Geoelectric Mapping of Aquifer Vulnerability Using Dar-Zarrouk Parameters in Parts of Bayelsa State, Southern Niger Delta, Nigeria

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ABSTRACT

Aquifer vulnerability assessment is essential for identifying areas where groundwater may be susceptible to contamination and for supporting sustainable groundwater protection. This study evaluated aquifer vulnerability in selected parts of Bayelsa State and the adjoining Mbiama area of Rivers State, southern Niger Delta, Nigeria, using Vertical Electrical Sounding (VES) data and Dar-Zarrouk parameters. Fifteen VES stations were investigated using the Schlumberger electrode configuration. The apparent resistivity data were interpreted through one-dimensional inversion using IPI2Win software to estimate subsurface layer resistivities, thicknesses and depths. Longitudinal conductance and transverse resistance were calculated using the interpreted overburden layers, while Surfer 18 and the Natural Neighbor interpolation method were employed to map the spatial distribution of vulnerability classes. The interpreted aquifer resistivities ranged from 130 Ωm at Etegwe to 9694 Ωm at Oyiakiri, with inversion root mean square errors ranging from 0.957% to 3.63%. Longitudinal conductance varied from 0.00653 S at Oyiakiri to 2.58715 S at Oloibiri, indicating substantial spatial differences in overburden protective capacity. Oyiakiri, Okorodia and Ojuokpoti were classified as having very high vulnerability, whereas Opu Nembe, Ogobiri, Tombia, Etegwe, Igbedi, Oloibiri, Agbalamabugokiri and Sampou were assigned low vulnerability. The overburden transverse resistance ranged from 434.66 Ωm² at Opu Nembe to 79,891.67 Ωm² at Oyiakiri, providing complementary information on subsurface electrical properties. The resulting vulnerability map identifies locations that warrant priority attention in groundwater-protection planning. However, the mapped patterns are preliminary estimates based on 15 VES stations, and the geoelectric interpretations do not independently establish groundwater contamination or water quality. Borehole lithological logs and groundwater-quality analyses are therefore recommended to validate the results and improve the reliability of vulnerability assessment in the study area.

Keywords: Aquifer vulnerability; Dar-Zarrouk parameters; longitudinal conductance; transverse resistance; vertical electrical sounding; Bayelsa State.

INTRODUCTION

Groundwater is an important source of freshwater for domestic and other uses, particularly in areas where access to reliable treated water is limited. However, its quality may be threatened by contaminants originating from inadequate sanitation, waste disposal, urban development and petroleum-related activities. Aquifer vulnerability assessment helps identify areas where groundwater may be susceptible to contamination, although vulnerability does not necessarily indicate that contamination has occurred [1,2].

The Niger Delta is underlain by a thick sedimentary succession comprising the Benin, Agbada and Akata formations. The predominantly sandy Benin Formation contains varying proportions of clay and other fine-grained materials, which influence groundwater occurrence and the natural protective capacity of overlying layers [3,4]. Since these geological materials vary spatially, assessing aquifer vulnerability requires information on subsurface resistivity, layer thickness and lithological characteristics.

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Vertical Electrical Sounding (VES) is a geoelectrical method used to investigate subsurface layering through variations in electrical resistivity. When interpreted alongside layer thicknesses and plausible lithological associations, VES data can support the delineation of aquifers and assessment of their overburden protection [5,6]. Dar-Zarrouk parameters provide additional information from interpreted geoelectric layers. Longitudinal conductance, calculated from layer thickness and resistivity, is commonly used to assess the protective characteristics of overburden, while transverse resistance provides complementary information about subsurface electrical properties [7,8]. These parameters are indirect indicators and should not be interpreted as direct measurements of groundwater quality.

Previous studies have applied geoelectrical methods to groundwater-potential and vulnerability assessment in different parts of Nigeria, including the Niger Delta [9–11]. Davies et al. [12], for example, used VES data to investigate aquifer vulnerability in parts of Bori Metropolis, reporting spatial variation in longitudinal conductance. Although this provides a useful regional comparison, the results cannot be assumed to represent conditions in Bayelsa State because geological characteristics, survey coverage and interpreted layer properties may differ.

This study therefore investigates aquifer vulnerability in selected parts of Bayelsa State and an adjoining location at Mbiama, Rivers State, using 15 Schlumberger VES stations. The interpreted geoelectric data were processed using IPI2Win, and spatial distributions of selected parameters were mapped using Surfer. The study examines longitudinal conductance, transverse resistance and related geoelectric characteristics to identify spatial variations in aquifer protective properties. The findings provide a preliminary basis for groundwater-protection planning and for identifying locations where further hydrogeological and groundwater-quality investigations may be required.

METHODOLOGY

VES Data Acquisition

The study involved 15 Vertical Electrical Sounding (VES) stations distributed across selected locations in Bayelsa State and an adjoining location at Mbiama, Rivers State, Nigeria. Fourteen stations were located in Bayelsa State and one at Mbiama. The investigated locations are shown in Table 1.

Table 1. Geographic coordinates of the 15 vertical electrical sounding (VES) stations in the study area.

VES station	Location	Latitude (°N)	Longitude (°E)
VES 1	Igbogene	5.025017	6.398860
VES 2	Kolo	4.811123	6.373420
VES 3	Okorodia	5.141713	6.444050
VES 4	Opu Nembe	4.531180	6.399970
VES 5	Opu Bassambiri	4.534745	6.412530
VES 6	Ojuokpoti	4.836907	6.210240
VES 7	Ogobiri	4.997760	6.115170
VES 8	Tombia	4.531007	6.396760
VES 9	Mbiama	5.066913	6.438910
VES 10	Etegwe	4.953830	6.351980
VES 11	Igbedi	5.120973	6.203450
VES 12	Oloibiri	4.697834	6.355340
VES 13	Agbalamabugokiri	4.533037	6.417210

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VES 14	Oyiakiri	5.002300	5.958530
VES 15	Sampou	5.141617	6.033490

VES measurements were acquired using the Schlumberger electrode configuration, comprising two current electrodes (A and B) and two potential electrodes (M and N). The current electrodes were progressively moved outward from the centre of the array to investigate increasing subsurface depths, while the potential electrodes were maintained at relatively small separations and adjusted when necessary. A Terrameter was used to measure current and potential difference, while a Global Positioning System (GPS) receiver was used to record station coordinates and elevation. Electrode spacing and resistance measurements were recorded for subsequent computation of apparent resistivity [13].

Apparent resistivity was calculated using;

$$\rho_a = KR \tag{1}$$

where ρ_a is apparent resistivity in Ωm, K is the geometric factor for the Schlumberger array, and R is the measured resistance in Ω. The geometric factor accounts for the electrode configuration [13,14].

For Schlumberger array, the geoelectric parameter is defined as;

$$K = \frac{\pi\left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right]}{MN} \tag{2}$$

Data Processing and Geoelectric Interpretation

The apparent-resistivity data were arranged according to current-electrode half-spacing $\frac{AB}{2}$, checked for consistency and plotted against electrode spacing on logarithmic axes to obtain the VES sounding curves. The curves were interpreted using IPI2Win software through computer-assisted one-dimensional inversion. The interpreted model parameters were iteratively adjusted to obtain agreement between measured apparent resistivity and the calculated model response. The root mean square (RMS) error was used as an indicator of model fit [14,15].

The inversion provided estimates of layer resistivity, thickness and depth. Probable aquifer-bearing units were identified from the interpreted resistivity and thickness characteristics in conjunction with the geological setting. Aquifer depth, thickness and resistivity were extracted for each station for subsequent parameter calculations and spatial mapping. Borehole lithological logs were not used to independently constrain the inversion; therefore, lithological assignments were interpreted from the geoelectric models and the regional geological context.

Dar-Zarrouk Parameters and Aquifer Protective Capacity

The interpreted aquifer layers were identified from the inverted vertical electrical sounding (VES) models by examining the sequence of layer resistivities, thicknesses and cumulative depths, together with the geoelectric curve characteristics and the expected hydrostratigraphic conditions of the study area. Candidate aquifer layers were selected by considering their resistivity contrasts and stratigraphic positions within the interpreted subsurface sequence. The selected layers were then matched with the corresponding aquifer resistivity and depth entries in the station summary table. Since resistivity is not uniquely diagnostic of lithology or groundwater occurrence, the interpreted aquifer assignments were treated as geoelectric interpretations rather than direct confirmation of water-bearing formations.

For each VES station, the overburden was defined as the sequence of interpreted geoelectric layers extending from the ground surface to the top of the selected aquifer layer. The thickness and resistivity of each layer above the aquifer were used to calculate the longitudinal conductance and transverse resistance of

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the overburden, following the Dar-Zarrouk parameter approach [7].

Longitudinal conductance (S) was calculated as;

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \quad (3)$$

where h_i is the thickness of layer i (m), ρ_i is its resistivity of layer $i(\Omega m)$, and n is the number of layers included in the calculation. Conductance is expressed in siemens (S).

Transverse resistance (T) was calculated as;

$$T = \sum_{i=1}^{n} h_i \rho_i \quad (4)$$

where h_i and ρ_i are defined above. Transverse resistance is expressed in Ωm^2. Note that the summation runs over the layers above the aquifer

Longitudinal conductance was used to assess the protective capacity of the overburden, whereas transverse resistance provided a complementary description of the subsurface electrical properties. Higher longitudinal conductance can indicate greater protective capacity where it reflects thick, relatively conductive clay-rich materials; lower values may indicate weaker protection against downward contaminant migration [7,16].

To ensure complete and mutually exclusive classification intervals, the longitudinal-conductance thresholds were expressed using continuous, non-overlapping ranges. The revised interval notation preserves the effective classification thresholds adopted from Oladapo and Akintorinwa [16] as shown in Table 2:

Table 2: Classification of aquifer protective capacity based on longitudinal conductance, with the vulnerability class and Surfer code assigned to each class

Longitudinal Conductance, S (S)	**Protective Capacity rating**	**Vulnerability level**	**Surfer Z code**
$S > 10$	Excellent	Very Low	1
$5 \leq S \leq 10$	Very Good	Very Low	1
$0.7 \leq S < 5$	Good	Low	2
$0.2 \leq S < 0.7$	Moderate	Moderate	3
$0.1 \leq S < 0.2$	Weak	High	4
$S < 0.1$	Poor	Very High	5

Each station was assigned a vulnerability level from its protective capacity rating, with Excellent and Very Good ratings treated as Very Low vulnerability, Good as Low, Moderate as Moderate, Weak as High and Poor as Very High (Table 2). These levels were then coded 1 to 5 for interpolation.

Spatial Interpolation and Vulnerability Mapping

The Natural Neighbor interpolation method was used to generate the vulnerability grid because it estimates values at unsampled locations using nearby data points and their spatial relationships, making it suitable for interpolating irregularly distributed sampling locations. Its local interpolation approach was adopted to represent spatial variations in vulnerability across the study area while limiting the influence of distant stations. The resulting grid was used to produce the aquifer vulnerability map, overlaid with the original VES station locations and labels. The mapped patterns were checked against the input station locations and

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their assigned vulnerability classes for consistency. Since the numerical codes represent ordered vulnerability categories rather than continuous physical measurements, the interpolated values were interpreted cautiously and classified into the five vulnerability levels for map presentation. The resulting map represents an estimate of spatial vulnerability patterns between the sampled locations, not direct measurements at unsampled locations.

RESULTS AND DISCUSSION

Result

Tables 3 and 4 presents the interpreted geoelectric parameters obtained from the 15 VES stations, including layer resistivity, thickness and depth, interpreted aquifer characteristics, Dar-Zarrouk parameters, overburden protective capacity, and aquifer vulnerability. The spatial distribution of aquifer vulnerability was also mapped in Surfer 18 using the Natural Neighbor interpolation method, with the original VES locations displayed for spatial reference (Figure 1).

Table 3: Summary of geoelectric properties in the study area

STATION NUMBER	VES STATION NAME	Resistivity (Ωm)						Thickness (m)					Depth (m)				Curve type		RMS (%)
VES 1	IGBOGENE	80.5	136	266	238	526		6.67	13.3	20	21.3		6.67	20	40	61.3		KH	3.48
VES 2	KOLO	107	46.5	211	490	525	3566	1.4	5.6	10.2	22.5	11.1	1.4	7	17.2	39.6	50.7	HA	0.957
VES 3	OKORODIA	217	334	412	3787	437	601.5	2	8	26.7	16.7	13.3	2	10	36.7	53.3		KH	1.27
VES 4	OPU NEMBE	34.55	14.8	155				2	24.7				2	26.7				H	2.75
VES 5	OPU BASSAMBIRI	1741	58	296	608			3.33	16.7	20			3.33	20	40			HA	3.63
VES 6	OJUOKPOTI	1696	337	590	1597	3879		3.26	5.64	25.6	48.3		3.26	8.9	34.5	82.8		HA	1.71
VES 7	OGOBIRI	35.7	21.6	80.5	597			2.94	18.5	21.5			2.94	21.5	43			HA	1.34
VES 8	TOMBIA	37.3	10.8	55.7	137	333		3.3	10	13.3	10		3.3	13.3	26.6	36.6		HA	2.26
VES 9	MBIAMA	122	136	98.9	690			2.17	3.64	15.1			2.17	5.81	20.9			HA	1.38
1.53	ETEGWE	29.1	45.1	130				6.67	23.3				6.67	30				A	
VES 11	IGBEDI	23.9	44.2	138	261	790		6.67	13.3	20	26.7		6.67	20	40	66.7		A	2.73

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VES 12	OLOIBIRI	34.9	16.7	260	134	79.4	292	2.04	18.2	19.5	14.5	99.7	2.04	20.2	39.7	54.2	154	KH	1.33
VES 13	AGBALAMAB-UGOKIRI	455	26	275	317			3.33	43.3	13.3			3.33	46.7	60			KH	3.23
VES 14	OYIAKIRI	968	2641	4934	9694	17819		2	4.67	13.3	26.7		2	6.67	20	46.7		A	2.81
VES 15	SAMPOU	26.79	17.87	39.81	133.3			4.667	12	50			4.667	16.67	66.67			HA	1.25

Table 4: Summary of Computed Dar-Zarrouk parameters for the Study area

VESTATION NUMBER	**VES STATION NAME**	**LAT (N°)**	**LONG (E°)**	**Aquifer (Ωm)**	**T = Σρh, overburden (Ωm²)**	**S = Σh/ρ, overburden (S)**	**Dominant overburden lithology**	**Protective capacity rating**	**Vulnerability level (Z code)**
VES 1	IGBOGENE	5.025017	6.39886	238	7,665.74	0.25584	Fine/Medium sand	Moderate	Moderate (3)
VES 2	KOLO	4.811123	6.37342	525	13,587.40	0.22777	Clay/Fine sand	Moderate	Moderate (3)
VES 3	OKORODIA	5.141713	6.44405	3787	14,106.40	0.09797	Coarse sand	Poor	Very High (5)
VES 4	OPU NEMBE	4.53118	6.39997	155	434.66	1.72681	Very thick clay/peat	Good	Low (2)
VES 5	OPU BASSAMBIRI	4.534745	6.41253	608	12,686.13	0.35741	Clay/silty clay	Moderate	Moderate (3)
VES 6	OJUOKPOTI	4.836907	6.21024	1597	22,533.64	0.06205	Sandy/coarse sand	Poor	Very High (5)
VES 7	OGOBIRI	4.99776	6.11517	597	2,235.31	1.20592	Thick clay/peat	Good	Low (2)
VES 8	TOMBIA	4.531007	6.39676	333	2,341.90	1.32617	Clay/peat/silt	Good	Low (2)
VES 9	MBIAMA	5.066913	6.43891	690	2,253.17	0.19723	Sandy silt/clayey	Weak	High (4)
VES 10	ETEGWE	4.95383	6.35198	130	1,244.93	0.74584	Silty clay	Good	Low (2)
VES 11	IGBEDI	5.120973	6.20345	790	10,475.97	0.82721	Silty clay	Good	Low (2)
VES 12	OLOIBIRI	4.697834	6.35534	292	15,304.32	2.58715	Thick clay/shale	Good	Low (2)

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VES 13	AGBALAMAB-UGOKIRI	4.533037	6.41721	317	6,298.45	1.72107	Sandy clay/clay	Good	Low (2)
VES 14	OYIAKIRI	5.0023	5.95853	9694	79,891.67	0.00653	Coarse sand/gravel	Poor	Very High (5)
VES 15	SAMPOU	5.141617	6.03349	133.3	2,329.97	2.10169	Clayey/silty sand	Good	Low (2)

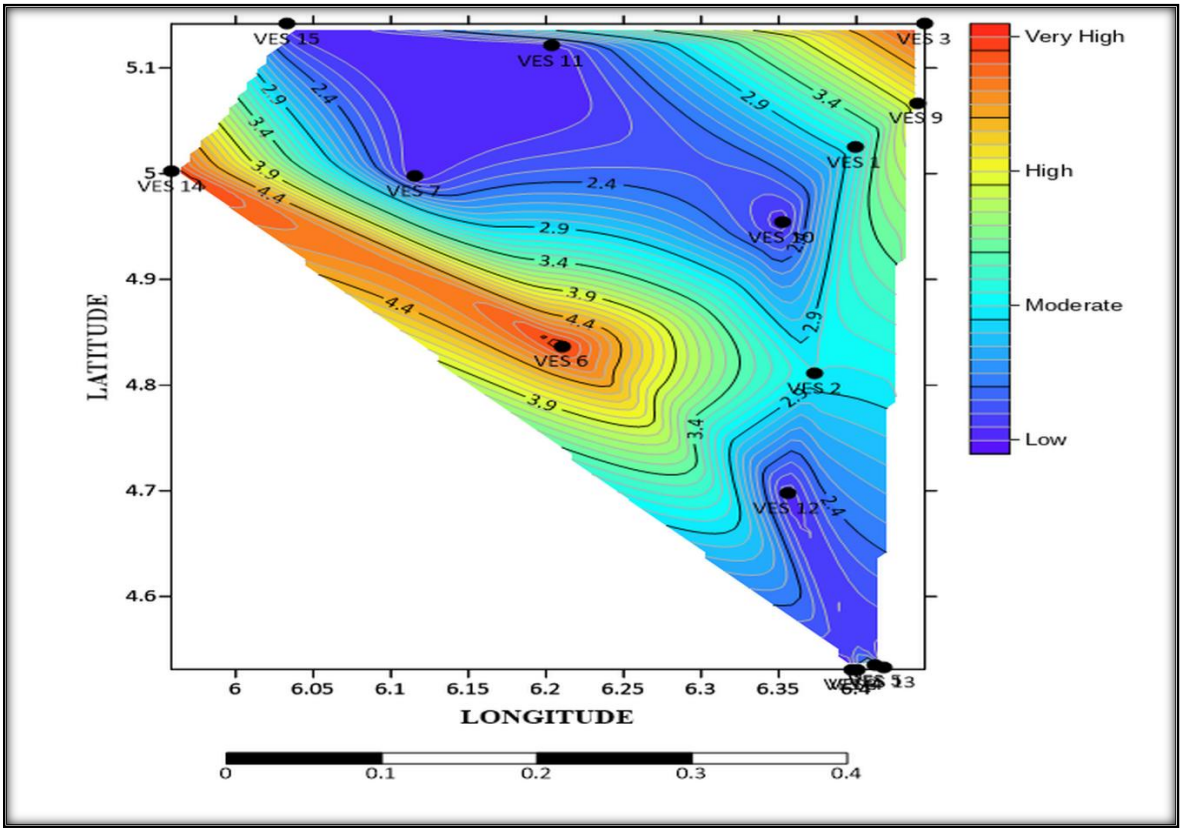


Figure 1: Natural Neighbor Interpolation Map of Aquifer Vulnerability in Parts of Bayelsa State, Southern Niger Delta, Nigeria.

DISCUSSION

Geoelectric Characteristics of the Interpreted Aquifers

Table 3 shows considerable variation in layer resistivity, thickness and depth across the 15 VES stations. The interpreted aquifer resistivities in Table 4 range from 130 Ωm at Etegwe to 9694 Ωm at Oyiakiri. These variations reflect differences in subsurface electrical properties, which may be influenced by lithology, pore structure and groundwater mineralisation [5,13,14]. However, resistivity alone cannot confirm groundwater quality or aquifer productivity. The RMS inversion errors of 0.957–3.63% indicate good agreement between the observed data and interpreted models, although a close fit does not uniquely establish the actual subsurface lithology [14,15].

Longitudinal Conductance and Protective Capacity

The longitudinal conductance values in Table 4 range from 0.00653 S at Oyiakiri to 2.58715 S at Oloibiri. Higher conductance generally indicates stronger overburden protection when associated with thick,

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electrically conductive clay-rich layers, whereas low values may indicate weaker protection against downward contaminant migration [7,11]. Oyiakiri, Okorodia and Ojuokpoti have low conductance values of 0.00653, 0.09797 and 0.06205 S, respectively, and are classified as having poor protective capacity. In contrast, Opu Nembe, Ogobiri, Tombia, Etegwe, Igbedi, Oloibiri, Agbalamabugokiri and Sampou have higher conductance values and are assigned good protective capacity under the classification scheme used in Table 2.

These findings are broadly consistent with previous geoelectric investigations in the Niger Delta. Mgbolu et al. [17] reported predominantly poor to weak aquifer protective capacity in parts of Ndokwa, associated with low longitudinal conductance values. Udosen et al. [19] also demonstrated spatial differences in aquifer protection using longitudinal conductance alongside other vulnerability indices. These comparisons support the usefulness of conductance for preliminary screening, although differences in survey coverage and classification criteria must be considered.

Transverse Resistance and Spatial Vulnerability

The overburden transverse resistance values in Table 4 range from 434.66 Ωm² at Opu Nembe to 79,891.67 Ωm² at Oyiakiri. Transverse resistance complements longitudinal conductance by describing the combined influence of layer resistivity and thickness; however, it is not a direct measurement of groundwater yield or contamination risk [7,8]. Oyiakiri's high transverse resistance alongside its very low longitudinal conductance illustrates that these parameters describe different electrical characteristics and should be interpreted together rather than interchangeably.

Figure 1 shows spatial variation in the vulnerability classes assigned to the 15 VES stations. Oyiakiri, Okorodia and Ojuokpoti are classified as very highly vulnerable, while several stations, including Opu Nembe, Ogobiri and Oloibiri, are classified as having low vulnerability. This pattern is consistent with the station-level conductance values and with previous Nigerian studies applying Dar-Zarrouk parameters to aquifer-protection assessment [11,12,18,19].

Nevertheless, Figure 1 is an interpolation based on 15 measurement locations, not a direct measurement of vulnerability at every point. The contours therefore indicate estimated spatial patterns between the VES stations. As the interpolated values originate from ordinal vulnerability codes, they should not be interpreted as quantitative estimates of contamination probability.

HYDROGEOLOGICAL IMPLICATIONS AND LIMITATIONS

The results provide a preliminary basis for prioritizing groundwater-protection investigations in the study area. The low longitudinal conductance values at Oyiakiri, Okorodia and Ojuokpoti suggest comparatively weak overburden protection under the adopted classification scheme, making these locations priorities for further investigation. However, the assessment is constrained by the limited spatial coverage of the 15 VES stations and the absence of independent geological and groundwater-quality validation. Consequently, the Natural Neighbor interpolation map should be interpreted as an indicative representation of spatial vulnerability patterns rather than a validated regional distribution. Furthermore, resistivity variations may reflect differences in lithology, clay content and pore-fluid chemistry, limiting the certainty of lithological interpretation from resistivity alone. The assigned vulnerability classes therefore represent indirect assessments of overburden protective characteristics and do not establish the occurrence of groundwater contamination. Previous research combining geoelectrical assessment with groundwater-quality measurements highlights the value of complementary evidence in evaluating aquifer protection [20]. Further investigations incorporating additional VES stations, borehole lithological records and groundwater-quality analyses are recommended to validate the interpretations and refine the vulnerability assessment.

CONCLUSION

This study applied Vertical Electrical Sounding (VES) data and Dar-Zarrouk parameters to assess aquifer

vulnerability in selected parts of Bayelsa State and the adjoining Mbiama area of Rivers State, Nigeria. The results revealed considerable spatial variation in overburden protective capacity, with longitudinal conductance values ranging from 0.00653 S at Oyiakiri to 2.58715 S at Oloibiri. Oyiakiri, Okorodia and Ojuokpoti were classified as having very high aquifer vulnerability, whereas several locations, including Opu Nembe, Ogobiri and Oloibiri, exhibited low vulnerability under the adopted classification scheme. These findings demonstrate the usefulness of VES-derived Dar-Zarrouk parameters for preliminary identification of areas requiring priority groundwater-protection attention. However, the vulnerability map represents an interpretation based on 15 VES stations and does not establish the occurrence of groundwater contamination. Borehole lithological information and groundwater-quality analyses are therefore recommended to validate the geoelectric interpretations and provide a more comprehensive assessment of groundwater vulnerability across the study area.

REFERENCES

1. Lapworth DJ, Nkhuwa DCW, Okotto-Okotto J, Pedley S, Stuart ME, Tijani MN, et al. Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health. Hydrogeology Journal. 2017;25(4):1093–1116. https://doi.org/10.1007/s10040-016-1516-6
2. Machiwal D, Jha MK, Singh VP, Mohan C. Assessment and mapping of groundwater vulnerability to pollution: current status and challenges. Earth-Science Reviews. 2018;185:901–927. https://doi.org/10.1016/j.earscirev.2018.08.009
3. Short KC, Stäuble AJ. Outline of geology of Niger Delta. AAPG Bulletin. 1967;51(5):761–779. https://doi.org/10.1306/5D25C0CF-16C1-11D7-8645000102C1865D
4. Reijers TJA. Stratigraphy and sedimentology of the Niger Delta. Geologos. 2011;17(3):133–162. https://doi.org/10.2478/v10118-011-0008-3
5. Reynolds JM. An Introduction to Applied and Environmental Geophysics. 2nd ed. Chichester: Wiley-Blackwell; 2011.
6. Orellana E, Mooney HM. Master Tables and Curves for Vertical Electrical Sounding over Layered Structures. Madrid: Interciencia; 1966.
7. Henriet JP. Direct applications of the Dar Zarrouk parameters in ground water surveys. Geophysical Prospecting. 1976;24(2):344–353. https://doi.org/10.1111/j.1365-2478.1976.tb00931.x
8. Niwas S, Singhal DC. Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. Journal of Hydrology. 1981;50:393–399.
9. Obiora DN, Alhassan UD, Ibuot JC, Okeke FN. Geoelectric evaluation of aquifer potential and vulnerability of Northern Paiko, Niger State, Nigeria. Water Environment Research. 2016;88(7):644–651. https://doi.org/10.2175/106143016X14609975746569
10. Oguama BE, Ibuot JC, Obiora DN, Aka MU. Geophysical investigation of groundwater potential, aquifer parameters, and vulnerability: a case study of Enugu State College of Education (Technical). Modeling Earth Systems and Environment. 2019;5(3):1123–1133. https://doi.org/10.1007/s40808-019-00595-x
11. Atakpo EA, Ayolabi EA. Evaluation of aquifer vulnerability and the protective capacity in some oil producing communities of western Niger Delta. Environmentalist. 2009;29:310–317. https://doi.org/10.1007/s10669-008-9191-3
12. Davies OA, Menegbo BG, Horsfall OI. Assessment of aquifer vulnerability using Vertical Electrical Sounding (VES) data in Parts of Bori Metropolis for groundwater exploration. Applied Journal of Physical Science. 2025;6(4):140–148. https://doi.org/10.31248/AJPS2025.128
13. Keller GV, Frischknecht FC. Electrical Methods in Geophysical Prospecting. Oxford: Pergamon Press; 1966.
14. Bhattacharya PK, Patra HP. Direct Current Geoelectric Sounding: Principles and Interpretation. Amsterdam: Elsevier; 1968.
15. Koefoed O. Geosounding Principles 1: Resistivity Sounding Measurements. Amsterdam: Elsevier; 1979.
16. Oladapo MI, Akintorinwa OJ. Hydrogeophysical study of Ondo State Housing Corporation Estate, Ijapo, Akure, Southwestern Nigeria. Journal of Mining and Geology. 2007;43(2):217–225.

17. Mgbolu CC, Obiadi II, Obiadi CM, Okolo CM, Irumhe PE. Integrated groundwater potentials studies, aquifer hydraulic characterisation and vulnerability investigations of parts of Ndokwa, Niger Delta Basin, Nigeria. Solid Earth Sciences. 2019;4(3):102–112. https://doi.org/10.1016/j.sesci.2019.06.002
18. Aladeboyeje AI, Adenoye TT, Agbasi OE. Assessment of groundwater vulnerability using GOD index and Dar Zarrouk parameters: a case study of OAUSTECH main campus, Okitipupa, Ondo State. Results in Engineering. 2024;2:100036. https://doi.org/10.1016/j.rines.2024.100036
19. Udosen NI, Ekanem AM, George NJ. Geo-electrical prognosis of aquifer protectivity, corrosivity, and vulnerability via index-based models within a major coastal milieu. Discover Geoscience. 2024;2:18. https://doi.org/10.1007/s44288-024-00020-6
20. Oseji JO, Egbai JC, Okolie EC, Ese EC. Investigation of the aquifer protective capacity and groundwater quality around some open dumpsites in Sapele Delta State, Nigeria. Applied and Environmental Soil Science. 2018;2018:3653021. https://doi.org/10.1155/2018/3653021