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Full Length Research

Assessment of aquifer vulnerability using Vertical Electrical Sounding (VES) data in Parts of Bori Metropolis for groundwater exploration

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ABSTRACT: This study evaluates the vulnerability of an aquifer in the study area using geophysical and hydrogeological parameters derived from Vertical Electrical Sounding (VES) data (obtained from 13 VES stations), including longitudinal conductance (S), transverse resistance (T), hydraulic conductivity (K), and aquifer transmissivity (T). The estimated longitudinal conductance (0.0070–0.1993 S) indicates moderate to low protective capacity of the overlying layers, while transverse resistance (4425.30–84758.40 Ωm^2) reveals variable hydraulic barriers, with lower values suggesting higher contamination risks. Hydraulic conductivity (8.11–356.55 m/day) and transmissivity (240.77–8664.19 m^2/day) further highlight high aquifer heterogeneity, with zones of extremely high permeability posing severe contamination risks due to rapid pollutant migration. The findings underscore the need for spatially differentiated groundwater protection strategies, emphasising high-risk zones where anthropogenic activities must be regulated to safeguard water quality. This research provides a framework for aquifer vulnerability assessment in similar hydrogeological settings, supporting sustainable groundwater management.

Keywords: Aquifer, conductance, conductivity, groundwater, resistance, transmissivity, vulnerability.

INTRODUCTION

The demand for reliable groundwater resources has risen due to the increasing need for potable water, especially in regions with contaminated or limited surface water. As noted by Lapworth *et al.* (2017), groundwater extraction plays a crucial role in addressing water scarcity in numerous metropolitan and semi-urban locations, including Bori Metropolis. Nonetheless, concerns regarding an aquifer's vulnerability to contamination and depletion persist, necessitating comprehensive research to evaluate this vulnerability and ensure sustainable management (Machiwal *et al.*, 2018; Sarah *et al.*, 2021).

Vertical Electrical Sounding (VES), a geophysical technique widely utilised in subsurface research, provides vital insights into the resistivity and structural characteristics of geological formations (Alao *et. al.*, 2019). By analysing resistivity variations, we can delineate aquifer systems, estimate their thickness, and determine their susceptibility to external factors like surface pollution or saltwater intrusion (Costall *et al.*, 2018; Menegbo *et al.*, 2024; Yang *et al.*, 2025). These evaluations are essential for effective groundwater exploration, management, and conservation.

Bori Metropolis, situated in the Niger Delta region of Nigeria, is marked by intricate hydrogeological conditions shaped by its geomorphology and human activities (Abam and Nwankwoala, 2020). The area encounters challenges such as increasing urbanisation, agricultural development and inadequate waste disposal, which, according to Brown and Chikagbum (2015), pose risks to groundwater quality and aquifer sustainability. This study aims to assess aquifer vulnerability in specific regions of Bori Metropolis using VES data. This study attempts to analyse aquifer vulnerability in selected sections of Bori Metropolis using VES data. The investigation seeks to identify the protective

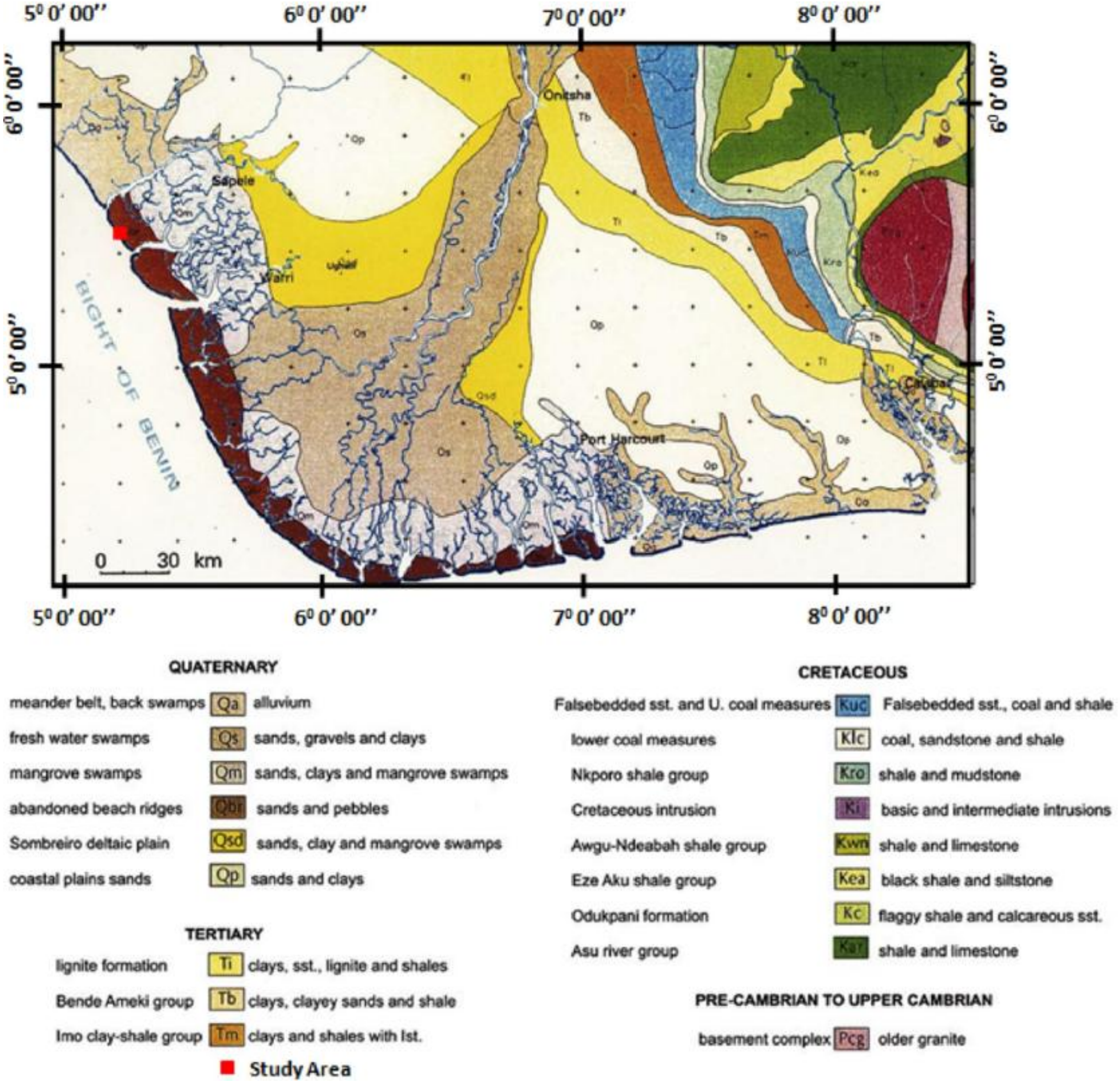

Figure 1. Geological map of Niger Delta and surroundings (Reijers, 2011).

capacity of subsurface layers relative to the already identified aquifer in the study area, providing a basis for informed decision-making regarding groundwater management in the area.

Bori Metropolis lies within the eastern Niger Delta's coastal plain, whose geological map is shown in Figure 1, underlain by recent fluvial and marine sediments of clays, silts, sands, gravels, and peat. The subsurface follows the Niger Delta stratigraphy: the Akata Formation (marine shales) at depth, overlain by the Agbada Formation (interbedded sands and shales), and capped by the Benin Formation of continental sands and gravels, which forms the main aquifer system (Short and Stauble, 1967; Doust and Omashola, 1989). Geoelectrical studies in Bori confirm thick, permeable sandy aquifers with strong groundwater potential, consistent with the broader Niger Delta model (Menegbo *et al.*, 2024).

This research contributes to the growing body of knowledge on aquifer vulnerability assessment, emphasising the importance of geophysical techniques in addressing environmental and resource management challenges. By integrating VES data with hydrogeological considerations, this study offers practical recommendations for safeguarding groundwater resources in Bori Metropolis and similar regions.

METHODOLOGY

In the assessment of aquifer vulnerability using Vertical

Table 1. Dataset for the study area.

VES stations in Bori	Coordinates		Aquifer resistivity (Ωm)	Depth (m)	Aquifer thickness (m)
	Longitude	Latitude			
Kenpoly convocation arena field	7.37414778	4.667667	3488	50.2	24.3
BMGS bori field	7.37207889	4.665453	3706	59.3	32.2
Kenpoly sec school field	7.36096	4.67842	2950	66.5	36.2
Kor road	7.379798	4.676532	1658	111	108
Bori police station	7.383455	4.672482	284	45	37.5
Market road	7.367565	4.677445	327	54.6	24.6
Court road	7.375072	4.67591	701	62.9	49.9
Tigidam street	7.372935	4.672565	1896	100	68.5
Monokpo street	7.365495	4.66705	1931	56.5	30.1
Bank road	7.36616	4.67171	2594	97.9	84.1
Gokana street	7.367968	4.673293	2246	50.9	33.5
Maakoro street	7.36597	4.665693	1109	49.4	25
Kogam street	7.36778	4.664385	149	57.3	29.7

Electrical Sounding (VES) data, several specific parameters are usually considered. These parameters help in characterising the subsurface conditions and understanding how they influence groundwater quality and movement. Key parameters include resistivity, depth, thickness, longitudinal conductance, transverse resistance, hydraulic conductivity and transmissivity of the aquifer (Oguama *et al*., 2019; de Almeida *et al*., 2021).

The resistivity, depth and thickness of the aquifer in the area of study will be obtained from Menegbo *et al.* (2024), who carried out a VES survey in thirteen VES stations from the study area and obtained resistivity, depth and thickness of the aquifer as summarised in Table 1. In their work, the VES survey was carried out employing the Schlumberger array configuration, with a maximum electrode spread of 300 m.

The longitudinal conductance (S) and transverse resistance (T) are often referred to as Dar-Zarrouk parameters (Tijani *et al*., 2021; Attwa and Nabih, 2015). While longitudinal conductance is a measure of the aquifer's ability to conduct electricity (with high values indicative of better shielding from contamination), transverse resistance is a measure of the bulk resistance of the aquifer (aids in identifying the protective capacity of the aquifer) (Alao *et. al.*, 2023). According to Tijani *et al.* (2021), these variables are usually expressed relative to the resistance (ρ) and thickness (h) of the aquifer, mathematically as,

$$S = \frac{h}{\rho} \quad (1)$$

$$T = h\rho \quad (2)$$

Hydraulic Conductivity (K) is a measure of how easily water can flow through the aquifer, descriptive of the aquifer's water-bearing properties, productivity, and its ability to transmit groundwater (Goodarzi et al., 2024). The aquifers in the Niger Delta have often been described as sand-dominated (Abam and Nwankwoala, 2020; Amajor, 1991). Hence, the hydraulic conductivity (in m/day) for the study area was defined according to Ekanem *et al*. (2020), who derived an empirical relationship for hydraulic conductivity, relative to aquifer resistivity, for sand-dominated aquifers in the Niger Delta region defined as.

$$K = 0.02 \times \rho^{1.2} \quad (3)$$

Aquifer transmissivity (Tr) is a measure of how much water can flow horizontally through an aquifer. It is descriptive of the speed at which contaminants spread through the aquifer according to Maliva (2016). According to Ekanem *et. al.* (2020), aquifer transmissivity is related to the thickness of the aquifer in such a way that,

$$Tr = K \times h \quad (4)$$

Table 2 shows the standard aquifer vulnerability. The classification highlights how aquifer vulnerability is strongly controlled by the interplay of overburden protective capacity (longitudinal conductance and transverse resistance) and aquifer hydraulic properties (hydraulic conductivity and transmissivity). Low values of conductance or resistance typically signify weak protective cover, making groundwater more prone to contamination. Conversely, high hydraulic conductivity and transmissivity, while favourable for groundwater yield, can also facilitate rapid contaminant transport. This duality underscores the need to interpret aquifer potential and vulnerability together when assessing groundwater systems.

RESULTS AND DISCUSSION

The obtained values of longitudinal conductance, transverse resistance, hydraulic conductivity and aquifer

Table 2. Estimated aquifer variables in the study area.

VES stations in Bori	Longitudinal conductance	Transverse resistance (Ωm)	Hydraulic conductivity (m)	Aquifer transmissivity (m)
Kenpoly convocation arena field	0.0070	84758.40	356.55	8664.19
BMGS bori field	0.0087	119333.20	383.46	12347.31
Kenpoly sec school field	0.0123	106790.00	291.62	10556.62
Kor road	0.0651	179064.00	146.06	15774.48
Bori police station	0.1320	10650.00	17.58	659.24
Market road	0.0752	8044.20	20.82	512.18
Court road	0.0712	34979.90	51.99	2594.13
Tigidam street	0.0361	129876.00	171.57	11752.40
Monokpo street	0.0156	58123.10	175.38	5278.80
Bank road	0.0324	218155.40	249.92	21017.93
Gokana street	0.0149	75241.00	210.24	7043.14
Maakoro street	0.0225	27725.00	90.15	2253.66
Kogam street	0.1993	4425.30	8.11	240.77

These variables were then used to create contour plots as shown in Figures 1 to 4.

Table 3. Aquifer vulnerability classification.

Parameter	Range	Aquifer Vulnerability Implication	Key References
Longitudinal Conductance (S) (mhos)	< 0.1	Very high vulnerability (poor protection)	Henriet (1976)
	0.1 – 0.19	High vulnerability (weak protection)	
	0.2 – 0.69	Moderate vulnerability	
	0.7 – 4.9	Low vulnerability (good protection)	
	≥ 5.0	Very low vulnerability (excellent protection)	
Transverse Resistance (T) (Ω·m²)	< 100	Very high vulnerability (poor aquifer potential & protection)	Olorunfemi and Fasuyi (1993)
	100 – 500	High vulnerability	
	500 – 1000	Moderate vulnerability	
	1000 – 5000	Low vulnerability (good aquifer protection)	
	> 5000	Very low vulnerability (excellent aquifer protection)	
Hydraulic Conductivity (K) (m/day)	< 1	Very low contamination risk (impermeable clay/shale barrier)	Goodarzi *et al.* (2024)
	1 – 10	Low risk (retards contaminant flow)	
	10 – 50	Moderate risk	
	50 – 100	High risk (contaminants migrate easily)	
	> 100	Very high risk (extreme vulnerability, rapid contaminant transport)	
Aquifer Transmissivity (Tr) (m²/day)	< 10	Low-yield aquifer, not exploitable; contamination impact minimal	Niwas and Singhal (1981)
	10 – 100	Low potential, localized contamination vulnerability	
	100 – 1000	Moderate vulnerability (moderate flow and contaminant spread)	
	1000 – 10,000	High vulnerability (high-yield aquifers, contaminants spread widely)	
	> 10,000	Very high vulnerability (extensive contamination risk)	

transmissivity for the different stations in the area of study are shown in Table 3. The contour maps of these estimated variables are also shown in Figures 2 to 5. These contour maps of the longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity in the study area show that aquifer properties in Bori are highly variable. Overall, the maps highlight that while certain parts of Bori hold strong groundwater potential, they also require strict management to prevent contamination.

The estimated longitudinal conductance (S) in the study area, ranging from 0.0070 to 0.1993 S, suggests a moderate to low protective capacity of the overlying layers against aquifer contamination according to Akindeji and Arinloye (2025). Where higher values (e.g., 0.1993 S) indicate relatively better protection due to greater cumulative conductivity (thickness/resistivity) of the confining layers, which can attenuate infiltrating pollutants, while the lower values (e.g., 0.0070 S) signify very weak protective layers, likely thin or highly resistive (e.g., sandy

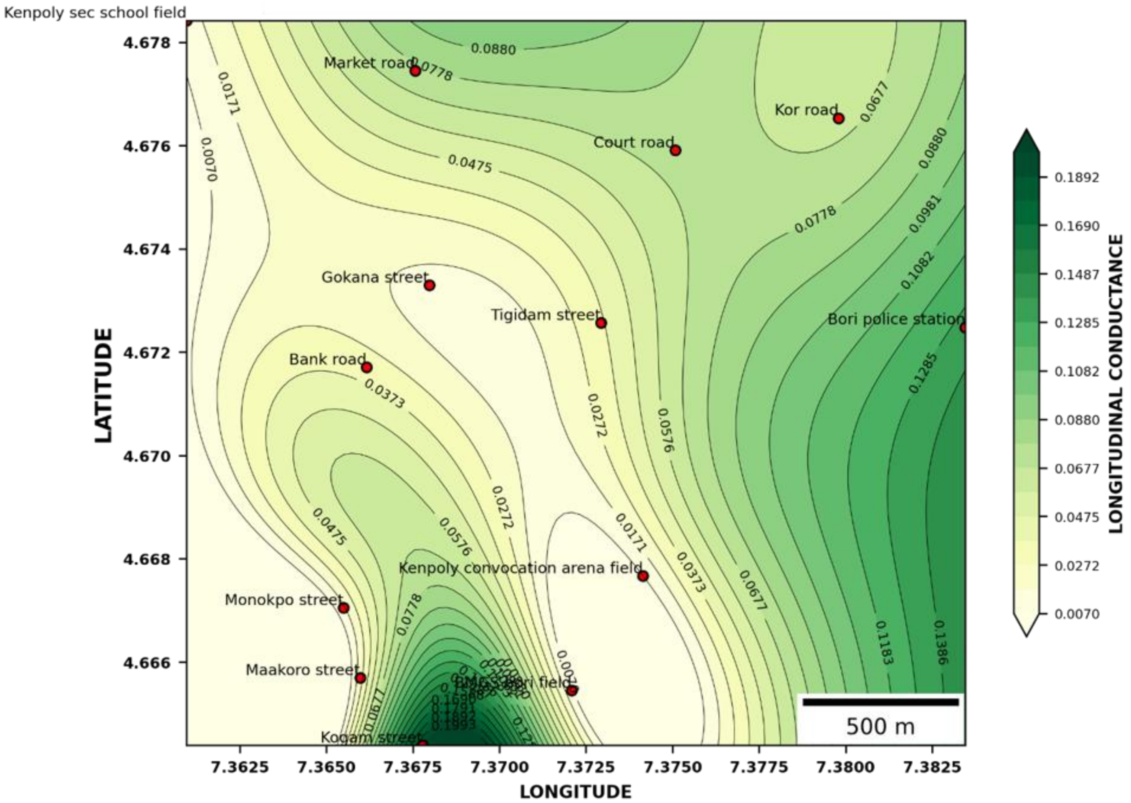

Figure 2. Contour map of longitudinal conductance.

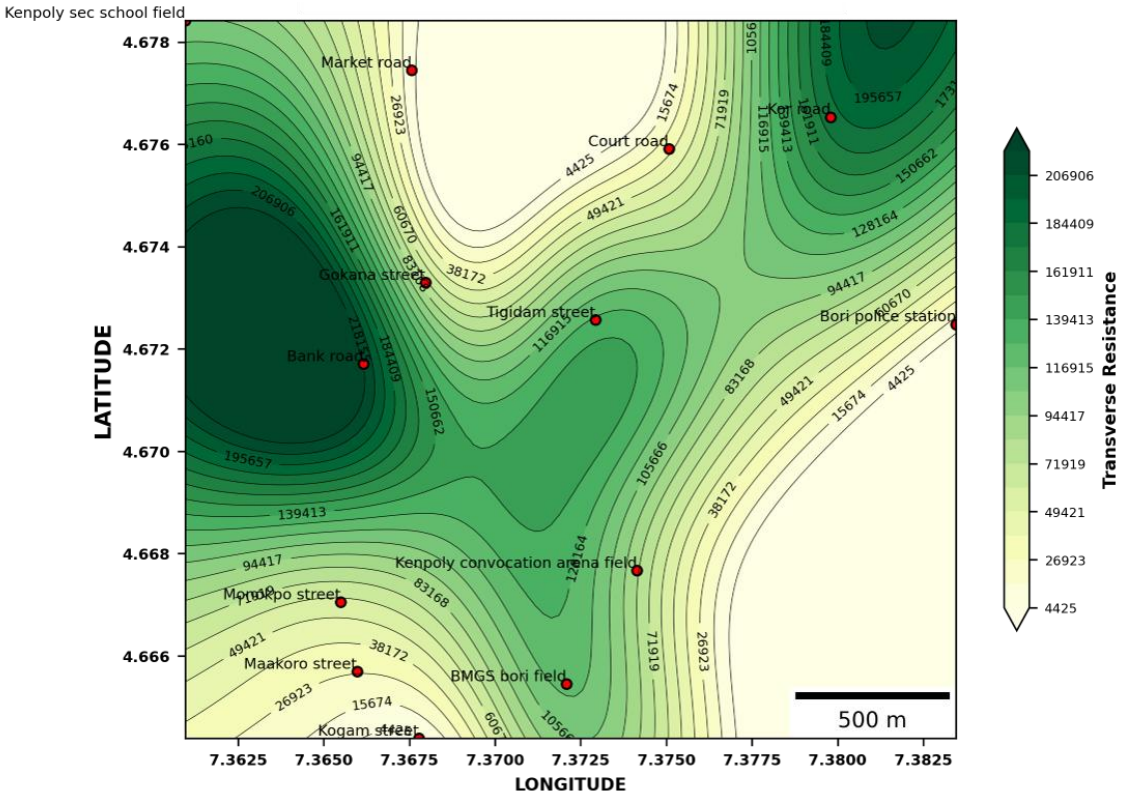

Figure 3. Contour map of transverse resistance.

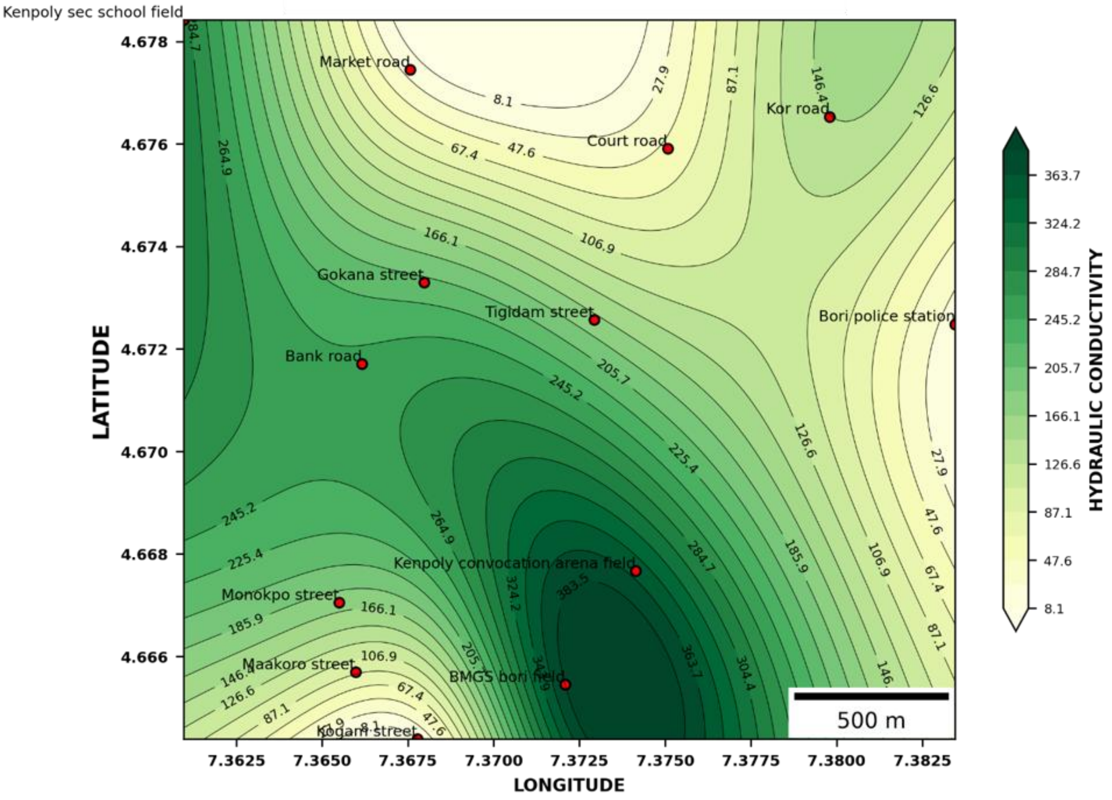

Figure 4. Contour map of hydraulic conductivity.

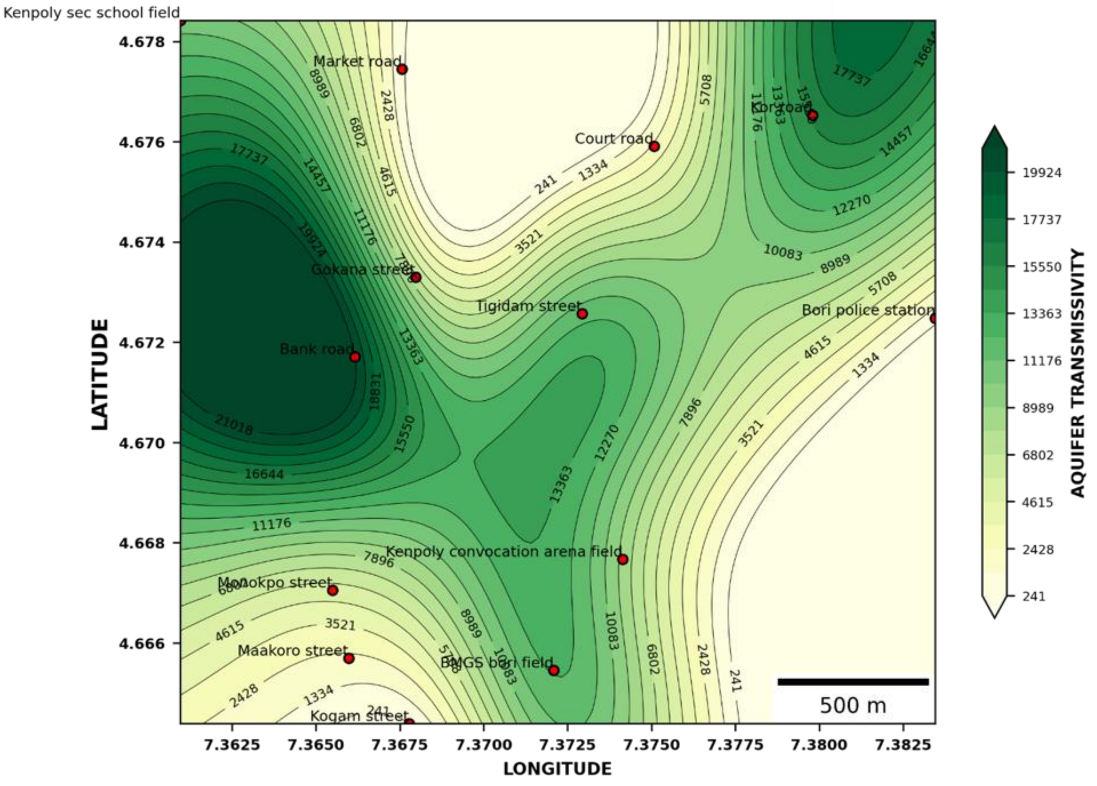

Figure 5. Contour map of aquifer transmissivity.

or fractured formations), making the aquifer beneath these zones highly vulnerable to surface-derived contaminants such as agricultural runoff, industrial effluents, or septic tank leakage (Eyankware *et al.,* 2020). This range implies spatially variable vulnerability, with areas closer to the lower end being critically exposed to contamination risks, necessitating prioritised mitigation measures like land-use restrictions or artificial recharge, whereas zones with higher longitudinal conductance may still require monitoring due to potential localised breaches in protective layers or anisotropic hydraulic behaviours that could compromise long-term aquifer integrity. In other words, the area of study is characterised by geoelectric layers, likely sandy or with minimal clay content, that offer little resistance to the downward migration of contaminants, posing a significant risk to groundwater quality.

The estimated transverse resistance (T) in the study area, ranging from 4425.30 to 84758.40 Ωm^2, reflects significant variability in the aquifer's hydraulic and protective characteristics. Lower values (e.g., 4425.30 Ωm^2) suggest higher permeability and porosity due to the dominance of less resistive layers (e.g., saturated sands or fractured zones), making the aquifer more susceptible to rapid contaminant infiltration and greater vulnerability in these regions, particularly if overlying layers are thin or absent (Makinde *et al*., 2024). Conversely, higher values (e.g., 84758.40 Ωm^2) indicate the presence of highly resistive formations (e.g., compacted clays, dense shales, or massive bedrock) that act as natural barriers, significantly reducing vertical fluid migration and thus offering stronger protection against surface pollutants (Tijani et al., 2021). However, such zones may also imply lower natural recharge rates and potential challenges for groundwater extraction. The broad range further suggests spatial heterogeneity in aquifer vulnerability, with areas of low transverse resistance requiring urgent protective measures (e.g., pollution source control or monitored abstraction) due to their heightened exposure, whereas high-T zones may still need assessment for lateral contamination pathways or secondary porosity effects (e.g., fault-driven flow) that could locally undermine resistance-based protection (Falowo, 2023).

The estimated hydraulic conductivity (K) in the study area, ranging from 8.11 to 356.55 m/day, indicates a highly variable and dynamic aquifer system. The lower end (8.11 m/day) represents moderately permeable formations—typical of fine sands or poorly fractured rocks—that still permit significant groundwater flow but with slower contaminant migration, thereby offering moderate natural attenuation and reduced short-term vulnerability to pollution (Fetter, 2001). In contrast, the upper extreme (356.55 m/day) suggests extremely high permeability, characteristic of coarse gravels, karstic limestones, or highly fractured aquifers, which are exceptionally vulnerable to rapid contaminant transport due to minimal filtration and short residence times (White, 2017). This wide range underscores a spectrum of vulnerability, where zones with K values approaching the upper limit demand stringent protective measures (e.g., wellhead protection zones or strict land-use regulations) to prevent irreversible contamination, whereas areas with lower K may sustain longer contaminant-plume dispersion but remain at risk from persistent pollutants (e.g., heavy metals or PFAS) (Sophocleous, 2002). Additionally, the high-K regions likely exhibit strong hydraulic connectivity with surface water, increasing susceptibility to seasonal contamination spikes, while the spatial disparity in K values may reflect heterogeneous depositional environments or tectonic influences, necessitating site-specific risk assessments (Sophocleous, 2002). The relatively wide range of hydraulic conductivity observed in the study areas implies that the aquifer is generally susceptible to contamination, particularly in zones with the highest conductivity, where the protective capacity of the overlying materials may be inadequate to filter or attenuate pollutants effectively (Machiwal *et al.,* 2018).

The estimated aquifer transmissivity (Tr) in the study area, ranging from 240.77 to 8664.19 m^2/day, reveals a highly heterogeneous hydrogeological system with significant implications for groundwater vulnerability according to Ako and Olorunfemi (1989). The lower values (e.g., 240.77 m^2/day) suggest moderate productivity and slower groundwater flow, typical of confined or semi-confined aquifers with limited thickness or lower permeability layers (e.g., fine sands or siltstones), which may provide some natural protection against contaminants due to longer travel times and greater opportunities for attenuation processes like adsorption and biodegradation (Fetter, 2001). However, these areas still face potential risks from persistent pollutants in the low-flow zone (Schwartz and Zhang, 2004). Conversely, the upper range (e.g., 8664.19 m^2/day) indicates exceptionally high transmissivity, characteristic of thick, unconfined, or highly permeable aquifers (e.g., coarse gravels, karstic systems, or intensely fractured bedrock), where rapid groundwater movement and minimal filtration render the aquifer extremely vulnerable to widespread and rapid contamination from surface pollutants, agricultural runoff, or industrial spills (Singhal and Gupta, 2010). In such high-Tr zones, contaminants may reach extraction wells or discharge areas in short timeframes, posing significant risks to the water supply (You *et al.,* 2020). This broad spectrum of transmissivity values highlights spatially variable risks, necessitating tailored management strategies—such as delineating priority protection zones in high-Tr areas (e.g., wellfield buffers or recharge-area controls) and monitoring lower-T regions for cumulative contaminant buildup (Sophocleous, 2002). The findings also reflect the aquifer's dual role as both a resource and a conduit for contamination, where high-Tr zones may support robust water supply but require stringent safeguards, and low-Tr areas, though less immediately vulnerable, may face challenges like stagnant flow and localised pollution hotspots. Overall, the variation in transmissivity suggests that aquifer vulnerability is spatially variable, with higher transmissivity zones requiring more protective attention in groundwater management (Chenini *et al.,* 2015).

It's quite important to note that possible errors may arise from poor electrode contact, cultural noise, and instrument drift during data acquisition; non-uniqueness and model assumption errors in resistivity inversion; oversimplification of heterogeneous subsurface conditions; empirical limitations in deriving hydraulic parameters; seasonal groundwater fluctuations; and interference from human activities such as buried utilities or waste dumps.

Conclusion

This study assessed aquifer vulnerability using longitudinal conductance, transverse resistance, hydraulic conductivity, and transmissivity as estimated from VES data. Conductance values (0.0070–0.1993 S) indicate weak resistance to contamination, with several zones vulnerable to pollutants. Transverse resistance (4425.30–84758.40 Ωm²) and hydraulic conductivity (8.11–356.55 m/day) show significant spatial variability, highlighting areas with high permeability and low resistance that are prone to rapid contaminant migration. Transmissivity values (240.77–8664.19 m²/day) reinforce this variability, showing that high transmissivity zones, while productive, are highly susceptible to surface contamination. The study is limited by reliance on geoelectric-hydraulic relationships and the lack of direct hydraulic measurements, meaning the results are indicative. Future research should incorporate geochemical data, pumping tests, and contaminant transport models to improve vulnerability assessments. Land-use mapping should also be used to link contamination risks. The findings emphasise the need for targeted monitoring and protection, especially in high-conductivity and high-transmissivity areas.

CONFLICT OF INTEREST

The author states that there is no conflict of interest.

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