

Assessment of Groundwater Potential and Aquifer Vulnerability at the University of Ilorin Teaching Hospital, Using Vertical Electrical Sounding Technique

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Abstract

Groundwater is critical for sustaining healthcare operations at the University of Ilorin Teaching Hospital (UTH), supporting patient care and hygiene. However, urbanization, pollution, and climate change threaten its quality and sustainability. This study evaluates groundwater potential and aquifer vulnerability at UTH, employing Vertical Electrical Sounding (VES) to assess subsurface resistivity and groundwater potential. Using a Schlumberger electrode configuration, data were collected at 12 locations near failed boreholes in order to validate layer thicknesses and depths. The VES results identified three to four geo-electric layers, including topsoil, weathered basement, fractured basement, and fresh basement. The aquifer vulnerability index (AVI) was applied to classify and distinguish aquifer vulnerability within the study area. The aquifer resistivity ranges from 27.9 Ωm to 522 Ωm , thickness ranges from 3.04 m to 67.6 m, and the depth ranges from 3.57 m and 71.6 m. The curve types including H, A, HK, and HA reflect lithological diversity and varying aquifer conditions. The weathered and fractured basement layers exhibited significant groundwater potential, particularly at VES5 and VES6, which showed high transmissivity values of 308.88 m^2/day and 254.93 m^2/day respectively. Moderate potential was observed at VES1, VES2, VES9, and VES10, while VES3, VES4, VES8, and VES12 showed lower potential due to thin weathered layers. Aquifer vulnerability varied across sites, with VES6 and VES12 demonstrating strong protection from contamination due to thick overburden, while VES4 and VES3 were highly susceptible. The study highlights the need for protective measures in vulnerable areas and sustainable groundwater management to ensure a reliable water supply for healthcare operations.

Keywords: Groundwater potential, Aquifer vulnerability, resistivity meter, Transmissivity, Hydraulic resistance

Introduction

Water is a fundamental resource in every healthcare setting, particularly in university teaching hospitals where patient care and academic activities intersect (Hernández, 2020). As centres of medical excellence, teaching hospitals depend heavily on water for a wide array of purposes, including clinical, instructional, and research activities. Essential uses such as bathing, wound cleansing, and hydration which contribute to patient comfort, cleanliness, and infection control all depend on clean water (Chandy et al., 2024; Ousey et al., 2016). An adequate and clean water supply is critical for maintaining hygiene standards, thereby reducing the incidence of Healthcare-Associated Infections (HAIs) (Mock et al., 2017). Furthermore, surgical and emergency medical facilities rely on water for maintaining sterile environments, essential for pre-operative and post-operative protocols (Maynard & Whapham, 2020).

Groundwater is a key resource, providing a significant portion of the freshwater required in teaching hospitals (Maynard & Whapham, 2020). However, concerns over its sustainability and quality have become increasingly urgent due to urbanization, agricultural runoff, chemical pollution, and climate change (Banerjee et al., 2023). Factors such as regional water flow, soil composition, climate conditions, land use practices, and pollutant types influence groundwater contamination risks (Hossain & Patra, 2020). Recent studies highlight the alarming impacts of urban development and climate change on groundwater resources (Ali et al., 2024; Dao et al., 2024). These findings underscore the need for site-specific exploration and management to ensure reliable water supply and mitigate contamination risks. Conducting groundwater evaluations and vulnerability assessments is crucial to understanding these risks and ensuring sustainable water management. Such assessments not only identify contamination hotspots but also provide actionable insights for preserving groundwater resources, which are indispensable for healthcare infrastructure.

At the University of Ilorin Teaching Hospital (UITH), the sustainability of groundwater resources has become a pressing issue. Challenges such as excessive groundwater extraction, limited recharge opportunities, population growth, competing residential and agricultural demands, and climate variability threaten the long-term availability of this critical resource. Additionally, the hospital's activities contribute to rising water demand and potential contamination from chemical and biological discharges. These challenges emphasize the necessity for systematic groundwater exploration coupled with robust water resource management practices, in order to guarantee wayyter supply for UITH and to mitigate adverse environmental impacts within the host community. This study focuses on assessing groundwater potential and evaluating the vulnerability of aquifer systems to contamination and overexploitation at UITH. By addressing these interconnected objectives, the study aims to provide actionable recommendations for maintaining a reliable water supply essential to the hospital's operations.

Within the UITH area, Olawuyi (2012) conducted the foundational geo-electrical investigation for groundwater, identifying four lithological units and two potential water-

bearing zones using a limited number of sounding stations. While this earlier work established the basic feasibility of geo-electrical exploration at the site, it did not incorporate quantitative hydraulic parameter estimation (hydraulic conductivity, transmissivity, or hydraulic conductivity) or a formal aquifer vulnerability assessment, both of which are essential for evaluating not just where groundwater exists, but how productive and how protected each potential source is. The present study advances this baseline by expanding spatial coverage to twelve VES stations sited at previously failed boreholes, rank aquifer productivity across the stations and introduced aquifer vulnerability index, to identify which zone requires protective intervention before being recommended for water supply use.

Modern geophysical methods, particularly the Vertical Electrical Sounding (VES) technique, have proven effective for delineating subsurface lithology and assessing aquifer potential (Arowoogun & Osinowo, 2022; Fajana, 2020). The approach enables precise identification of geo-electric layers, aquifer thickness, and hydraulic properties. Sunkari et al. (2021) demonstrate how VES can identify weathered and fractured basement zones with high groundwater potential, while Obiora & Ibuot(2020) emphasize their role in evaluating aquifer vulnerability to surface contaminants. These studies provide critical insights into aquifer dynamics and vulnerability assessment but all lack a healthcare-specific focus, particularly in addressing the unique demands and contamination risks associated with hospital settings.

This study distinguishes itself by addressing groundwater exploration a healthcare-specific context, where water quality and reliability are critical for operations. While previous research focused broadly on urban or agricultural applications, this study tailors its approach to UITH, utilizing VES to evaluate subsurface lithology and aquifer properties with direct implications for healthcare needs. The incorporation of advanced hydraulic property estimation and vulnerability assessment ensures a comprehensive analysis, setting a precedent for similar institutions. Additionally, this work provides actionable recommendations, bridging the gap between academic research and practical groundwater management strategies. By combining resistivity data, transmissivity analysis, and contamination risk evaluation, the study not only contributes to the state of the art but also serves as a model for sustainable groundwater use in healthcare environments globally.

Study Area Description

The research site is located in the southern section of the University of Ilorin permanent campus, Kwara State, Nigeria. The university is approximately 12 km East of Ilorin Township and spans a total area of about 15,000 hectares. The study area lies between longitudes 4° 38' 40" E and 4° 39' 55" E, and latitudes 8° 30' 35" N and 8° 31' 55" N (Figure 1). The site is accessible via major roads and interconnected footpaths. Key features surrounding the study area include a hospital complex, administrative buildings, telephone masts, lecture theatres, and laboratories.

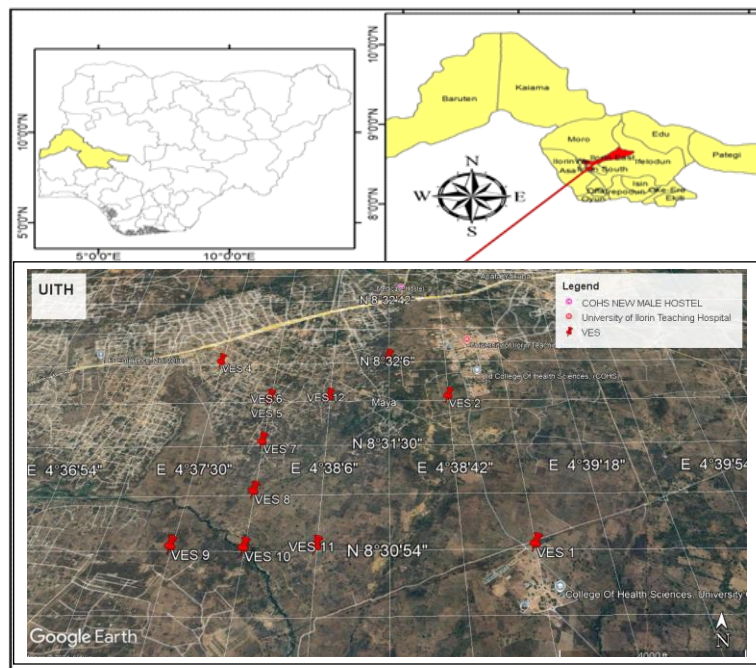


Figure 1: Aerial photograph of UITH showing the spatial distribution of the VES Survey Points

Ilorin, which hosts the hospital campus, is located in the transitional zone between the humid forest and dry savannah. The region experiences an average annual rainfall of approximately 1200 mm, making groundwater an essential resource for domestic, agrarian, and manufacturing uses. The climate is characterized by two distinct seasons: the rainy season starting in March and ending in October and the dry season which begins in November and ends by early March of every year. The average annual temperature ranges between 30–35 °C, with an average relative humidity of 60 % (Olubanjo, 2019).

Geologically, the study area lies within the basement rock terrain of West-Central Nigeria. It is predominantly underlain by the Migmatite–Gneiss–Quartzite complex, which dates back to the Precambrian to Cambrian age (Figure 2). These formations have been intruded by granitic bodies collectively referred to as the Older Granitoids. These include porphyritic granite, medium- to coarse-grained biotite granite, hornblende granite, granodiorite, and granite gneiss, all of which are associated with the Pan-African orogeny (Ajibade & Wright, 1989; Obaje, 2009). Additionally, younger metasedimentary rocks, also linked to the Pan-African age, underlie the southeastern portion of the area. These rock types are characterized by low primary porosity and permeability.

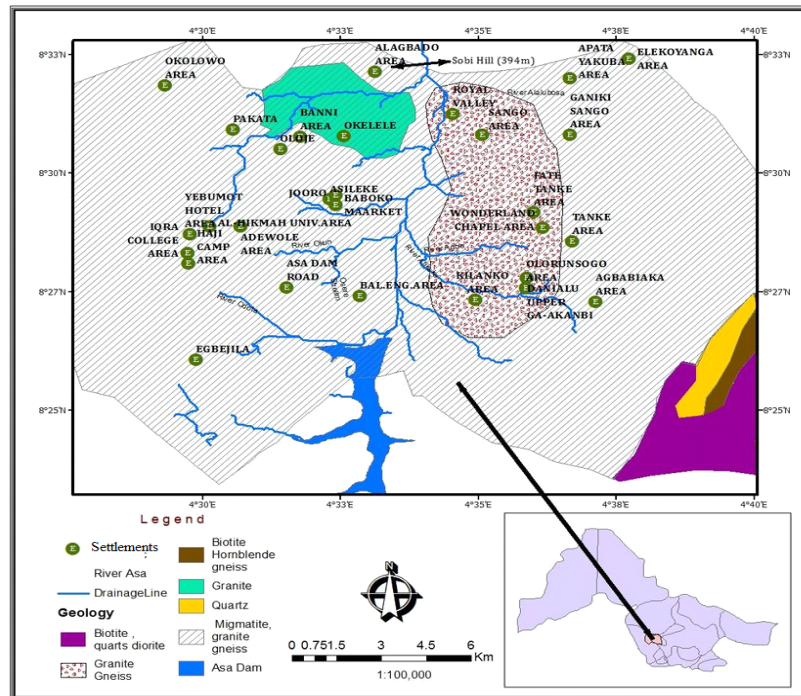


Figure 2: Geological Map of Ilorin (Ifabiyei et al., 2016)

Materials and Methods

Vertical Electrical Sounding (VES), a geophysical technique based on resistivity analysis, is widely used to investigate subsurface resistivity variations for identifying aquifer zones. This method helps delineate subsurface boundaries, estimate groundwater depth, and evaluate groundwater potential. For this survey, a resistivity meter was employed to measure apparent resistivity values, utilizing a four-electrode configuration (two current electrodes and two potential electrodes). A handheld GPS device with Real-Time Kinematic (RTK) correction was used to accurately record the coordinates of each survey site, ensuring sub-meter accuracy. Supporting field equipment included a measuring tape for electrode spacing, a hammer for electrode insertion, and a gyroscopic compass for high-precision site alignment and orientation.

The survey was conducted at twelve (12) strategically selected locations near existing failed boreholes, using the Schlumberger electrode arrangement. The maximum half-current electrode spacing ($AB/2$) extended to 100 m. During the survey, direct current was injected into the ground through the outer electrodes (A and B), while the resulting potential difference between the inner electrodes (M and N) was measured. Resistance values were displayed on the resistivity meter and recorded for each electrode spacing. To ensure data reliability, measurements were repeated to confirm

consistency. The apparent resistivity (ρ) was calculated by multiplying the recorded resistance values by the geometric factor (G), as described by Ojo et al, (2014). This systematic approach ensured accurate delineation of subsurface properties for effective groundwater exploration.

$$G = \pi \frac{\left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right]}{MN} \quad 1$$

The estimated apparent resistivity values were plotted against AB/2 using the IPI2WIN inversion software. The resulting VES curves provided insights into the thicknesses and apparent resistivities of the distinct geoelectric layers. These values, including layer resistivity (ρ) and depth (h), were used to derive additional parameters: hydraulic conductivity (HC), aquifer transmissivity (T), and hydraulic resistance (C), based on the assumption of horizontal, homogeneous, and isotropic layers (Obiora & Ibuot, 2020). Hydraulic resistance indicates the time it takes for water to travel through the various porous media above the topmost saturated aquifer surface by advection. As noted by Dashti et al (2023), transmissivity quantifies an aquifer's ability to transmit water across its entire saturated thickness. Hydraulic conductivity, on the other hand, describes an aquifer's dynamic behaviour by facilitating the flow of fluid through its porous structures. Niwas & Singhal (1981) proposed an equation for estimating transmissivity values in a saturated aquifer, as outlined below.

$$T = HC \times S \times \rho_{\text{aquifer}} = \frac{HC \times S}{\sigma} = HC \times d \quad 2$$

S, ρ_{aquifer} , d and σ represent the longitudinal conductance, aquifer apparent resistivity, aquifer thickness, and the inverse of aquifer apparent resistivity, respectively. When transmissivity (T) is expressed in $\text{m}^2 \text{day}^{-1}$, the aquifer potential is classified as follows (Table 1)

Table 1: Classification of aquifer potential based on transmissivity values

Transmissivity Range ($\text{m}^2 \text{day}^{-1}$)	Classification
> 500	High Potential
$50 \leq T \leq 500$	Moderate Potential
$5 \leq T < 50$	Low Potential
$0.5 \leq T < 5$	Very Low Potential
< 0.5	Negligible Potential

The Aquifer Vulnerability Index (AVI) was applied to classify and distinguish aquifer vulnerability within the study area. AVI quantifies vulnerability based on the hydraulic resistance to the vertical flow of water through the overlying strata (Shah et al., 2021; Stempvoort et al., 1993). AVI estimation relies on two key parameters: Thickness (d) of the protecting layers and probable hydraulic conductivity (HC).

Hydraulic resistance (C), which measures resistance to water flow through the protective layer above an aquifer, was computed using these parameters and is expressed as:

$$C = \sum_{i=1}^n \frac{d_i}{HC_i} \quad 3$$

Here, HC_i is the hydraulic conductivity, and d_i is the thickness of the vadose zone materials. Hydraulic resistance (C) is expressed in years, and aquifer vulnerability classification is based on the logarithmic scale of C: $\log C < 1$ is Very high vulnerability, $1 \leq \log C < 2$ is High vulnerability, $2 \leq \log C < 3$ is Moderate vulnerability, $3 \leq \log C < 4$ is Low vulnerability while $\log C > 4$ is a Very low vulnerability.

The empirical formula between HC and ρ_{aquifer} is given in equation 4 (Emeka & Samuel, 2023).

$$HC = 386.4(\rho_{\text{aquifer}})^{-0.93283} \quad 4$$

Results and Discussions

The survey carried around UITH consists of 12 VES points. The results of the inferred VES plots and geo-electric units gave three (3) to four (4) layers with their respective thickness, depths, and apparent resistivities (Table 2). The inferred lithology, typical models illustrated in Figure 3 - 7, shows that it consists mainly of geo-electric signature involving H curve type (indicates a resistive top layer, a less resistive middle layer (weathered or clayey layer)), and a more resistive bottom layer), A curve type (shows increasing resistivity with depth, typical of a transition from loose surface material to more compact or fresh basement), HK curve type (suggests a resistive top layer, a conductive second layer (clay or sandy clay), followed by a highly resistive basement) and HA curve type (represents a resistive top layer, followed by a relatively conductive layer, and then an increase in resistivity to the basement).

The H curve type is hydrologically significant because the conductive middle unit typically represents the weathered zone where groundwater accumulates within clay-rich, porous regolith. This curve was most frequently observed in the study area in VES 1, VES 2, VES 3, VES 4 and VES 9). The A curve type reflects a gradational transition from loose, moisture-retaining surface material directly into compact, less weathered basement, without a distinct intervening conductive horizon. This pattern is observed at VES 5, VES 8, VES 10 and VES 11, suggesting a comparatively thinner or less developed weathering profile. HK curve type seen at VES 6 and VES 12, indicates a more complex four-layer sequence. The presence of additional intermediate conductive layer is hydrologically important because it suggests a thicker or more differential regolith profile, often associated with greater water storage capacity. The HA curve type indicates a layered weathering sequence with a discrete clay horizon that may locally perch or redirect infiltrating water before it reaches the main weathered basement aquifer.

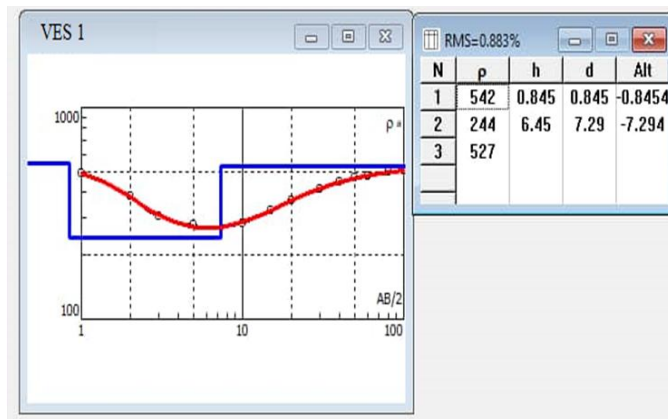


Figure 3: Resistivity sounding curve for VES 1

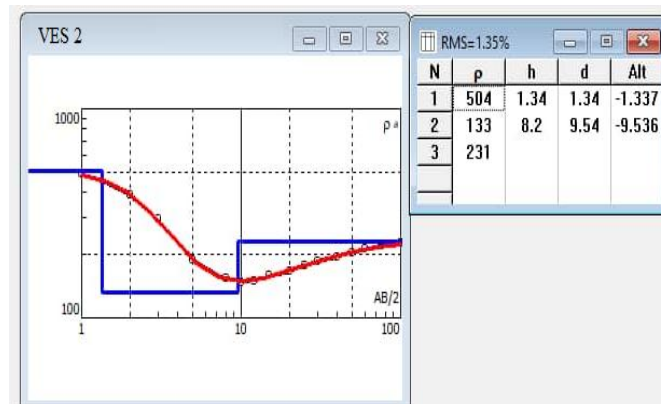


Figure 4: Resistivity sounding curve for VES 2

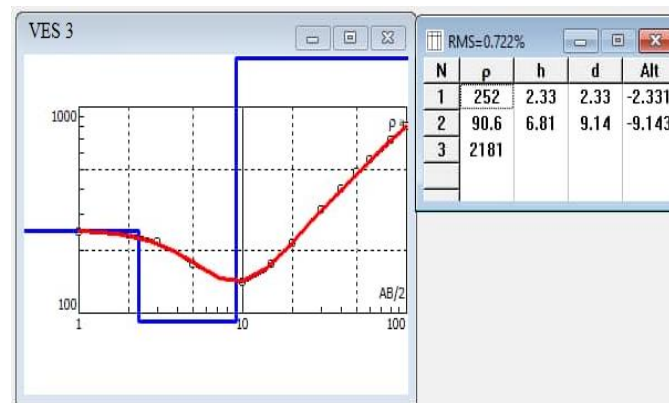


Figure 5: Resistivity sounding curve for VES 3

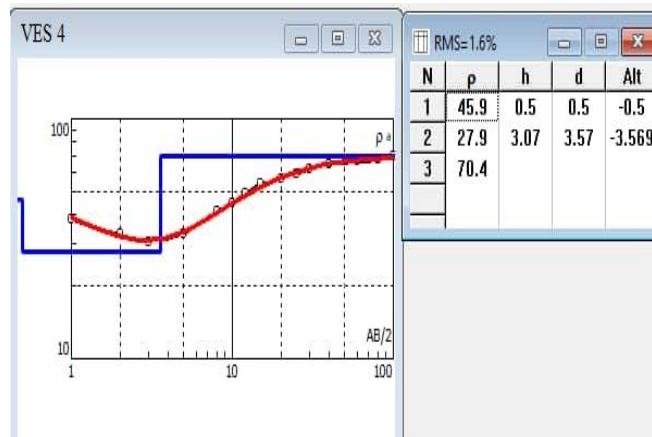


Figure 6: Resistivity sounding curve for VES 4

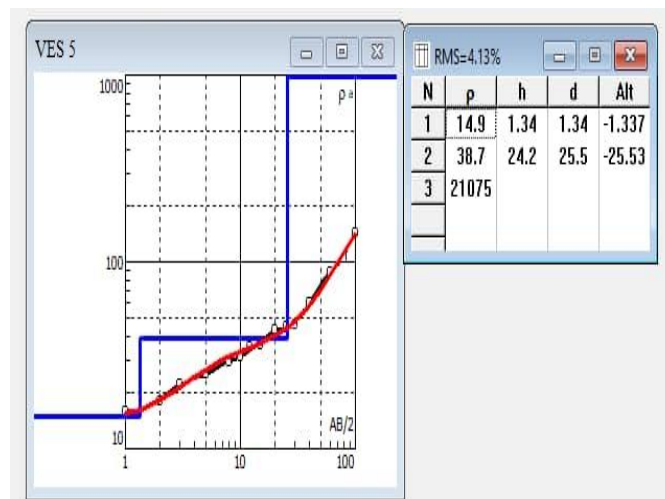


Figure 7: Resistivity sounding curve for VES 5

In the present research, the first layer which is referred to as the topsoil consists of clayey sand to sandy clay material with resistivity and thickness range of 14.9 to 615 Ωm and 0.5 to 2.3 m respectively indicating diverse surface conditions like sandy or clayey soil. This layer also occurs in multi-layer in some parts of the study area serving as the second layer. Beneath this, is a weathered basement rock with resistivity and thickness range of 27.9 to 522 Ωm and 3 to 67.6 m respectively. This layer overlaid an infinitely continuous layer suspected to be fractured/fresh basement rock which has a resistivity range of 70 to 121277 Ωm and is characterized by infinite thickness. Therefore,

weathered to fracture basement layer which has a lower resistivity value constitutes a good water zone and highly decomposes schist or granite.

Summarily, the VES results reveal varying subsurface conditions with aquifer potential primarily in the weathered and fractured basement layers. The curve types (H, A, HK, and HA) indicate lithological diversity, with weathered layers generally acting as the main groundwater reservoirs. VES5 and VES6 show high aquifer potential due to their thick weathered layers, while moderate potential exists in VES1, VES2, VES9, and VES10, which also feature fractured basement layers. Low aquifer potential is observed in VES3, VES4, VES8, and VES12, where weathered layers are either thin or less conductive. The resistivity trends suggest a mix of sandy clay, clay-rich, and crystalline rock formations influencing groundwater storage capacity.

Table 2: Summary of Sounding Curve Parameters

VES No	No of Layers	Layer Resistivity (Ωm)	Layer Thickness (m)	Aquifer Depth (m)	Curve Type	Inferred Lithology
VES1	3	542	0.845	7.29	H	Topsoil
		244	6.45			Weathered Basement
		527				Fractured Basement.
VES2	3	504	1.34	9.54	H	Topsoil
		133	8.2			Weathered Basement
		231				Fractured Basement.
VES3	3	252	2.33	9.14	H	Topsoil
		90.6	6.81			Weathered Basement
		2181				Fresh Basement.
VES4	3	45.9	0.5	3.57	H	Topsoil
		27.9	3.04			Weathered Basement
		70.4				Fractured Basement.
VES5	3	14.9	1.34	25.5	A	Topsoil
		38.7	24.2			Weathered Basement
		21075				Fresh Basement.
VES6	4	68.2	1.47	71.6	HK	Topsoil
		19.6	2.52			Sandy clay
		143	67.6			Weathered Basement
		14567				Fresh Basement.
VES7	4	107	0.782	33.7	HA	Topsoil
		44.2	8.15			Sandy clay
		316	24.8			Weathered Basement
		30152				Fresh Basement

VES8	3	177	0.923	11.1	A	Topsoil
		214	10.1			Weathered Basement
		121277				Fresh Basement
VES9	3	615	0.5	16.9	H	Topsoil
		215	16.4			Weathered Basement
		603				Fractured Basement.
VES10	3	110	1.13	19.8	A	Topsoil
		237	18.7			Weathered Basement
		686				Fractured Basement.
VES11	3	182	1.68	28	A	Topsoil
		237	26.3			Weathered Basement
		54903				Fresh Basement
VES12	4	347	0.5	16.3	HK	Topsoil
		126	1.72			Sandy clay
		522	14.1			Weathered Basement
		1682				Fresh Basement.

Results of the hydraulic categorization of the aquifer using the VES data are presented in Table 3. The aquifer resistivity values vary widely across the study area, ranging from 27.9 Ωm (VES 4) to 522 Ωm (VES 12). High resistivity values, such as at VES 12, suggest the presence of sandy or gravelly aquifer materials, which are typically good for water transmission. Conversely, low resistivity values, like at VES 4, indicate clayey or conductive materials that could hinder groundwater flow. The aquifer thickness also shows significant variability, from just 3.04 m at VES 4 to 67.6 m at VES 6, highlighting the differing water-bearing capacities of these aquifers. The aquifer thickness map is shown in Figure 8. VES5, VES6, and VES7, situated in the northeastern part of the study area, correspond to regions of high aquifer thickness (30–60 m), indicating significant groundwater potential. Intermediate aquifer thickness (14–30 m) is observed at VES1, VES2, VES3, VES9, VES10, VES11, and VES12, reflecting moderate groundwater storage capacity across these locations. In contrast, VES4 and VES8 are associated with thin aquifer formations (<10 m), indicating limited groundwater potential. This distribution shows a general trend of thicker aquifers towards the northeastern part of the study area, with intermediate thickness in the northwestern portion and thinner formations towards the southern areas. The present study's aquifer thickness map reveals that aquifer thickness is highest in the northeastern portion of the study area (30–60 m), aligning with the trend identified by Olawuyi (2012).

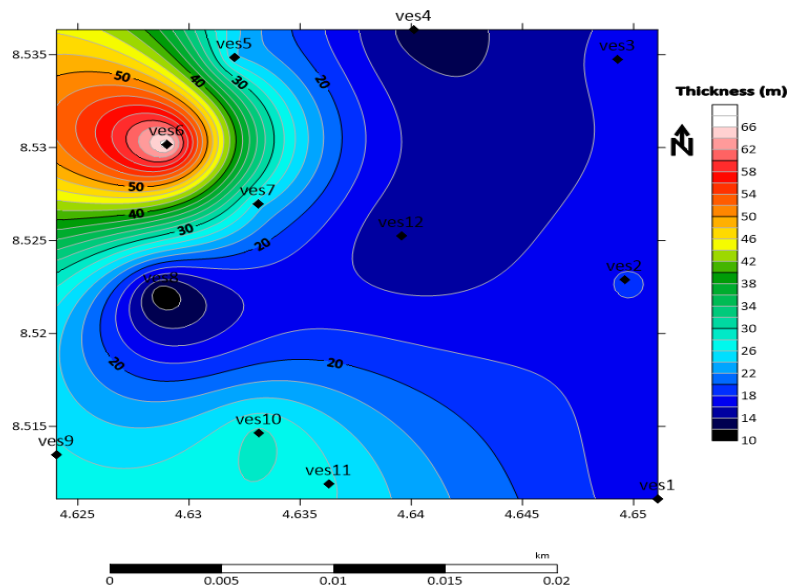


Figure 8: Aquifer thickness map

Hydraulic conductivity values range from 1.13 m/day (VES 12) to 17.32 m/day (VES 4). These values reflect the ease with which water flows through the aquifer, with higher values indicating more permeable materials. The depth of the aquifer ranges between 3.57 m (VES 4) and 71.6 m (VES 6), showing a mix of shallow and deep aquifers across the sites. Similarly, the overburden thickness follows the same pattern, with thicker overburdens potentially requiring more time for recharge. Areas with shallow aquifers, such as VES 4, might be more susceptible to contamination but offer easier groundwater access compared to deeper aquifers like VES 6. The aquifer transmissivity, a product of hydraulic conductivity and aquifer thickness, varies significantly, from 14.78 m²/day (VES 1) to 308.88 m²/day (VES 5). Locations with high transmissivity, like VES 5, are indicative of productive aquifers with high groundwater potential.

Hydraulic resistance, which measures the time water takes to recharge an aquifer, spans a wide range from 0.18 years (VES 4) to 17.93 years (VES 6). High resistance values are associated with thick overburden or low hydraulic conductivity, indicating slower recharge rates. The log C values align with transmissivity trends, confirming the productivity and recharge potential of the aquifers. Overall, VES 5 and VES 6 emerge as promising sites for groundwater exploitation due to their substantial aquifer thickness and high transmissivity. VES 6 possesses the greatest aquifer thickness yet records a transmissivity lower than VES 5 with considerably thinner aquifer. This is explained by the inverse relationship between transmissivity and aquifer vulnerability embedded in the Niwas & Singhal (1981) equation. VES 1 and VES 12, despite reasonable aquifer

thickness of 6.45 m and 14.1 m respectively recorded some of the lowest transmissivity values. Their aquifer material is likely less weathered, more compact and consequently less permeable.

Table 3: Aquifer parameters and hydraulic property estimated from VES data

VES NO	Aquifer Resistivity ($\Omega \cdot m$)	Aquifer Thickness (m)	Depth to Aquifer (m)	Overburden Thickness (m)	Hydraulic Conductivity (m/day)	Hydraulic Resistance (years)	Log C	Aquifer Transmissivity (m^2/day)
1	244	6.45	7.29	7.29	2.29	2.82	0.45	14.78
2	133	8.20	9.54	9.54	4.04	2.03	0.31	33.09
3	90.6	6.81	9.14	9.14	5.77	1.18	0.07	39.31
4	27.9	3.04	3.57	3.57	17.32	0.18	-0.76	52.65
5	38.7	24.20	25.50	25.50	12.76	1.90	0.28	308.88
6	143	67.60	71.60	71.60	3.77	17.93	1.25	254.93
7	316	24.80	33.70	33.70	1.80	13.78	1.14	44.64
8	214	10.10	11.10	11.10	2.59	3.90	0.59	26.15
9	215	16.40	16.90	16.90	2.58	6.36	0.80	42.28
10	237	18.70	19.80	19.80	2.35	7.94	0.90	44.02
11	237	26.30	28.00	28.00	2.35	11.17	1.05	61.91
12	522	14.10	16.30	16.30	1.13	12.51	1.10	15.89

The log C value in the context of aquifer vulnerability typically reflects the aquifer's protective capacity. A higher log C value indicates a less vulnerable aquifer with greater protection from surface contaminants, while lower log C values suggest higher vulnerability. VES 6, VES 7, VES 11 and VES 12 have a value of log C greater than 1 but less than 2, these values suggest that the aquifers have significant protection from surface contamination. The areas surrounding the aquifer generally feature thick overburden layers or low permeability materials that act as a barrier, slowing the infiltration of potential contaminants which could be fine sand or sandy loam with relatively little structure. Moreover, VES 6 has a thick overburden of 71.6 m and a relatively high hydraulic resistance of 17.93 years. This indicates a well-protected aquifer with a low risk of contamination despite its substantial depth. Similarly, VES 12 exhibits a strong protective capacity due to its high overburden thickness and resistance, coupled with moderate transmissivity. VES 7, has a moderate overburden thickness (33.7 m) and hydraulic resistance (13.78 years). These characteristics indicate moderate protection, where the aquifer may recharge at a reasonable rate while maintaining some resistance to surface contaminants. VES 10, with a log C of 0.90, may also demonstrate moderate high vulnerability but could be more prone to contamination than sites with log C values between 1 and 2.

VES1, VES2, VES3, VES4, VES5, VES8 and VES9 have low log C values and are indicative of aquifers with very high vulnerability to contamination. These sites have

thin overburden layers and low hydraulic resistance, allowing contaminants to infiltrate quickly. For example, VES 4, with a $\log_{10}C$ value of -0.76, has a shallow aquifer (3.57 m depth) and minimal overburden (3.57 m thickness), making it highly susceptible to pollution from surface activities. Similarly, VES 3, with a $\log C$ of 0.07, has limited protection due to its shallow depth and low hydraulic resistance. These areas require stricter monitoring and protection measures, such as controlling land use and pollution sources.

This study delineates lithological units, assesses aquifer potential, and evaluates hydraulic properties. It holds significant implications for groundwater management, particularly in regions with similar geological settings. The research builds upon earlier work by Olawuyi (2012), offering updated insights and a broader spatial understanding of the aquifer systems within the UITH area. Compared to Olawuyi's study, which identified four lithological units and two potential water-bearing zones, the current research further refines these observations by characterizing the resistivity and thickness variations in greater detail. This enhances the ability to identify high-potential zones for groundwater extraction, making the results more actionable for practical applications. The current study's integration of hydraulic conductivity, transmissivity, and protective capacity analysis adds depth to the understanding of aquifer dynamics.

Conclusions

This study conducted a detailed investigation of groundwater potential and aquifer vulnerability in the UITH area using VES techniques. By analyzing the subsurface geological layers, hydraulic properties, and aquifer parameters, the research provides critical insights into the sustainable management of groundwater resources essential for hospital operations. The findings revealed that the subsurface in the study area is characterized by diverse lithological and hydraulic properties, with four primary geo-electric curve types identified as H, A, HK, and HA, reflecting varying subsurface conditions ranging from sandy clay and clayey sand to weathered, fractured and fresh basement. Aquifer potential was predominantly associated with the weathered and fractured basement layers, which served as the principal groundwater reservoirs across the study area. VES 5 and VES 6 emerged as the highest-potential sites, with substantial weathered-layer thickness and transmissivity values of 308.88 m²/day and 254.93 m²/day, respectively, while VES 1, VES 2, VES 9 and VES 10 exhibited moderate potential, and VES 3, VES 4, VES 8 and VES 12 showed comparatively lower potential due to their thinner or less conductive weathered layers.

In terms of aquifer vulnerability, the application of hydraulic resistance and $\log C$ classification revealed marked spatial variation in protective capacity. VES6 and VES12 demonstrated strong protection against surface contamination, attributable to thick overburden layers and high hydraulic resistance, whereas VES4 and VES3 were identified as highly vulnerable, owing to shallow depths, minimal overburden, and low hydraulic resistance. These findings demonstrate that high groundwater potential and strong aquifer protection do not necessarily coincide at the same location, underscoring

the importance of evaluating productivity and vulnerability jointly, rather than relying on either parameter in isolation, when identifying suitable groundwater sources for a healthcare facility where both water reliability and contamination risk carry direct operational and clinical significance.

Based on the findings of this study, VES 5 and VES 6 should be prioritized for sustainable groundwater extraction, given their high transmissivity and substantial aquifer thickness, while VES 4 and VES 3 require immediate protective intervention, given their high vulnerability classification. To enhance the accuracy and reliability of future hydrogeological assessment, future research should integrate complementary geophysical techniques alongside VES. Electrical Resistivity Tomography (ERT) would provide 2D and 3D subsurface imaging, offering higher spatial resolution than traditional 1D VES techniques. By incorporating ERT, future research can improve lateral and vertical delineation of weathered and fractured basement aquifers, detect subtle lithological variations and structural features that may influence groundwater movement. Ground Penetrating Radar (GPR) can also complement VES by providing high-resolution shallow subsurface imaging.

Conflict Of Interest Statement

All authors certify that they have no affiliations with or involvement in any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this manuscript.

Data Availability Statement

Available on reasonable request

References

- Ajibade, A. C., & Wright, J. B. (1989). The Togo-Benin-Nigeria Shield: Evidence of crustal aggregation in the Pan-African belt. *Tectonophysics*, 165(1–4), 125–129. [https://doi.org/10.1016/0040-1951\(89\)90041-3](https://doi.org/10.1016/0040-1951(89)90041-3)
- Ali, J., Islam, F., Bibi, T., Islam, I., Mughal, M. R., Sabir, M., Awwad, F., & Ismail, E. (2024). Quantifying the impact of climate change and urbanization on groundwater resources using geospatial modelling. *Frontiers in Earth Science*, 12, 1377367. <https://doi.org/10.3389/feart.2024.1377367>
- Arowoogun, K. I., & Osinowo, O. O. (2022). 3D resistivity model of 1D vertical electrical sounding (VES) data for groundwater potential and aquifer protective capacity assessment: A case study. *Modelling Earth Systems and Environment*, 8(2), 2615–2626. <https://doi.org/10.1007/s40808-021-01254-w>
- Banerjee, A., Creedon, L., Jones, N., Gill, L., & Gharbia, S. (2023). Dynamic Groundwater Contamination Vulnerability Assessment Techniques: A Systematic Review. *Hydrology*, 10(9), 182. <https://doi.org/10.3390/hydrology10090182>

- Chandy, M., Collett, S., Samarin, I., Bhalchandra, R., Soundaranayagam, J. R., Garai, S., & Bhattacharya, S. (2024). Water usage in a multi-speciality hospital and its effective management. *Journal of The Academy of Clinical Microbiologists*, 18(2), 135–137. <https://doi.org/10.4103/0972-1282.194956>
- Dao, P. U., Heuzard, A. G., Le, T. X. H., Zhao, J., Yin, R., Shang, C., & Fan, C. (2024). The impacts of climate change on groundwater quality: A review. *Science of The Total Environment*, 912, 169241. <https://doi.org/10.1016/j.scitotenv.2023.169241>
- Dashti, Z., Nakhaei, M., Vadiati, M., Karami, G. H., & Kisi, O. (2023). Estimation of Unconfined Aquifer Transmissivity Using a Comparative Study of Machine Learning Models. *Water Resources Management*, 37(12), 4909–4931. <https://doi.org/10.1007/s11269-023-03588-9>
- Department of Agricultural and Environmental Engineering, Federal University of Technology, Akure, Nigeria, & Olubanjo, O. (2019). Climate Variation Assessment Based on Rainfall and Temperature in Ilorin Kwara State Nigeria. *Applied Research Journal of Environmental Engineering*, 2(1), 1–18. <https://doi.org/10.47721/ARJEE20190201018>
- Emeka, A. L., & Samuel, Y. M. (2023). Estimation of aquifer hydraulic parameters using electrical resistivity method: A case study for Damaturu, Northeast Nigeria. *Dutse Journal of Pure and Applied Sciences*, 9(2a), 191–202. <https://doi.org/10.4314/dujopas.v9i2a.19>
- Fajana, A. O. (2020). Groundwater aquifer potential using electrical resistivity method and porosity calculation: A case study. *NRIAG Journal of Astronomy and Geophysics*, 9(1), 168–175. <https://doi.org/10.1080/20909977.2020.1728955>
- Hernández, D. (2020). Water systems in healthcare facilities. In *Clinical Engineering Handbook* (pp. 694–698). Elsevier. <https://doi.org/10.1016/B978-0-12-813467-2.00098-5>
- Hossain, M., & Patra, P. K. (2020). Water pollution index – A new integrated approach to rank water quality. *Ecological Indicators*, 117, 106668. <https://doi.org/10.1016/j.ecolind.2020.106668>
- Ifabiyi, I., Ashaolu, E., & Omotosho, O. (2016). Hydrogeological Characteristics of Groundwater Yield in Shallow Wells of the Regolith Aquifer: A Study from Ilorin, Nigeria. *Momona Ethiopian Journal of Science*, 8(1), 23. <https://doi.org/10.4314/mejs.v8i1.2>
- Maynard, E., & Whapham, C. (2020). Quality and supply of water used in hospitals. In *Decontamination in Hospitals and Healthcare* (pp. 45–69). Elsevier. <https://doi.org/10.1016/B978-0-08-102565-9.00003-0>
- Mock, C. N., Nugent, R., Kobusingye, O., & Smith, K. R. (2017). *Disease Control Priorities, Third Edition (Volume 7): Injury Prevention and Environmental Health*. Washington, DC: World Bank. <https://doi.org/10.1596/978-1-4648-0522-6>

- Niwas, S., & Singhal, D. C. (1981). Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *Journal of Hydrology*, 50, 393–399. [https://doi.org/10.1016/0022-1694\(81\)90082-2](https://doi.org/10.1016/0022-1694(81)90082-2)
- Obaje, N. G. (2009). *Geology and mineral resources of Nigeria* [Map]. Springer.
- Obiora, D. N., & Ibuot, J. C. (2020). Geophysical assessment of aquifer vulnerability and management: A case study of University of Nigeria, Nsukka, Enugu State. *Applied Water Science*, 10(1), 29. <https://doi.org/10.1007/s13201-019-1113-7>
- Ojo, A. O., Omotoso, T. O., & Adekanle, O. J. (2014). Determination of Location and Depth of Mineral Rocks at Olode Village in Ibadan, Oyo State, Nigeria, Using Geophysical Methods. *International Journal of Geophysics*, 2014, 1–13. <https://doi.org/10.1155/2014/306862>
- Olawuyi, A. K. (2012). Geo-electrical exploration for groundwater within the premises of University of Ilorin Teaching Hospital, Ilorin, Kwara state, Nigeria. *Nigerian Journal of Technological Development*. Vol. 9 No. 2 (2012) / Articles
- Ousey, K., Cutting, K. F., Rogers, A. A., & Rippon, M. G. (2016). The importance of hydration in wound healing: Reinvigorating the clinical perspective. *Journal of Wound Care*, 25(3), 122–130. <https://doi.org/10.12968/jowc.2016.25.3.122>
- Shah, S. H. I. A., Yan, J., Ullah, I., Aslam, B., Tariq, A., Zhang, L., & Mumtaz, F. (2021). Classification of Aquifer Vulnerability by Using the DRASTIC Index and Geo-Electrical Techniques. *Water*, 13(16), 2144. <https://doi.org/10.3390/w13162144>
- Stempvoort, D. V., Ewert, L., & Wassenaar, L. (1993). Aquifer Vulnerability Index: A GIS - Compatible Method for Groundwater Vulnerability Mapping. *Canadian Water Resources Journal*, 18(1), 25–37. <https://doi.org/10.4296/cwrj1801025>
- Sunkari, E. D., Kore, B. M., & Abioui, M. (2021). Hydrogeophysical appraisal of groundwater potential in the fractured basement aquifer of the federal capital territory, Abuja, Nigeria. *Results in Geophysical Sciences*, 5, 100012. <https://doi.org/10.1016/j.ringsps.2021.100012>