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Research Article

Investigation of Saltwater Intrusion into Freshwater Aquifers in Some Estuary Environment in Niger Delta

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Abstract

Groundwater is an important source for Nigerian water balance. Therefore assessing its experimental evidence supporting saltwater intrusion is necessary before initiating developmental plans using this resources. In this research, the extent of saltwater intrusion, physiochemical properties of groundwater samples and suitability was experimented in the study areas. Geophysical and geochemical techniques were employed in a research study to investigate saltwater intrusion in freshwater aquifers in coastal areas of Delta State, Nigeria. The resistivity data from fifty Vertical Electrical Soundings (VES) in the aquifer layers revealed high water content and saline intrusion, with resistivity ranging from 0.4 to 769.9 Ωm. The hydraulic resistance values ranged from 2.877m-1 to 27.2831m-1, determining the Aquifer Vulnerability Index (AVI). The findings from the Groundwater Occurrence and Depth (GOD) index classified the study area into low and moderate vulnerability classes, with values ranging from 0.168 to 0.420. Groundwater analysis indicated elevated levels of electrical conductivity, salinity, and total dissolved solids, exceeding WHO standards. Moreover, high concentrations of chloride, sodium, and potassium confirmed saltwater intrusion.

Keywords

Saltwater Intrusion, Freshwater, Aquifer, Groundwater Analysis and Resistivity

1. Introduction

Groundwater is an important freshwater resource worldwide, particularly in coastal communities. It is renewable and finite natural resource, vital for human life, for social and economic development and moreover a valuable component of the ecosystem. The knowledge of the subsurface hydro geological properties is essential before drilling a borehole to ensure having prolife aquifer repositories [1].

When aquifers are exposed to contaminants as a result of natural and anthropogenic activities, which can lead to groundwater quality degradation, including drinking water sources, and other consequences and will lead to serious health issues such as cancer, cholera and typhoid [2-4]. Saltwater intrusion can naturally occur in coastal aquifers, owing to the hydraulic connection between groundwater and seawater. Because saline water has a higher mineral content than freshwater, it is denser and has a higher water pressure. As a result, saltwater can push inland beneath the freshwater [5]. Many studies were carried out on groundwater quality evaluation and hydrochemical characterization [6-13].

Geophysical survey using electrical resistivity method was applied in getting background information on the distribution, formation and type of rear subsurface aquifers as a means of delineating the areas that may be prone to groundwater contamination and determine the location and depth appreciable

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and portable water supply could be achieved [14-16]. The resistivity method has been used by various researchers to investigate the subsurface and is preferred to other electrical techniques because it can clarify the subsurface structure, and is inexpensive [17]. This method has been found suitable for determining fresh water and salt water bearing formations [18, 19]. The low resistivity zones seen in the area are most likely caused by geogenic processes rather than aquifer overstressing. This assertion is supported by evidence revealed from the ground water flow and simulation of saltwater intrusion into aquifer [20].

Ground water vulnerability indicates contamination of the aquifer applying geoelectric indices to ensure the protective nature of the aquifer [21].

Groundwater quality generally encompasses the physical, chemical, biological, radiological and morphological characteristics of the water [22, 23].

The current investigation shows resistivity data from fifty vertical electrical soundings (VES) indicated a highly heterogeneous subsurface with low resistivity values (0.4 to 769.9 Ωm) in the aquifer layers, delinating high water content and saline intrusion The result of the water samples is considered not portable (not drinkable) due to the high values of the electrical conductivity (EC), Biological oxygen demand (BOD), sodium, potassium, magnesium and total dissolved solid (TDS) which far exceed the permissible level for portable water from WHO standards. The values of hydraulic resistance determines the aquifer vulnerability index (AVI). The AVI delineated the study area into high and very high vulnerability classes. The Groundwater Occurrence and Depth (GOD) index values classified the study area into low and moderate vulnerability classes.

Study Area

The area under investigation consist of two communities Burutu and Ogulagha Local Government Areas of Delta State, Nigeria. It lies within the Niger Delta region, known for its complex geological and environmental characteristics, with coordinates 5.3567 °N latitude and 5.5073 °E longitude. Burutu and Ogulagha are situated in the coastal plain of the Niger Delta which is one of the world's largest and most prominent deltaic plains known for its low-lying topography and extensive network of creeks, rivers, and swamps [24]. The area is intersected by several major rivers, including the Niger River and its tributaries such as the Forcados River and the Escravos River [25].The sedimentary rocks found in Burutu and Ogulagha consist mainly of shale, sandstone, and clay deposits, which are associated with the formation of oil and gas reservoirs [26]. These geological formations have made the Niger Delta region a major oil-producing area in Nigeria and one of the largest oil-producing regions in Africa.

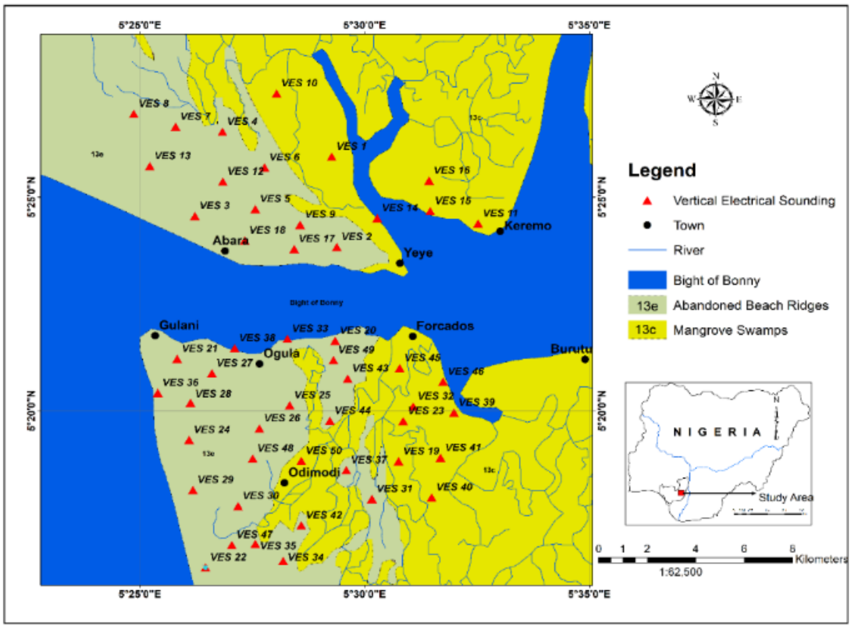

Figure 1. *Geologic map of the study area.*

2. Materials and Method

The research methodology is the electrical resistivity method using schlumberger array, integrated Geochemical method. The apparent resistivity of the subsurface and voltage generated by a transmission of current between electrodes (Current and potential electrodes) placed in the surface of the earth. The apparent electrical resistivities are then calculated from the measured data and these are used to determine the geoelectric datas. These geoelectric parameters are then interpreted to determine subsurface resistivity anomalies, depths and thicknesses [27, 28].

2.1. Water Samples

Water samples were collected from four different location within the vicinity of the study area without contamination. This was done in the Laboratory Unit, Department of Chemistry Delta State University, Abraka. The locations were: Ogulagha, Youbebe sea, Youbebe sea II, and Burutu well II. The water samples were split into two containers, one for anions and the other for cations in order to determine their concentration in milligrammes per litre (mg/L). The values of pH were measured using a multi-parameter analyser. The values electrical conductivity of the water samples were measured at the point of collection using a Wissenschaft-lich-TechnischeWerkstätten LF91 (Ec) meter. The total dissolved solids (TDS) and dissolved oxygen (DO) were determined at the point collection. The DO was measured with the aid of a dissolved oxygen meter and sensor. The values of the chemical oxygen demand (COD) and biological oxygen demand (BOD) were determine in the laboratory using standard procedures. These containers were initially washed with 0.05 M HCl and filtered through membranes of 0.45 μm pores and then rinsed with ionized water. The water samples were acidified with concentrated nitric acid (HNO_3) in order to homogenize and prevent metallic ions sticking to the walls. The analysis of the bicarbonates ($HCO_3{}^-$) was carried out using a standard technique of titration to obtain their concentrations. The concentrations of the cations (K^+, Na^{2+},$Zn^{2+}Ca^{2+}$, $Mg^{2+}Mn^{2+}$,$Pb^{2+}$and Fe^{2+}) were determined using the Atomic Adsorption Spectrometer model AA-7000 Shimadzu, Japan ROM version 1.01, while the anions ($SO_4{}^{2-}$, Cl^-, $HCO_3{}^-$) were determined in the laboratory using standard procedure of titrimetric method.

2.2. Assessing Drinking Water Quality and Pollution Level

This study makes use of different indices in order to assess the water quality of the study area. The indicators include; water quality index (WQI), contamination factor (CF) and pollution load index (PLI) [31].

2.3. Water Quality Index (WQI)

The Water Quality Index (WQI) is a numerical expression that summarizes the overall quality of water based on several physical, chemical, and biological parameters. It provides a simple way to communicate complex water quality information to the public and policymakers. The index typically combines multiple water quality parameters into a single value, allowing for easy comparison of water quality over time or between different locations. This index was computed employing the method of weighted arithmetic index. The sample concentration (C_i) in $\frac{mg}{L}$ of each is divided by each respective WHO standard (S_i) in $\frac{mg}{L}$ to obtain the quality rating scale (q_i). The ratio of C_i/S_i is then multiply by a factor of 100 to give a mathematical expression given in equation 1 [29, 30].

$$q_i = \frac{C_i}{S_i} \times 100 \tag{1}$$

The inverse of the WHO standard corresponding to each of the analyzed parameters gives the relative weight (W_i) of each sample

$$W_i = \frac{1}{S_i} \tag{2}$$

The water quality index (WQI) is then expressed mathematically in equation 3 as the product of equations 1 and 2;

$$WQI = \sum q_i W_i \tag{3}$$

2.4. GOD Index

The GOD index, also known as the "GOD" vulnerability index, is a method used to assess groundwater vulnerability to pollution. This index considers geological and hydrogeological factors that influence the susceptibility of groundwater to contamination. The GOD index is determine by multiplying the effect of the three parameters, namely groundwater (G) (confined or unconfined aquifer), occurrence of lithological character of the vadose zone (O) and depth to the aquifer (D). The GOD index combines these factors to provide a comprehensive assessment of groundwater vulnerability to pollution. Areas with geologically permeable formations, shallow water tables, and thin or permeable overlying lithology are likely to have higher vulnerability scores, indicating a greater risk of contamination and vice versa. Table 1 gives the vulnerability ranges corresponding to GOD parametric index while Table 2 is the attribution of notes for GOD model Parameters.

$$GOD_{index} = G \times O \times D \tag{4}$$

Table 1. *GOD parametric index rating [32].*

Vulnerability class	Index rating
Negligible	0.0 – 0.1
Low	0.1 – 0.3
Moderate	0.3 – 0.5
High	0.5 – 0.7
Extreme	0.7 – 1.0

Table 2. *Attribution of Notes for GOD model Parameters [33].*

Aquifer type	Note	Lithology (Ω-m)	Note	Depth to aquifer (m)	Note
Non-aquifer	0	<60	0.4	<2	1
Artesian	0.1	60 - 100	0.5	2 – 5	0.9
Confined	0.2	100 - 300	0.7	5 – 10	0.8
Semi-confined	0.3 – 0.5	300 - 600	0.8	10 – 20	0.7
Unconfined	0.6 – 1.0	>600	0.6	20 – 50	0.6

3. Results and Discussion

3.1. Geoelectric Section

The interpreted resistivity results from fifty (50) VES points is presented in Table 3 and the varying values of resistivity, thickness and depth reveal the heterogeneous nature of the subsurface. Three to four geoelectric layers were delineated. The observed model curve types are dominated by H which is about 34 % of the total curve type, other curve types K, A, Q, AK, QH, AA, HA, KH, HK, and QQ. The frequency distribution of the curve types is displayed in Figure 2. The topmost geoelectric layer has resistivity values that varies from 0.1 Ωm at VES 38 to 1264.5Ωmat VES 11 with thickness and depth varying from 0.5 to 8.0 m respectively. The second layer is characterized by resistivity values ranging from0.5 Ωm at VES 27 to 439.2Ωm at VES 32 and its thickness and depth range from 1.2 to 37.7 m and 4.0 to 38.3 m respectively. The resistivity and thickness of the aquifer layer (saturated layer) range from 0.4to769.9Ωm and 4.2 to 43.6 m and was delineated as a low resistivity layer. This low resistivity may be attributed to saline water infiltration and high water content. Since, the coastal areas often have intrusion of saline water from the sea into the aquifers. Saline water has lower resistivity compared to freshwater, so its presence can significantly decrease the overall resistivity of the aquifer layers.

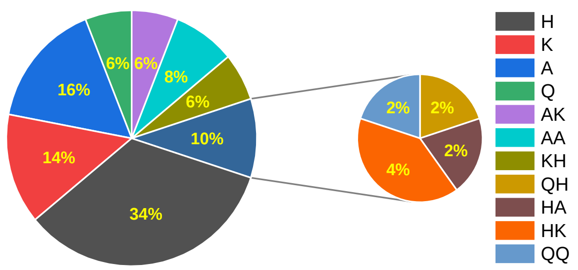

Figure 2. *Pie of pie plot showing the frequency distribution of the curve types.*

Table 3. *Result of Interpreted Geoelectric Data.*

VES No.	Location Name	Longitude (^{O}E)	Latitude (^{O}N)	Elevation (m)	Layer Resistivity (Ωm)				Layer thickness (m)			Layer depth (m)			Curves types
					ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	d_1	d_2	d_3	
1		5.3551	5.5080	-1	13.0	3.3	5.2	-	3.7	18.7	-	3.7	22.4		H
2		5.3558	5.5108	-4	632.3	72.2	150.3	20.4	1.0	8.0	13.2	1.0	9.0	22.2	AK
3		5.3564	5.5122	3	133.0	11.0	96.3	-	3.2	7.2		3.2	5.4		H
4		5.3586	5.5177	3	0.5	7.3	1.4	-	2.5	12.9		2.5	15.5		K
5		5.3574	5.5164	2	5.2	16.6	6.4	-	0.6	37.7		0.6	38.3		K
6		5.3567	5.5127	2	114.6	39.8	8.4	-	1.3	8.9		1.3	10.2		Q
7		5.3567	5.5143	2	19.0	361.7	66.7	-	0.5	4.3		0.5	4.3		K
8		5.3522	5.5107	13	4.6	1.3	14.9	-	1.2	10.8		1.2	12.0		H

VES No.	Location Name	Longitude (^{O}E)	Latitude (^{O}N)	Eleva-tion (m)	Layer Resistivity (Ωm)				Layer thickness (m)			Layer depth (m)			Curves types
					ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	d_1	d_2	d_3	
9		5.3535	5.5118	8	8.3	2.2	10.3	-	0.6	14.9		0.6	15.4		H
10		5.3549	5.5121	10	13.9	23.5	57.7	-	8.0	9.7		8.0	17.7		A
11		5.3535	5.5060	1	1264.5	417.9	58.4	1010.6	2.8	1.2	5.9	2.8	4.0	9.9	QH
12		5.3534	5.5060	1	73.4	20.0	24.1	-	3.1	23.5		3.1	26.6		H
13		5.3513	5.5022	10	79.7	50.0	517.4	-	1.7	10.3		1.7	12.0		H
14		5.3503	5.5060	9	257.3	27.7	2.3	-	1.2	7.9		1.2	9.1		Q
15		5.3506	5.5043	9	16.7	4.8	16.1	-	1.4	9.3		1.4	10.7		H
16		5.3466	5.5019	8	122.2	22.1	5.0	-	3.6	8.4		3.6	12.0		Q
17		5.3510	5.5050	7	26.2	3.2	16.5	-	2.2	18.0		2.2	20.3		H
18		5.3517	5.5065	4	743.4	7.2	42.4	-	2.1	11.8		2.1	13.8		H
19		5.3564	5.3214	5	0.5	0.8	3.1	21.8	2.7	9.1	15.5	2.7	11.8	27.4	AA
20		5.3564	5.3214	5	0.5	1.2	2.7	-	1.3	16.1		1.3	17.5		A
21		5.3564	5.3215	8	0.6	0.6	2.1	7.0	1.8	4.5	23.9	1.8	6.3	30.2	AA
22		5.3577	5.2215	11	0.3	2.1	1.9	-	4.4	18.3		4.4	22.6		K
23		5.3584	5.3219	15	31.5	13.3	133.1	618.0	2.9	8.0	11.2	2.9	10.8	22.0	HA
24		5.3641	5.3214	5	69.5	10.0	477.3	-	1.6	4.8		1.6	6.4		H
25		5.3642	5.3212	-1	1.1	2.0	1.4	6.8	1.9	11.0	20.0	1.9	12.9	30.9	KH
26		5.3643	5.3211	0	0.4	0.8	4.0	4.4	1.2	9.6	21.3	1.2	10.8	32.1	AA
27		5.3654	5.3221	0	0.6	0.5	4.7	4.4	2.6	8.1	28.8	2.6	10.7	39.5	HK
28		5.3652	5.3222	10	0.5	3.0	20.3	-	5.0	5.8		5.0	10.8		A
29		5.3652	5.3215	5	0.4	2.7	13.1	-	4.8	6.8		4.8	11.6		A
30		5.3656	5.3230	4	0.7	0.4	5.6	-	4.5	8.2		4.5	12.6		H
31		5.3620	5.3219	6	161.1	10.1	149.7	-	1.6	9.0		1.6	10.6		H
32		5.3615	5.3294	13	45.8	439.2	781.6	-	1.4	7.9		1.4	9.2		A
33		5.3598	5.3317	9	494.6	49.7	116.8	-	1.1	24.3		1.1	25.4		H
34		5.3478	5.3230	-3	0.4	1.2	2.2	0.8	1.4	9.4	29.4	1.4	10.8	40.2	AK
35		5.3479	5.3231	6	2.4	5.7	8.9	-	3.8	13.5		3.8	17.3		A
36		5.3486	5.3231	-1	1.4	68.7	46.5	-	3.9	16.4		3.9	20.3		K
37		5.3492	5.3227	-1	0.4	14.8	7.5	-	2.6	20.8		2.6	23.4		K
38		5.3542	5.3212	4	0.1	0.5	18.6	6.0	1.5	5.6	43.6	1.5	7.1	50.7	AK
39		3.3556	5.3214	5	0.5	1.7	1.2	20.3	1.6	9.2	14.2	1.6	10.8	25.0	KH
40		5.3556	5.3210	5	0.4	2.2	1.5	5.1	3.0	8.9	25.7	3.0	11.8	37.5	KH
41		5.3556	5.3210	8	0.3	6.5	40.3	-	3.7	4.2		3.7	7.9		A
42		5.3560	5.3220	9	0.7	2.1	3.5	-	2.3	18.2		2.3	20.6		A
43		5.3560	5.3221	7	1.2	1.0	27.9	-	3.5	5.2		3.5	8.8		H
44		5.3565	5.3226	11	2.4	3.3	29.6	310.9	1.6	9.6	8.4	1.6	11.2	19.7	AA

VES No.	Location Name	Longitude (^OE)	Latitude (^ON)	Eleva-tion (m)	Layer Resistivity (Ωm)				Layer thickness (m)			Layer depth (m)			Curves types
					ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	d_1	d_2	d_3	
45		5.3601	5.3458	1	21.4	7.0	407.1	-	2.0	5.7		2.0	7.7		H
46		5.3512	5.3447	-3	239.9	156.2	178.8	-	5.9	15.1		5.9	20.9		H
47		5.3505	5.3438	5	257.7	364.5	339.2	-	3.4	16.8		3.4	20.1		K
48		5.3505	5.3430	-7	90.1	59.9	769.9	412.8	3.0	7.4	33.4	3.0	10.4	43.9	HK
49		5.3516	5.3415	-1	123.2	42.5	9.7	7.4	2.6	7.3	28.3	2.6	9.9	38.2	QQ
50		5.3551	5.3382	7	142.0	19.9	171.7	-	1.5	14.9		1.5	16.4		H

3.2. Geochemical Section

Table 4. Results of Water quality index (WQI).

Sample	Concentrations (mg/L)									WQI
	$SO_4{}^{2-}$	Cl^-	$HCO_3{}^-$	Na^+	K^+	Ca^{2+}	Mg^{2+}	Mn^{2+}	Zn^{2+}	440.85
Ogulagha well	26.00	210.00	74.00	849.00	241.00	14.00	314.00	0.98	0.73	460.17
Youbebe sea I	29.00	198.00	68.00	789.00	239.00	13.00	321.00	1.03	0.82	617.77
Youbebe sea II	40.30	214.00	81.00	910.00	256.00	11.37	298.00	1.43	0.91	486.99
Burutu well	28.10	194.00	91.00	841.00	291.00	14.63	428.00	1.08	0.76	440.85

Table 5. WQI rating [34].

S/N	WQI Values	Water Quality Status
1	< 50	Excellent
2	50 – 100	Good
3	100 – 200	Poor
4	200 – 300	Very poor
5	>300	Unsuitable for drinking

The results revealed evidence of salt water intrusion in fresh water aquifers. This could be attributed to several factors such as the thin layers thickness observed across the study area. Geochemical processes such as ion exchange, mineral dissolution, and precipitation can affect the behavior of dissolved salts in groundwater, influencing the extent of saltwater intrusion.

Table 6. Summary of the range and averages of the Physicochemical parameters.

S/N	Parameters	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)
1	pH	7.7	8.0	7.85
2	Electrical conductivity ($\mu s/cm$)	19600.00	27000.00	22935.00
3	Salinity (mg/L)	24.00	31.00	28.00

S/N	Parameters	Minimum (mg/L)	Maximum (mg/L)	Average (mg/L)
4	TDS (mg/L)	810.00	1100.00	925.00
5	DO (mg/L)	2.40	3.80	2.98
6	BOD (mg/L)	3.03	6.67	4.39
7	COD (mg/L)	2.00	3.07	2.39
8	$SO_4{}^{2-}(mg/L)$	26.00	40.30	30.85
9	$Cl^-(mg/L)$	194.00	214.00	204.00
10	$HCO_3{}^-(mg/L)$	68.00	91.00	78.50
11	$Na^+(mg/L)$	789.00	910.00	847.25
12	$K^+(mg/L)$	239.00	291.00	256.75
13	$Ca^{2+}(mg/L)$	11.37	14.63	13.25
14	$Mg^{2+}(mg/L)$	298.00	428.00	340.25
15	$Mn^{2+}(mg/L)$	0.98	1.43	1.13
16	$Zn^{2+}(mg/L)$	0.73	0.91	0.81

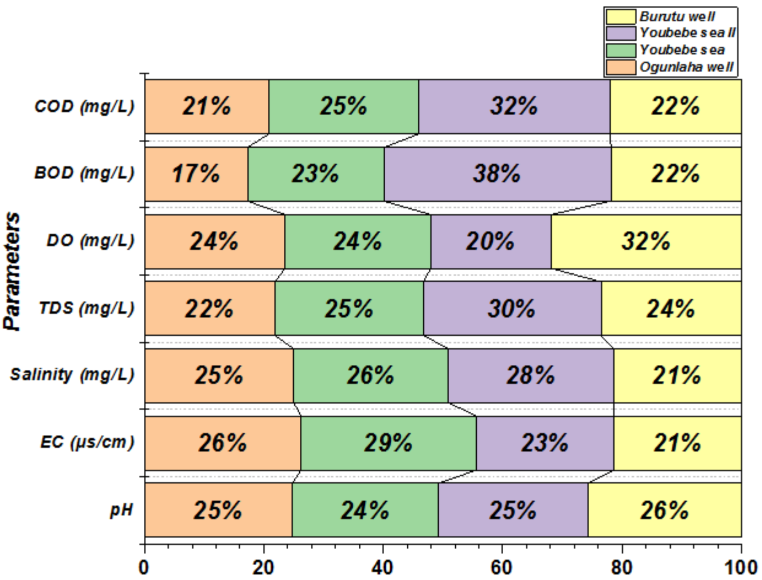

Figure 3. *Percentage distribution of physical and oxygen related parameters.*

Salinity is a measure of the total amount of dissolved salts in water, the values of salinity varied between 24.00 mg/L in Burutu well and 31.00 mg/L in Youbebe sea II, this range suggest the potential presence of saltwater intrusion, and that the water is slightly saline to moderately saline. This shows there is freshwater aquifer contact with saline or seawater. TDS values ranged from 810 mg/L in Ogulagha well to 1100 mg/L in Youbebe sea II, consistently above WHO standards in all locations [34].

Table 7. *Summary of aquifer vulnerability indices using GOD parametric model.*

VES points	Longitude (^{O}E)	Latitude (^{O}N)	G	O (Ωm)	D	G	O	D	GOD Index	Vulnerability class
1	5.4551	5.5080	Unconfined	13	3.7	0.6	0.4	0.9	0.216	Low

VES points	Longitude (^{O}E)	Latitude (^{O}N)	G	O (Ωm)	D	G	O	D	GOD Index	Vulnerability class
2	5.3558	5.5108	Unconfined	704.5	9.0	0.6	0.6	0.8	0.288	Low
3	5.3564	5.5122	Unconfined	133	3.2	0.6	0.7	0.9	0.378	Low
4	5.3586	5.5177	Unconfined	0.5	2.5	0.6	0.4	0.9	0.216	Low
5	5.3574	5.5164	Unconfined	5.2	0.6	0.6	0.4	1.0	0.240	Low
6	5.3567	5.5127	Unconfined	114.6	1.3	0.6	0.7	1.0	0.420	Moderate
7	5.3567	5.5143	Unconfined	19	0.5	0.6	0.4	1.0	0.240	Low
8	5.3522	5.5107	Unconfined	4.6	1.2	0.6	0.4	1.0	0.240	Low
9	5.3535	5.5118	Unconfined	8.3	0.6	0.6	0.4	1.0	0.240	Low
10	5.3549	5.5121	Unconfined	13.9	8	0.6	0.4	0.8	0.192	Low
11	5.3535	5.5060	Unconfined	1682.4	4.0	0.6	0.6	0.8	0.288	Low
12	5.3534	5.5060	Unconfined	73.4	3.1	0.6	0.5	0.9	0.270	Low
13	5.3513	5.5022	Unconfined	79.7	1.7	0.6	0.5	1.0	0.300	Low
14	5.3503	5.5060	Unconfined	257.3	1.2	0.6	0.7	1.0	0.420	Moderate
15	5.3506	5.5043	Unconfined	16.7	1.4	0.6	0.4	1.0	0.240	Low
16	5.3466	5.5019	Unconfined	122.2	3.6	0.6	0.7	0.9	0.378	Moderate
17	5.3510	5.5050	Unconfined	26.2	2.2	0.6	0.4	0.9	0.216	Low
18	5.3517	5.5065	Unconfined	743.4	2.1	0.6	0.6	0.9	0.324	Moderate
19	5.3564	5.3214	Unconfined	1.3	11.8	0.6	0.4	0.7	0.168	Low
20	5.3564	5.3214	Unconfined	0.5	1.3	0.6	0.4	1.0	0.240	Low
21	5.3564	5.3215	Unconfined	1.2	6.3	0.6	0.4	0.8	0.192	Low
22	5.3577	5.2215	Unconfined	0.3	4.4	0.6	0.4	0.8	0.192	Low
23	5.3584	5.3219	Unconfined	44.8	10.8	0.6	0.4	0.7	0.168	Low
24	5.3641	5.3214	Unconfined	69.5	1.6	0.6	0.5	1.0	0.300	Moderate
25	5.3642	5.3212	Unconfined	3.1	12.9	0.6	0.4	0.7	0.168	Low
26	5.3643	5.3211	Unconfined	1.2	10.8	0.6	0.4	0.7	0.168	Low
27	5.3654	5.3221	Unconfined	1.1	10.7	0.6	0.4	0.7	0.168	Low
28	5.3652	5.3222	Unconfined	0.5	5.0	0.6	0.4	0.8	0.192	Low
29	5.3652	5.3215	Unconfined	0.4	4.8	0.6	0.4	0.8	0.192	Low
30	5.3656	5.3230	Unconfined	0.7	4.5	0.6	0.4	0.8	0.192	Low
31	5.3620	5.3219	Unconfined	161.1	1.6	0.6	0.7	1.0	0.420	Moderate
32	5.3615	5.3294	Unconfined	45.8	1.4	0.6	0.4	1.0	0.240	Low
33	5.3598	5.3317	Unconfined	494.6	1.1	0.6	0.8	1.0	0.480	Moderate
34	5.3478	5.3230	Unconfined	1.6	10.8	0.6	0.4	0.7	0.168	Low
35	5.3479	5.3231	Unconfined	2.4	3.8	0.6	0.4	0.9	0.216	Low
36	5.3486	5.3231	Unconfined	1.4	3.9	0.6	0.4	0.9	0.216	Low
37	5.3492	5.3227	Unconfined	0.4	2.6	0.6	0.4	0.9	0.216	Low
38	5.3542	5.3212	Unconfined	0.6	7.1	0.6	0.4	0.8	0.192	Low
39	3.3556	5.3214	Unconfined	2.2	10.8	0.6	0.4	0.7	0.168	Low

VES points	Longitude (^{O}E)	Latitude (^{O}N)	G	O (Ωm)	D	G	O	D	GOD Index	Vulnerability class
40	5.3556	5.3210	Unconfined	2.6	11.8	0.6	0.4	0.7	0.168	Low
41	5.3556	5.3210	Unconfined	0.3	3.7	0.6	0.4	0.9	0.216	Low
42	5.3560	5.3220	Unconfined	0.7	2.3	0.6	0.4	0.9	0.216	Low
43	5.3560	5.3221	Unconfined	1.2	3.5	0.6	0.4	0.9	0.216	Low
44	5.3565	5.3226	Unconfined	5.7	11.2	0.6	0.4	0.7	0.168	Low
45	5.3601	5.3458	Unconfined	21.4	2.0	0.6	0.4	0.9	0.216	Low
46	5.3512	5.3447	Unconfined	239.9	5.9	0.6	0.7	0.8	0.336	Moderate
47	5.3505	5.3438	Unconfined	257.7	3.4	0.6	0.7	0.9	0.378	Moderate
48	5.3505	5.3430	Unconfined	150	10.4	0.6	0.7	0.7	0.294	Low
49	5.3516	5.3415	Unconfined	165.7	9.9	0.6	0.7	0.8	0.336	Moderate
50	5.3551	5.3382	Unconfined	142	1.5	0.6	0.7	1.0	0.420	Moderate

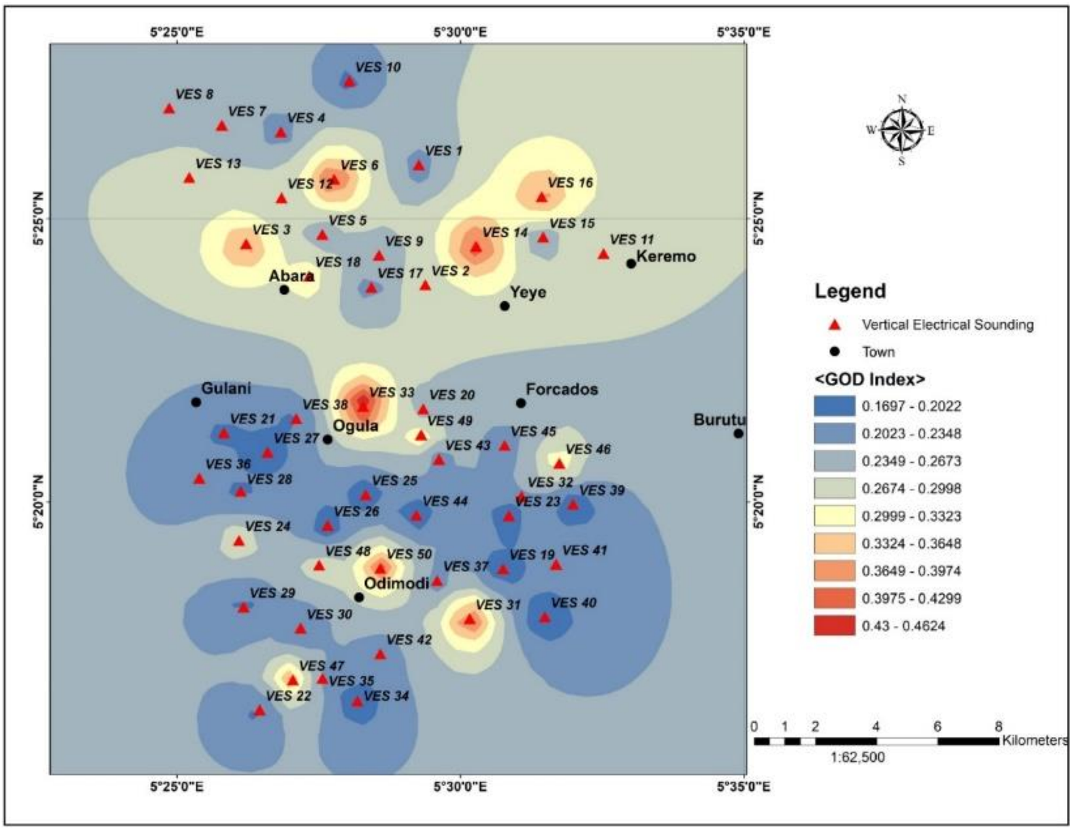

Figure 4. Contour showing the variation of GOD index.

The values estimated ranged from 0.168 to 0.420 (Table 7) and the study area was classified into low and moderate vulnerability class. Regions of low vulnerability rating indicates that the geological and hydrogeological conditions of the area are such that they provide substantial protection against groundwater pollution. Regions of moderate vulnerability (VES 6, 14, 16, 18, 24, 31, 33, 46, and 47) while the rest were delineated as low.

4. Conclusion

The geophysical and geochemical investigation of saltwater intrusion into freshwater aquifers in coastal areas of Delta State, Nigeria, revealed significant evidence of saline water infiltration and highlighted various factors contributing to the vulnerability of these aquifers. The investigation revealed significant saltwater intrusion into the freshwater aquifer, driven by factors such as thin aquifer layers, low protective capacity, high hydraulic conductivity, and adverse geochemical processes. The GOD index guides decision-making processes related to groundwater management, protection, and land use planning to ensure the sustainable use of groundwater resources while minimizing pollution risks in the study area.

Abbreviations

GOD	Groundwater Occurrence and Depth
WQI	Water Quality Index
VES	Vertical Electrical Sounding

Software Permission

The ipi2win and winResist software used for this research were obtained prior to permission from the vendors.

Data Availability Statement

The authors declare that the data used for this research were obtained from the field, laboratory experimentation. The data stored in a repository will be made available prior to request.

Conflicts of Interest

The authors declare conflicts of interest.

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