variability in aquifer characteristics due to lithological changes, structural controls, and climatic influences (Adelana et al., 2008; Obiora et al., 2015).

However, despite these regional studies, there is a lack of detailed, site-specific geoelectric investigations in Makurdi that integrate resistivity data with aquifer hydraulic properties for groundwater assessment. Most existing studies focus on general hydrogeological descriptions without providing sufficient quantitative evaluation of aquifer potential using geophysical techniques. This represents a significant knowledge gap, particularly in the context of increasing water demand driven by population growth and urbanization.

The application of VES in this study provides a systematic approach to investigating subsurface geoelectric layering and identifying potential aquifer horizons. By analyzing resistivity variations, layer thicknesses, and derived hydraulic parameters, the study aims to develop a more reliable hydrogeological model of the area. Such integration enhances the predictive capability for groundwater occurrence, flow, and recharge processes.

In addition, groundwater sustainability and quality are critical concerns in the face of environmental change and anthropogenic pressures. Poorly understood subsurface conditions can lead to indiscriminate borehole drilling, over-exploitation, and contamination risks. Therefore, geophysical investigations such as this study provide essential data for evidence-based groundwater management, policy formulation, and resource protection.

In summary, this study addresses the identified gap by employing Vertical Electrical Sounding techniques to characterize subsurface geoelectric layers and evaluate groundwater potential in Makurdi Local Government Area. The results are expected to contribute to improved understanding of aquifer distribution and hydraulic properties, thereby supporting sustainable groundwater development and management in the region.

Theoretical Framework

The theoretical framework for this study is based on the integration of hydrogeological principles and electrical resistivity theory, which together provide a scientific basis for evaluating groundwater occurrence and flow using geoelectric methods. These principles explain how variations in subsurface electrical properties relate to lithology, fluid content, and aquifer characteristics (Telford et al., 1990; Reynolds, 2011).

Concept of Geoelectric Layering

Geoelectric layering refers to the subdivision of the subsurface into distinct layers based on variations in electrical resistivity. Each layer reflects relatively uniform electrical properties controlled by lithology, porosity, permeability, degree of saturation, clay content, and pore fluid conductivity (Keller & Frischknecht, 1966; Telford et al., 1990).

The theoretical assumption underlying geoelectric layering is that changes in resistivity correspond to variations in subsurface material properties. Low resistivity zones are commonly associated with saturated sands, gravels, or clayey materials, whereas high resistivity zones typically represent dry sediments, lateritic materials, or consolidated bedrock (Freeze & Cherry, 1979; Reynolds, 2011). The thickness and depth of these layers, obtained from resistivity sounding curves, provide critical information about aquifer geometry and groundwater storage potential (Zohdy et al., 1974).

Electrical Resistivity Theory

Electrical resistivity methods are based on Ohm's law, which relates the flow of electrical current through a medium to the applied potential difference (Telford et al., 1990). The apparent resistivity is expressed as presented in equation (1).

$$\rho_a = K\frac{\Delta V}{I} \qquad (1)$$

Where ρ_a = apparent resistivity (Ωm), K = geometric factor dependent on electrode configuration, ΔV = measured potential difference (V), I = injected current (A).

This expression is standard in resistivity surveying and is derived from the fundamental theory of current flow in a homogeneous medium (Telford et al., 1990; Keller & Frischknecht, 1966).

In Vertical Electrical Sounding (VES), the spacing of current electrodes is progressively increased to probe deeper subsurface layers, while the potential electrodes remain relatively close. This enables the determination of resistivity variation with depth. The Schlumberger configuration is widely used because it provides greater depth penetration with reduced field effort (Zohdy et al., 1974; Reynolds, 2011).

The method assumes a horizontally stratified subsurface with layers of uniform resistivity. Although natural formations are often heterogeneous, this assumption provides a reasonable approximation for groundwater exploration when supported by geological information.

Relationship Between Resistivity and Hydrogeological Properties

The interpretation of resistivity data in hydrogeology relies on the relationship between electrical resistivity and subsurface physical properties. Aquifer materials with high porosity and interconnected pore spaces filled with conductive groundwater generally exhibit low to moderate resistivity values, whereas impermeable formations such as compacted clays or crystalline rocks may show contrasting responses depending on moisture content and mineral composition (Freeze & Cherry, 1979; Reynolds, 2011).

Archie's law provides a theoretical relationship between bulk resistivity, pore water resistivity, and porosity in clean (clay-free) formations shown in equation (2).

$$\rho = a\,\rho_w\,\phi^{-m} \qquad (2)$$

Where ρ = bulk resistivity of the formation, ρ_w = resistivity of pore water, ϕ = porosity, a = tortuosity factor (empirical constant), m = cementation exponent (empirical constant).

This relationship was originally developed by Archie (1942) and has been widely applied in hydrogeophysical studies (Niwas & Singhal, 1981).

Although Archie's law is limited in clay-rich environments due to surface conduction effects, its application in sedimentary basins such as the Benue Trough is justified because significant portions of the aquifer units consist of relatively clean sandstones and alluvial deposits. In such settings, Archie's law provides a useful first-order approximation for relating resistivity to porosity and groundwater content. However, interpretations must be supported by geological information and, where necessary, complemented by empirical correlations (Niwas & Singhal, 1981; Singh et al., 2004).

Aquifer Hydraulic Parameters and Groundwater Flow Theory

Groundwater occurrence and movement are governed by the hydraulic properties of aquifer materials. Darcy's law describes fluid flow through porous media as shown in equation (3)

$$Q = KA\frac{dh}{dl} \qquad (3)$$

Where Q = discharge (m³/s), K = hydraulic conductivity (m/s), A = cross-sectional area (m²), $\frac{dh}{dl}$ = hydraulic gradient.

This equation forms the basis for groundwater flow analysis (Freeze & Cherry, 1979).

Transmissivity, which represents the capacity of an aquifer to transmit water, is defined as presented in equation (4).

$$T = Kb \qquad (4)$$

Where T = transmissivity (m²/s), K = hydraulic conductivity (m/s), b = aquifer thickness (m).

These equations are standard in hydrogeology and are not derived in this study; they are adopted from established groundwater theory (Freeze & Cherry, 1979).

In this study, resistivity derived parameters such as layer thickness and resistivity are used to estimate hydraulic conductivity and transmissivity through empirical relationships. High transmissivity values indicate productive aquifers, while low values suggest limited groundwater potential.

Geology and Hydrogeology

The geology of Makurdi and its environs is predominantly underlain by sedimentary formations belonging to the Middle Benue Trough, a major structural depression that extends northeast–southwest across central Nigeria as shown in figure 1. The lithological units within the area consist mainly of Cretaceous sandstones, shales, and siltstones of the Makurdi Formation, which unconformably overlie older Precambrian Basement rocks to the south (Offodile, 2002; Nton, 2011). The Makurdi Sandstone is characterized by moderately consolidated, fine- to coarse-grained sandstones interbedded with clayey horizons and shale lenses. These lithologic variations significantly influence the hydrological properties of the subsurface, including porosity and permeability, which in turn control groundwater movement and contaminant migration.

Hydro-geologically, the aquifer system in the area is predominantly unconfined to semi-confined, occurring within the weathered and fractured sandstone units. The water table is generally shallow, ranging between 5 and 20 m below ground surface, depending on local topography and proximity to the Benue River (Ocheri et al., 2014). Groundwater flow is typically directed toward the river channel, suggesting that leachate generated from dumpsites located on elevated terrains may migrate laterally and vertically toward these lower-lying discharge zones. The presence of clay-rich horizons locally retards vertical infiltration but may also promote lateral plume dispersion along more permeable sand layers.

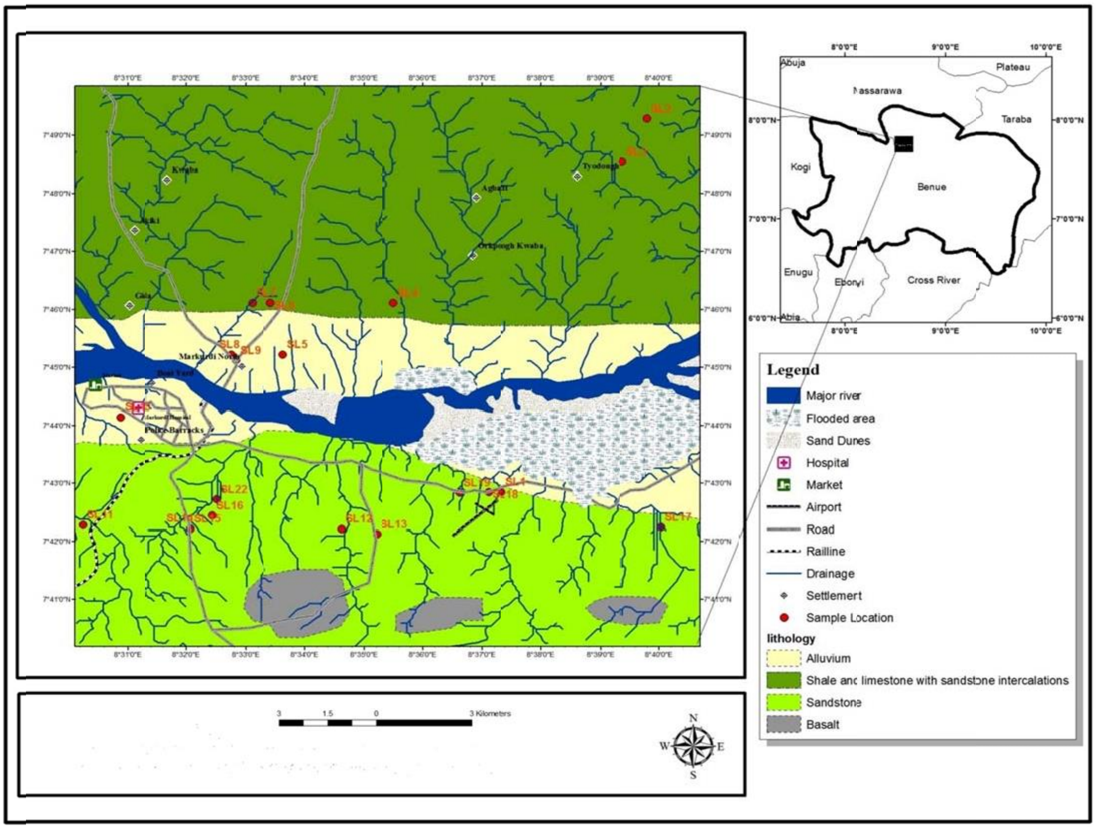

Figure 1: Geological Map of the Study Area Adopted by Geological Survey Agency (2006)

Topography and Drainage

The topography of Makurdi is generally undulating, with elevations ranging between 97 and 150 meters above sea level. The terrain slopes gently northward toward the Benue River, providing natural drainage pathways that facilitate surface runoff and subsurface flow. The Benue River, which bisects the city, is the dominant hydrological feature, receiving numerous ephemeral tributaries and stormwater channels during the wet season. The drainage pattern is primarily dendritic, controlled by the underlying lithology and structural trends of the Makurdi Formation. The dumpsites along Gboko Road and Naka Road occupy relatively high grounds, while the North Bank dumpsite lies on a slightly lower elevation adjacent to the river floodplain conditions that collectively influence the direction and extent of potential leachate migration.

Climate and Vegetation

Makurdi experiences a tropical wet-and-dry climate (Aw) according to Köppen's classification. The climate is characterized by two distinct seasons: the wet season, which extends from April to October, and the dry season, spanning November to March. The area records a mean annual rainfall of approximately 1,200–1,500 mm, with the peak occurring between July and September (NIMET, 2023). Average monthly temperatures range between 25°C and 33°C, and relative humidity fluctuates between 60% and 85%. These climatic conditions enhance the generation and percolation of leachate, particularly during the rainy season when large volumes of water infiltrate through decomposing waste materials.

Land Use and Waste Management Setting

The land-use pattern in Makurdi comprises residential, commercial, institutional, and agricultural areas, with rapid urban expansion often encroaching on natural drainage systems. The study specifically focuses on three major dumpsites located along Gboko Road, Naka Road, and the North Bank area of Makurdi, which serve as the primary collection points for domestic, agricultural, and industrial wastes.

These dumpsites are typically unlined and lack engineered leachate management systems, allowing waste to be deposited directly on the ground surface. Consequently, rainfall infiltration leads to the generation of leachate, which percolates into the subsurface through porous soils and fractured sandstone formations. The proximity of these dumpsites to groundwater sources, including hand-dug wells and boreholes, as well as the Benue River, increases the risk of contamination of both surface and groundwater systems.

MATERIALS AND METHODS

Description of the Study Area

Makurdi Local Government Area is located in Benue State, North-Central Nigeria, within the Benue Trough. The area lies between latitudes approximately 7°40′N and 7°50′N and longitudes 8°30′E and 8°40′E. Makurdi experiences a tropical savanna climate characterized by distinct wet and dry seasons, with annual rainfall ranging between 1,100 and 1,300 mm. The River Benue and its tributaries constitute the major surface water bodies, influencing recharge conditions and groundwater dynamics.

Geologically, the area is underlain predominantly by Cretaceous sedimentary formations of the Benue Trough, consisting of sandstones, shales, siltstones, and alluvial deposits. These lithologies exhibit varying degrees of weathering, fracturing, porosity, and permeability, which collectively control groundwater occurrence and movement. The hydrogeology of the area is dominated by weathered and fractured sedimentary units that serve as aquifers, overlain by lateritic and alluvial materials.

Research Design

This study adopted a quantitative hydrogeophysical research design using the Vertical Electrical Sounding (VES) technique to investigate subsurface geoelectric layers and assess groundwater availability. The approach integrates field resistivity measurements, geoelectric interpretation, and estimation of aquifer hydraulic parameters. The design ensures systematic data acquisition, reliable interpretation, and meaningful hydrogeological evaluation.

Materials and Equipment

The materials and equipment used for this study include:

i. Digital resistivity meter (Herojat resistivity meter)
ii. Stainless steel electrodes (current and potential electrodes)
iii. Insulated connecting cables and cable reels
iv. Measuring tapes for electrode spacing
v. Global Positioning System (GPS) device for location referencing
vi. Hammer and saline water for improving electrode grounding
vii. Field notebook/data sheets for recording measurements

The software used include: IPI2Win for resistivity curve interpretation, Microsoft Excel for data processing and tabulation and Surfer13 for plotting geoelectric sections and graphs

Data Acquisition Method

Electrical Resistivity Survey

A total of thirty-three (33) Vertical Electrical Sounding (VES) stations were conducted across Makurdi Local Government Area. The number of VES points were selected to ensure adequate spatial coverage and representation of the different geological and hydrogeological settings within the study area.

Criteria for Selection of VES Locations

The selection of VES stations was guided by the following factors:

i. Geological variability (sandstone, shale, and alluvial zones)
ii. Proximity to major dumpsites (Gboko Road, Naka Road, and North Bank)
iii. Topographic variation (elevated and low-lying areas)
iv. Accessibility and safety of the terrain
v. Presence of existing wells/boreholes for correlation
vi. Minimization of cultural noise (e.g., power lines, metallic objects, roads)

These factors ensured that the acquired data adequately represent subsurface conditions and groundwater potential across the study area.

Field Data Acquisition Procedure

The Vertical Electrical Sounding (VES) technique was carried out using the Schlumberger electrode configuration, selected for its efficiency in achieving greater depth penetration with minimal electrode movement.

At each VES station:

i. Four electrodes were inserted into the ground along a straight line: two current electrodes (A and B) and two potential electrodes (M and N).
ii. A direct current was injected into the ground through electrodes A and B using the resistivity meter.
iii. The resulting potential difference between electrodes M and N was measured.
iv. The current electrode spacing (AB/2) was progressively increased to probe deeper subsurface layers.
v. The potential electrode spacing (MN/2) was kept relatively small and only increased when necessary to obtain measurable voltage readings.
vi. Apparent resistivity values were computed automatically by the resistivity meter or manually using standard equations.

Data Processing and Interpretation

The field data obtained from each VES station were plotted on a log-log scale of apparent resistivity versus electrode spacing. The resulting sounding curves were interpreted using IPI2Win software, which applies iterative curve matching and inversion techniques to determine subsurface layer resistivities and thicknesses.

The interpreted parameters include: number of geoelectric layers, layer resistivity, layer thickness and depth to aquifer. Geoelectric sections were generated to illustrate subsurface layering across the study area.

Estimation of Hydraulic Parameters

Hydraulic conductivity and transmissivity were estimated from interpreted resistivity values using established empirical relationships.

Hydraulic conductivity (K) was derived from resistivity hydraulic relationships and Transmissivity (T) was computed as stated in equation (5).

$$T = K \times b \tag{5}$$

where b is aquifer thickness

These parameters were used to evaluate groundwater potential and aquifer productivity.

RESULTS AND DISCUSSION

Geoelectric Layering and Subsurface Characterization

The interpretation of Vertical Electrical Sounding (VES) data across Makurdi Local Government Area reveals a highly heterogeneous subsurface composed of laterally varying geoelectric layers. The Schlumberger array results indicate between four and seven geoelectric layers across the study area, reflecting variations in lithology, weathering intensity, fracturing, and groundwater saturation.

The spatial distribution of VES stations and their geographic coordinates are presented in Table 1. Low apparent resistivity values (<10 Ωm) are associated with clayey or silty materials, often saturated. These materials typically act as aquitards, enhancing aquifer protection but limiting groundwater yield. Conversely, very high resistivity values (up to 58,000 Ωm) indicate dry lateritic layers, compact sands, or fresh basement rocks with minimal porosity.

It is important to note that the VES method primarily measures apparent resistivity (ρ_a), which differs from true resistivity (ρ). Apparent resistivity represents a bulk response of subsurface layers and is later interpreted to obtain true resistivity values through curve matching and inversion.

Extremely high aquifer resistivity values (>300 Ωm), observed at locations such as MKD 8, MKD 10, MKD 11, MKD 18, and MKD 26, are indicative of Fractured but relatively dry basement rocks, Coarse-grained formations with low clay content and Zones of limited water saturation. Such formations may yield groundwater where fracturing is significant but can also indicate low storage capacity and reduced permeability in poorly fractured zones.

A typical geoelectric sequence across the study area includes: Topsoil, Lateritic/sandy layer, Weathered/fractured basement (main aquifer) and Fresh basement rock.

Table 1: VES Locations and Elevation Data

VES NO	Location	Latitude (N)	Longitudes (E)	Elevation (Ft)
MKD 1	Corner stone imperial sch Makurdi	7.69426	8.50526	533
MKD 2	NKST Church onyar, Makurdi	7.69009	8.50090	633
MKD 3	kanshio market, Makurdi	7.68533	8.53384	561
MKD 4	NKST Church yariko, Makurdi	7.60310	8.57347	564
MKD 5	ovation Resort, Makurdi	7.60310	8.57347	581
MKD 6	yaiko market, Makurdi	7.67320	8.54439	446
MKD 7	wajina international Shc Makurdi	7.66907	8.52967	512
MKD 8	NKST Church Usahemba Makurdi	7.65780	8.53611	637
MKD 9	faduja Academy Makurdi	7.69846	8.57010	620
MKD 10	best Brain Academy Makurdi	7.70833	8.59520	452
MKD 11	Benue State University Teaching Hospital Makurdi	7.72619	8.56842	566
MKD 12	Rahama clinic and maternity, Makurdi	7.72011	8. 56216	617
MKD 13	Benue Hotel and Resort Makurdi	7.73546	8.53430	
MKD 14	4, GondoAlvor Road Makurdi	7.734777	8.525206	545
MKD 15	North Bank Market Makurdi	7.75498	8.54653	583
MKD 16	Mountain of Fire and Miracle Ministries Makurdi	7.75553	8.55555	
MKD 17	NASME junction Makurdi	7.76692	8.5595954	
MKD 18	Christ the king Church Nor. Bank Makurdi	7.76395	8.57010	531
MKD 19	NKST Sule, Makurdi	7.78074	8.56134	377
MKD 20	Ankpa Quarters, Makurdi	7.737068	8.506352	469
MKD 21	NKST Church Iortyer, Makurdi	7.72125	8.48198	453
MKD 22	NTA Makurdi	7.73965	8.53219	564
MKD 23	Eyah Hotel and Resort, Makurdi	7.73386	8.53019	462
MKD 24	Kapajo apartment, Makurdi	7.73669	8.52483	436
MKD 25	Aper Aku Stadium Makurdi	7.73066	8.52369	476

VES NO	Location	Latitude (N)	Longitudes (E)	Elevation (Ft)
MKD 26	mount St. Gabriel Sec. Sch. Makurdi	7.73083	8.51804	615
MKD 27	42 Js Tarka Road Makurdi	7.732546	8.522191	395
MKD 28	Grace cottage Hospital Makurdi	7.72586	8.52404	566
MKD 29	City Bay park Makurdi	7..72658	8.53708	486
MKD 30	Trust Resort Hotel Makurdi	7.71080	8.54506	556
MKD 31	St .Joseph parish Akpehe Makurdi	7.71123	8.55451	522
MKD 32	Achusa market Makurdi	7.69754	8.51567	545
MKD 33	Benue investment and property company Makurdi	7.70647	8.50889	354

Aquifer Geometry and Spatial Distribution

The aquifer characteristics derived from VES interpretation are presented in Table 2. The aquifer resistivity, thickness, and depth to aquifer derived from VES interpretation are summarized in Table 2 and spatially illustrated in Figures 2–4. Aquifer resistivity values range from as low as 1.2 Ω·m at MKD 23 to as high as 2180 Ω·m at MKD 18. Extremely low resistivity values are indicative of clay-rich or highly saturated formations, which, although capable of storing groundwater, may exhibit low permeability and poor yield. In contrast, moderate resistivity values ranging between approximately 50 and 300 Ω·m observed at locations such as MKD 2, MKD 3, MKD 15, and MKD 20 are characteristic of weathered or fractured basement aquifers with favourable hydraulic properties.

Aquifer thickness across the study area varies significantly, from less than 2 m at MKD 12 and MKD 28 to over 67 m at MKD 16 (Table 2; Figure 4). Thick aquifer zones are particularly important for sustainable groundwater abstraction, as they generally indicate larger groundwater reserves and improved borehole yields. The depth to aquifer also exhibits substantial spatial variation, ranging from very shallow depths (<5 m) to depths exceeding 140 m (Figure 3). This variation suggests the coexistence of shallow and deep groundwater systems within Makurdi, influenced by local geological and structural conditions.

Notably, MKD 16 and MKD 17 are characterized by thick aquifer zones occurring at considerable depths, suggesting the presence of deep-seated weathered basement aquifers with significant groundwater storage potential. However, groundwater development at such depths may involve higher drilling and pumping costs, which must be considered during groundwater resource planning.

Table 2: Identified Aquifer Units

VES. No	Latitude (°N)	Longitudes (°E)	Aquifer Resistivity (Ωm)	Aquifer thickness (m)	Depth to Aquifer (m)	Aquifer Type
MKD 1	7.69426	8.50526	55.40	4.30	10.20	Sandy Clay Aquifer
MKD 2	7.69009	8.50090	60.00	44.20	67.00	Sandy Clay Aquifer
MKD 3	7.68533	8.53384	81.00	48.00	179.00	Sandy Clay Aquifer
MKD 4	7.60310	8.57347	171.00	15.80	23.60	Sand/Weathered Aquifer
MKD 5	7.60310	8.57347	5.50	19.10	29.00	Clay Aquifer
MKD 6	7.67320	8.54439	143.00	10.90	21.10	Sand/Weathered Aquifer
MKD 7	7.66907	8.52967	222.0	4.10	6.10	Sand Aquifer
MKD 8	7.65780	8.53611	610.0	17.70	30.50	Coarse Sand/Gravel Aquifer
MKD 9	7.69846	8.57010	19.30	10.80	17.30	Clayey Sand Aquifer
MKD 10	7.70833	8.59520	472.00	27.00	134.00	Sand Aquifer
MKD 11	7.72619	8.56842	534.00	19.30	63.30	Coarse Sand/Gravel Aquifer
MKD 12	7.72011	8. 56216	23.00	1.00	1.90	Clayey Sand Aquifer
MKD 13	7.73546	8.53430	350.00	6.20	8.90	Sand Aquifer
MKD 14	7.734777	8.525206	270.00	9.30	10.20	Sand Aquifer
MKD 15	7.75498	8.54653	75.00	17.10	30.50	Sandy Clay Aquifer
MKD 16	7.75553	8.55555	26.60	67.10	146.00	Clayey Sand Aquifer
MKD 17	7.76692	8.5595954	18.80	40.60	51.20	Clayey Sand Aquifer
MKD 18	7.76395	8.57010	2180.00	18.40	39.90	Fractured Rock / Resistive Formation
MKD 19	7.78074	8.56134	5.50	5.60	9.00	Clay Aquifer
MKD 20	7.737068	8.506352	97.00	16.40	38.60	Sandy Clay Aquifer
MKD 21	7.72125	8.48198	118.00	9.70	19.20	Sand Aquifer

VES. No	Latitude (°N)	Longitudes (°E)	Aquifer Resistivity (Ωm)	Aquifer thickness (m)	Depth to Aquifer (m)	Aquifer Type
MKD 22	7.73965	8.53219	14.00	11.00	13.30	Clayey Sand Aquifer
MKD 23	7.73386	8.53019	1.20	3.80	6.40	Clay / Conductive Zone
MKD 24	7.73669	8.52483	9.20	5.00	9.50	Clay Aquifer
MKD 25	7.73066	8.52369	2.70	3.50	8.10	Clay Aquifer
MKD 26	7.73083	8.51804	790.00	9.30	15.40	Coarse Sand/Gravel Aquifer
MKD 27	7.732546	8.522191	11.70	3.80	8.40	Clayey Sand Aquifer
MKD 28	7.72586	8.52404	19.20	1.10	1.70	Clayey Sand Aquifer
MKD 29	7.72658	8.53708	4.10	3.70	5.60	Clay Aquifer
MKD 30	7.71080	8.54506	381.00	14.90	41.00	Sand Aquifer
MKD 31	7.71123	8.55451	263.00	6.00	10.00	Sand Aquifer
MKD 32	7.69754	8.51567	33.00	2.90	4.90	Clayey Sand Aquifer
MKD 33	7.70647	8.50889	13.10	12.10	43.10	Clayey Sand Aquifer

Table 3: Groundwater Potential and Protective Capacity

VES. No	Thickness (m)	Resistivity (Ωm)	Conductivity (S/m)	Longitudinal Conductance, S (Siemens)
MKD 1	4.30	55.40	0.01805	0.0776
MKD 2	44.20	60.00	0.0166	0.7367
MKD 3	48.00	81.00	0.0123	0.5926
MKD 4	15.80	171.00	0.0054	0.0924
MKD 5	19.10	5.50	0.1818	3.4727
MKD 6	10.90	143.00	0.0069	0.0762
MKD 7	4.10	222.0	0.0045	0.0185
MKD 8	17.70	610.0	0.0016	0.0290
MKD 9	10.80	19.30	0.0518	0.5596
MKD 10	27.00	472.00	0.0021	0.0572
MKD 11	19.30	534.00	0.0018	0.0361
MKD 12	1.00	23.00	0.0434	0.0435
MKD 13	6.20	350.00	0.0028	0.0177
MKD 14	9.30	270.00	0.0037	0.0344
MKD 15	17.10	75.00	0.0133	0.2280
MKD 16	67.10	26.60	0.0375	2.5226
MKD 17	40.60	18.80	0.0531	2.1596
MKD 18	18.40	2180.00	0.0004	0.0084
MKD 19	5.60	5.50	0.1818	1.0182
MKD 20	16.40	97.00	0.0103	0.1691
MKD 21	9.70	118.00	0.0084	0.0822
MKD 22	11.00	14.00	0.0714	0.7857
MKD 23	3.80	1.20	0.8333	3.1667
MKD 24	5.00	9.20	0.1086	0.5435
MKD 25	3.50	2.70	0.3703	1.2963
MKD 26	9.30	790.00	0.0012	0.0118
MKD 27	3.80	11.70	0.0854	0.3248
MKD 28	1.10	19.20	0.0520	0.0573
MKD 29	3.70	4.10	0.2439	0.9024
MKD 30	14.90	381.00	0.0026	0.0391
MKD 31	6.00	263.00	0.0038	0.0228
MKD 32	2.90	33.00	0.0303	0.0879
MKD 33	12.10	13.10	0.0763	0.9237

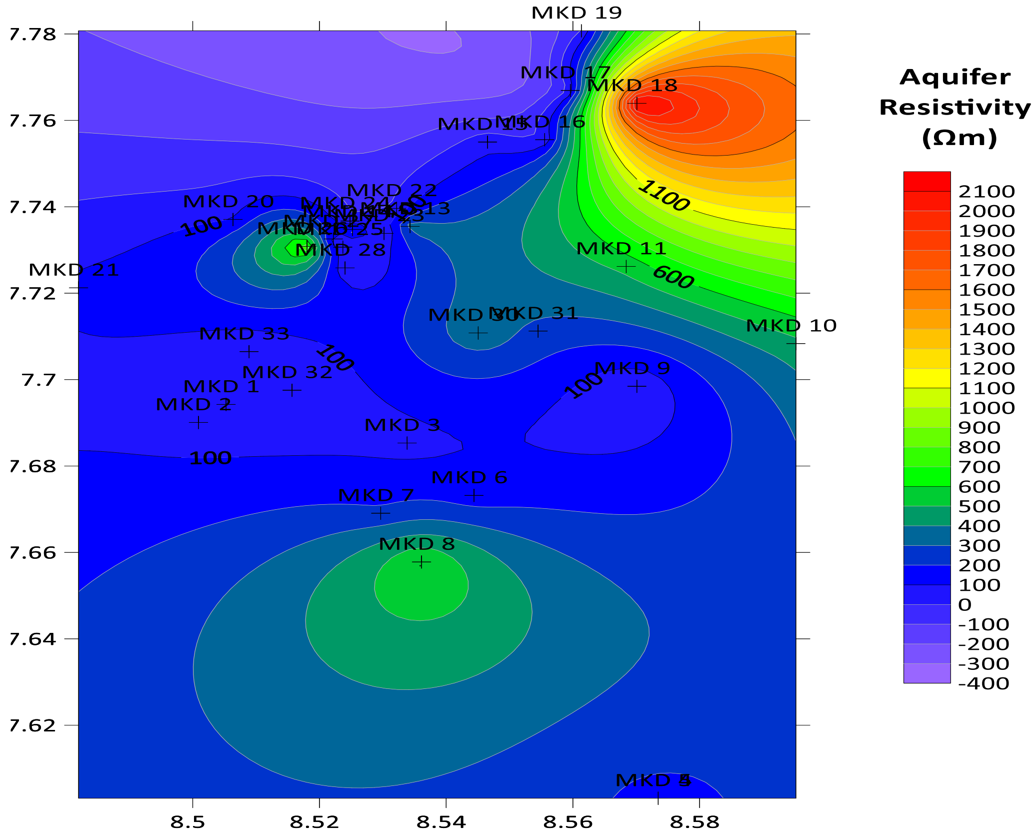

Figure 2: Aquifer Resistivity Map of the Study Area

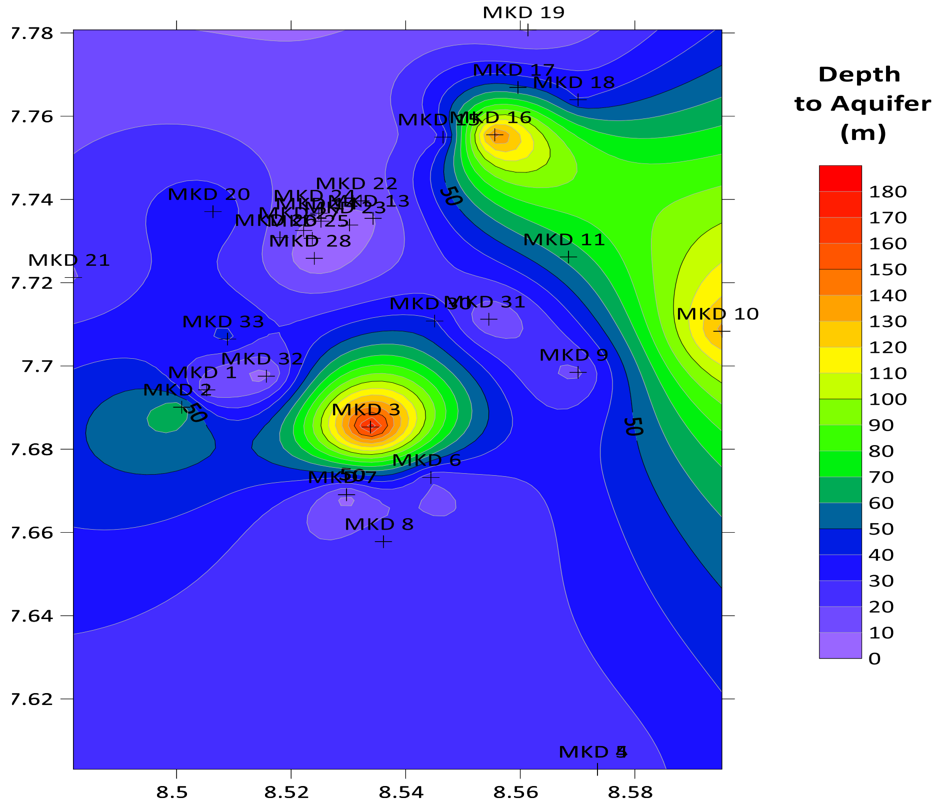

Figure 3: Depth to Aquifer Map of the Study Area

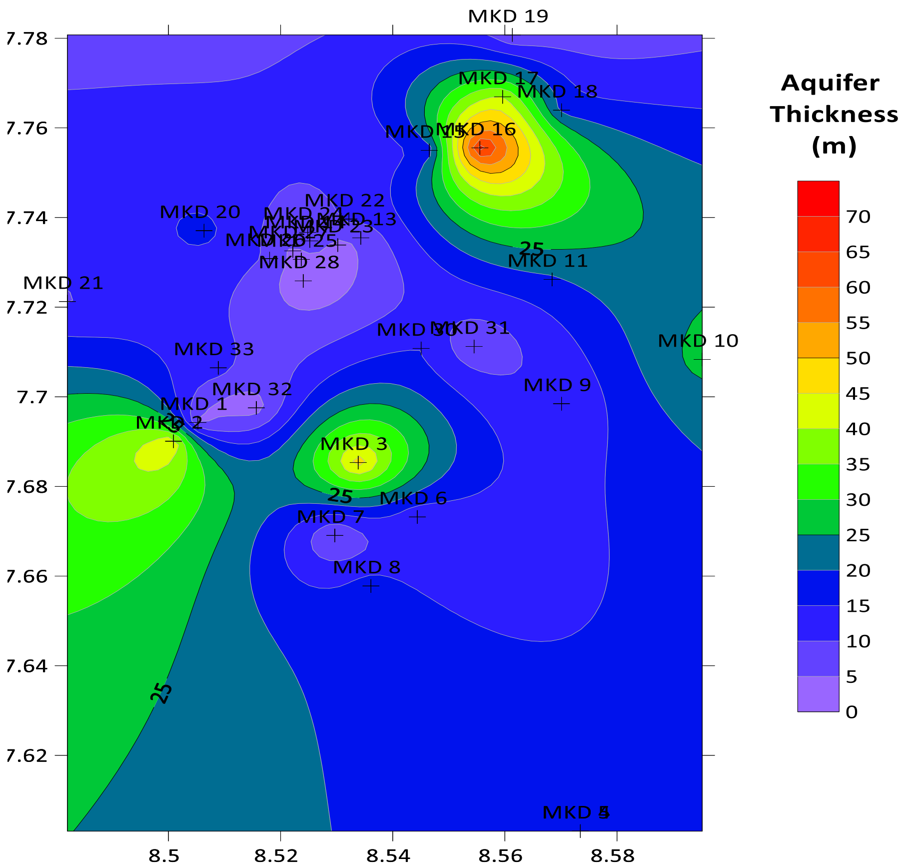

Figure 4: Aquifer Thickness Map of the Study Area

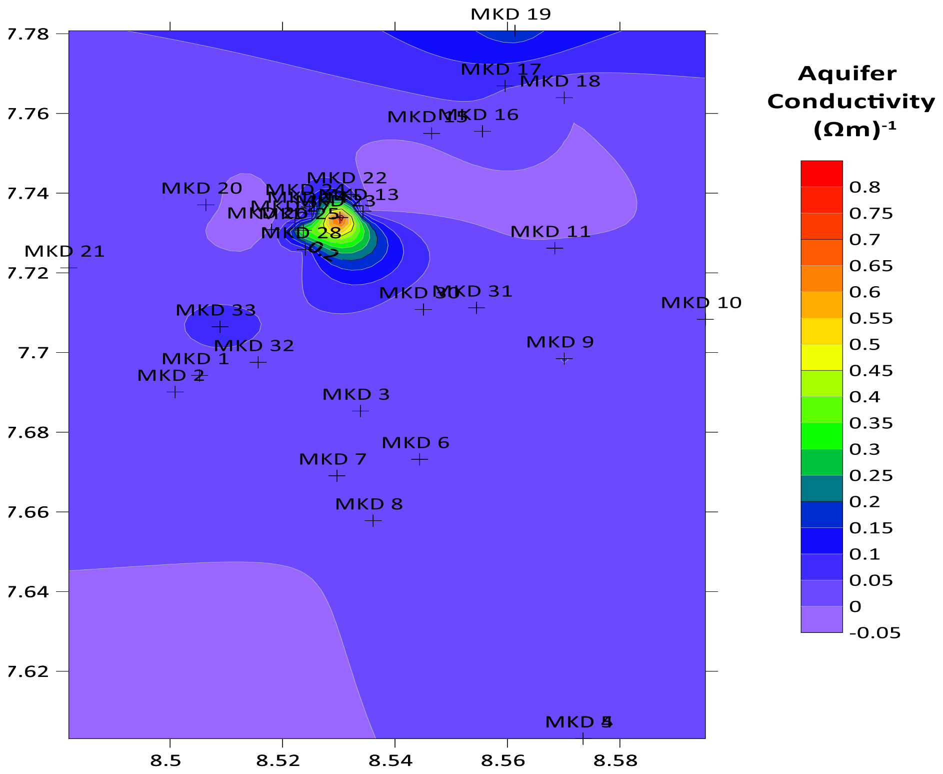

Figure 5: Aquifer Conductivity Map of the Study Area

Aquifer Protective Capacity

The protective capacity of the aquifer systems was evaluated using longitudinal conductance (S), which reflects the ability of overlying materials to attenuate contaminant migration from the surface. The computed conductivity and inferred protective capacity values are presented in Table 3, while their spatial distribution is illustrated in Figure 5. From table 3, the protective capacity classification based longitudinal conductance on S shows the following:

i. S > 1.0: Excellent
ii. 0.7-1.0: Very Good
iii. 0.2-0.7: Moderate
iv. 0.1-0.2: Weak
v. <0.1: Poor

High conductance values (e.g., MKD 23, MKD 16) indicate thick clayey overburden, offering strong protection. While Low values (e.g., MKD 18, MKD 10) indicate vulnerability to contamination.

The longitudinal conductance values range from very low to very high across the study area, indicating varying degrees of aquifer vulnerability. Locations such as MKD 23, MKD 16, MKD 17, MKD 25, and MKD 19 exhibit relatively high conductance values, corresponding to thick, low resistivity overburden materials typically clayey sediments that provide effective natural protection against surface contamination. These areas can therefore be classified as having good to excellent aquifer protective capacity.

In contrast, sites with very low longitudinal conductance values, including MKD 18, MKD 8, MKD 10, and MKD 11, are characterized by thin or highly resistive overburden layers. Such conditions imply poor natural protection, rendering the underlying aquifers more vulnerable to contamination from surface derived pollutants. This vulnerability is of particular concern in urban and peri-urban areas of Makurdi, where anthropogenic activities may pose significant risks to groundwater quality.

Groundwater Potential Assessment

Groundwater potential across the study area was assessed using aquifer thickness and resistivity parameters, supported by transverse resistance and conductivity values presented in Table 4.3, as well as the aquifer resistivity and thickness maps (Figures 2 and 4). Thick aquifer units with moderate resistivity values generally correspond to zones of higher groundwater potential, as they suggest favourable combinations of storage capacity and permeability.

Locations such as MKD 10, MKD 8, MKD 11, MKD 18, and MKD 26 are identified as zones with relatively high groundwater yield potential due to their appreciable aquifer thickness and resistivity characteristics. MKD 18, in particular, exhibits exceptionally high resistivity and thickness, suggesting the presence of a fractured basement aquifer capable of yielding substantial groundwater. However, this location also exhibits very low longitudinal conductance, indicating poor aquifer protection and heightened vulnerability to contamination. This observation highlights the importance of integrating both groundwater yield potential and aquifer protective capacity in groundwater development planning, rather than relying solely on yield-related parameters.

Implications for Groundwater Development in Makurdi

An integrated evaluation of aquifer resistivity, thickness, depth to aquifer, groundwater potential, and protective capacity suggests spatial variability in groundwater suitability across Makurdi Local Government Area. While several locations exhibit high groundwater yield potential, not all are adequately protected from surface contamination.

Among the investigated sites, MKD 10 emerges as one of the most favourable locations for groundwater development, combining relatively high groundwater potential with moderate protective capacity. Such locations are suitable for borehole development with comparatively lower contamination risk. Overall, the results demonstrate that groundwater occurrence and vulnerability in Makurdi are strongly controlled by the thickness and resistivity of weathered basement layers, as well as the nature of the overburden materials. Areas characterized by thick weathered zones and moderate resistivity values constitute the most productive aquifers, while clay-rich overburden materials enhance aquifer protection.

Hydraulic Parameters and Groundwater Flow Characteristics

Estimated hydraulic parameters derived from the interpreted geoelectric data further confirm the spatial variability in groundwater potential across the study area. Transmissivity values range from low to high, reaching a maximum of 200.196 m²/day, while hydraulic conductivity varies between 0.000164 and 0.034578 m/day.

High transmissivity values observed in locations such as MKD 10, MKD 16, and MKD 17 indicate aquifer zones with significant capacity to transmit groundwater, suggesting favourable conditions for sustainable groundwater abstraction. These areas are typically associated with relatively thick aquifer units and moderate resistivity values, characteristic of well-developed weathered or fractured basement formations.

Conversely, low transmissivity and hydraulic conductivity values recorded in locations such as MKD 18, MKD 23, and MKD 25 indicate limited groundwater flow potential. These zones are commonly associated with either highly resistive formations (e.g., compact or poorly fractured basement rocks) or low-resistivity clay-rich materials, both of which restrict groundwater movement.

The variation in hydraulic conductivity further reflects differences in aquifer permeability across the study area. Moderate hydraulic conductivity values correspond to sandy or weathered formations that enhance groundwater flow, whereas very low values are indicative of clay-dominated or compact lithologies with poor permeability. Overall, the spatial distribution of transmissivity and hydraulic conductivity aligns closely with the interpreted geoelectric parameters, confirming that aquifer thickness and resistivity are key controls on groundwater occurrence and movement in Makurdi. The integration of these hydraulic parameters therefore strengthens the delineation of zones with high and low groundwater productivity.

CONCLUSION

This study has demonstrated the effectiveness of the Vertical Electrical Sounding (VES) technique in delineating subsurface geoelectric layers and assessing groundwater potential in Makurdi Local Government Area, Benue State, Nigeria. The interpreted geoelectric models reveal a heterogeneous subsurface characterized by alternating clayey, sandy, lateritic, weathered, and fractured basement formations, which collectively control groundwater occurrence and distribution.

The results show that aquifer resistivity values across the study area range from 1.2 Ωm to 2180 Ωm, reflecting significant lithological variability and varying degrees of saturation, weathering, and fracturing. Low resistivity values are associated with clay-rich or highly saturated formations that may possess high storage capacity but low permeability, whereas moderate resistivity values (approximately 50–300 Ωm) correspond to weathered and fractured basement aquifers with favourable groundwater potential. High resistivity values (>300 Ωm) are indicative of compact or less saturated formations, although in some cases they may represent productive fractured zones.

Aquifer thickness and depth vary considerably across the study area, indicating the presence of both shallow and deep groundwater systems. Thick aquifer zones identified in several locations suggest significant groundwater storage potential, while shallow aquifers may be more susceptible to seasonal fluctuations and contamination.

The evaluation of aquifer protective capacity using longitudinal conductance (S) reveals substantial spatial variation in aquifer vulnerability. Areas characterized by high conductance values are associated with thick, low-resistivity overburden materials that provide effective protection against surface contamination. Conversely, zones with low conductance values are indicative of thin or highly resistive overburden, making the underlying aquifers more vulnerable to pollution. This highlights the importance of considering both aquifer productivity and protective capacity in groundwater development planning.

Groundwater potential assessment indicates that locations with moderate resistivity and appreciable aquifer thickness constitute the most favourable zones for groundwater development. However, areas with high groundwater potential do not always exhibit adequate protective capacity, emphasizing the need for integrated evaluation in borehole siting and groundwater management.

Overall, the study underscores the strong influence of lithology, degree of weathering, and overburden characteristics on groundwater occurrence in Makurdi. The integration of resistivity, conductivity, and longitudinal conductance parameters provides a reliable framework for groundwater exploration and vulnerability assessment. The findings therefore offer valuable guidance for sustainable groundwater development, borehole siting, and groundwater protection strategies in Makurdi and similar basement complex terrains.

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