ARTICLE

Integrated Geophysical and Hydrogeochemical Characterization and Assessment of Groundwater Studies in Adum West Area of Benue State, Nigeria

Moses Oghenenyoreme Eyankware[1,2*]   Christopher Ogwah[1]   Umayah Otitie Star[3]

1. Department of Geology, Faculty of Science Ebonyi State University, Abakaliki, Nigeria
2. Geomoses Consultancy Limited Warri, Delta State, Nigeria
3. Department of Physics, Faculty of Science Delta State, University, Abakaliki, Nigeria

ARTICLE INFO	ABSTRACT

Integration of geophysical and hydrogeochemical methods has been scientifically proven to be useful in vulnerability study and groundwater characterization. Subsurface geoelectric parameters such as resistivity and thickness obtained from geophysical method (Vertical Electrical Sounding VES) was used to determine aquifers vulnerability, longitudinal resistance (ρL) and transverse unit resistance (Rt). Thirty four water samples were collected from groundwater sources for physicochemical analysis. Estimated results from longitudinal conductance (S), (Rt) and (ρL) showed that the values ranges from 0.03 to 2.5mhos, 103.64 to 1964417.8 Ω/m^2 and 215.41 to 65731.68 Ω-m respectively. Result from S suggested that 50 % of groundwater is considered to be vulnerable to contamination from the earth surface, while the remaining 50 % is considered to be slightly vulnerable to surface contamination. Further findings obtained from hydrogeochemical analysis such as Gibb's and Chadba plots revealed that groundwater is highly influenced by rock water interaction, groundwater is classified to be $Na^+ + HCO_3^-$, $Ca^{2+} + Mg^{2+} + HCO_3^-$, $Na^+ + Cl^-$ and $Ca^{2+} + Mg^{2+} + Cl^-$ water type. Deduction from Soltan classification suggested that groundwater is classified to be of $Na^+ - HCO_3^-$ and $Na^+ - SO_4^{2-}$ water type. Results obtained from Ec and pH suggested that the values were below WHO permissible limit, while result obtained from TDS showed that at some sampling points TDS values were above WHO limit. Based on pH value obtained groundwater within the study area fell within slightly basic to acidic.

*Corresponding Author:
Moses Oghenenyoreme Eyankware,
Department of Geology, Faculty of Science Ebonyi State University, Abakaliki, Nigeria & Geomoses Consultancy Limited Warri, Delta State, Nigeria;
Email: geomoses203@gmail.com

1. Introduction

Report from various scholars suggested that groundwater account for over 95 percent of global storage of fresh water [1-3]. Based on this there is high demand for groundwater across the world, although human activities have negatively influence on groundwater quality. There are varieties of human activities that Parameters such as threat to groundwater quality within the study area. There are varieties of human activities that poses as threat to groundwater quality within the study area. These activities include leakage from sewage systems, solid waste dumpsites, household waste pits, peri-urban agriculture, underground storage tanks, surface water infiltration spots and petrol service stations. On a global scale, several methods have been used to determine groundwater potential and asses groundwater vulnerability. Several scientific methods have been developed to constantly monitor groundwater quality to further advert several health related disease associated with drinking water. [4] reported that groundwater vulnerability assessment is considered paramount in evaluating anthropogenic activities with respect to the advancement of population liability insurance and the evaluation of economic impacts of disposal cost in highly vulnerable areas. Preliminary information and criteria for decision-making in such areas as designation of land use controls, delineation of monitoring networks and management of water resources in the context of regional planning are related to protection of groundwater quality [5]. Several reports by various scholars have proven that the combination of VES and hydrogeochemical studies is to considered successful in assessment of groundwater vulnerable to surface contamination in sedimentary and hard rock terrain [6-9]. [10,11] were of the opinion, that the VES is one of the geoelectrical method mostly used in measuring the vertical alterations of electrical resistivity of rock unit. This method has been recognized to be more suitable for a hydrogeological survey of sedimentary basins than the other resistivity methods. [12] further reported that the successful use of VES in determination of aquifer protective capacity and groundwater water potential. Findings from [13]; [14] suggested that the selection of geophysical methods in groundwater studies rely on the contrast between the physical properties of the target and the surrounding medium. Report from previous authors revealed that the delineation and characterization of groundwater potential within the Benue Trough becomes necessary as water samples from some existing wells and boreholes in the study area were below acceptable limits, especially during the dry season when most of the well and boreholes most have drop to a minimum yield and sometimes get dried up. Due to lack of hydrogeological information of the Benue Trough and improper delineation of the water bearing unit to facilitate the precise identification of desired water bearing unit before drilling and well completion for sustainable supply of potable water to the inhabitant of the study area [15,16]. [12] were of the opinion that basic resistivity parameters such as thickness, depth and resistivity of rock unit are vital in the determination of secondary aquifer which in turn help in the assessment of aquifer vulnerability. Findings according to [17] showed the successful use of VES in assessment of groundwater vulnerability in southern eastern part of Nigeria. [18] used surface geophysical method to decipher the groundwater potential in Mian Channu area of Pakistan. [19] further reported the successful use of hydrogeophysical method in determination of transmissivity, storativity of Njaba River Basin, Nigeria. An integration of VES data and hydraulic properties was also used in delineation of aquifer potential zones in central Uganda [20]. [21] also use the VES method to estimate hydraulic conductivity in alluvial aquifers of Pakistan. [22] reported the successful use of VES method in the determination of Quaternary aquifer of semi arid region of Khanasser of Syria. [23] used near-surface geophysical methods in estimating hydraulic conductivity and porosity of Ruhrtal aquifer in Germany. [24] were of the opinion that groundwater vulnerability is the risk of contaminates dispose near groundwater surface to influence groundwater quality. According to [25] parameters such as permeability, porosity, local geology and thickness of aquifer are considered to major factors in determining aquifer vulnerability. Reconnaissance survey within the study area, was is line with report by [24] which stated that pit toilets and dumpsites are in most case sited indiscriminately without taking into consideration the hydrogeological settings of the area, in so doing rendering the future of groundwater at risk. [26] suggested that groundwater flow also enhances the spread of contaminant in aquifer, the flow of these contaminations is highly controlled by inter-granular pores, fissures and interconnected fractures. Water bearing unit (aquifer) vulnerability is usually high when the earth material provide protection to groundwater repositories from surface contaminants, while aquifer vulnerability will be on the low side when natural factor that provide protection from surface contaminants. If groundwater protection studies are considered mandatory, it is therefore necessary to take into consideration factor that may trigger vulnerability of groundwater in order to ensure sustainable groundwater management strategy. For effective groundwater management it is therefore mandatory to have preliminary knowledge of the properties of water baring rocks. This is based on the fact that such

properties have great influence on aquifer repositories. [27-31] stated that the heterogeneous nature of the subsurface rocks varies widely depending on the local geology of the area. With all the aforementioned factors that play a role in groundwater pollution and aquifer vulnerability it is therefore necessary to constantly monitor groundwater within the study area.

Geology/Hydrogeology

The study area lies within Eze Aku Formation of the Southern Benue Trough, is known to be one of major stratigraphic unit in the Southern Benue Trough erected by the shell D"Arcy geologists, in the 1950. The term Eze Aku shale group appears to have been introduced by [32]. The Eze Aku Group includes all the stratigraphic units that was deposited from the late Cenomanian to Turonian in the Southern Benue Trough. And from the western to southeastern flank of the some aniticlinorial core, [33] and [34] indentified lithofacies broadly similar to those of the western flank. It is noteworthy that a condensed arm of the Eze Aku facies extends far southeastwards and partially overlies the Odukpani area between the Oban massif and the elements of the Nkporo group in that extremity. Because of folding and facies changes the thickness of the main mass of the group which is the shale facies, is not clear [16]. According to [35]; [16] Eze Aku unit is subdivided into several lithofacies; the sandstone, siltstone, shale and limestone. The thickness of the Eze Aku group is estimated to between the ranges of 600 to 1,200 m [16]. The hydrogeological characteristics of the Southern Benue Trough are directly dependent on their structure, climate and geology of the area. This makes it be extremely poor in groundwater prospect [16]. Report according to Nwajide, [16] aquiferous unit of the Eze Aku Group are formed in the sandstone and occasionally an fractured limestone.

2. Materials and Methods

A total of 26 VES was carried out within the study area as shown in Figure 2 using ABEM Terrameter SAS 1000, Schlumberger array configuration was employed for each VES profile with a maximum half current (AB/2) electrode separation of 150 m and half potential (MN/2) electrode of 10 m. The observed field data were converted to apparent resistivity (ρa) values using the following equation (1):

$$\rho a = \pi \left(\frac{\left(\frac{AB}{2}\right) - \left(\frac{MN}{2}\right)}{MN} \right) \Delta V / I \qquad (1)$$

Apparent resistivity data was plotted against the current electrode spacing (AB/2) to generate geoelectrical
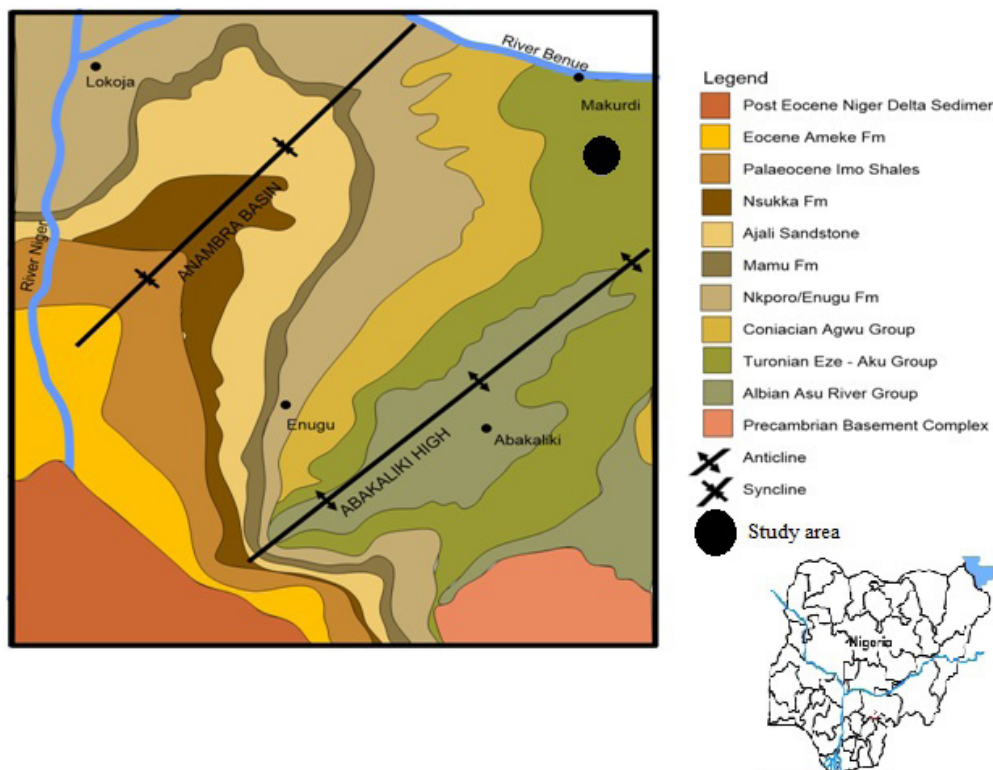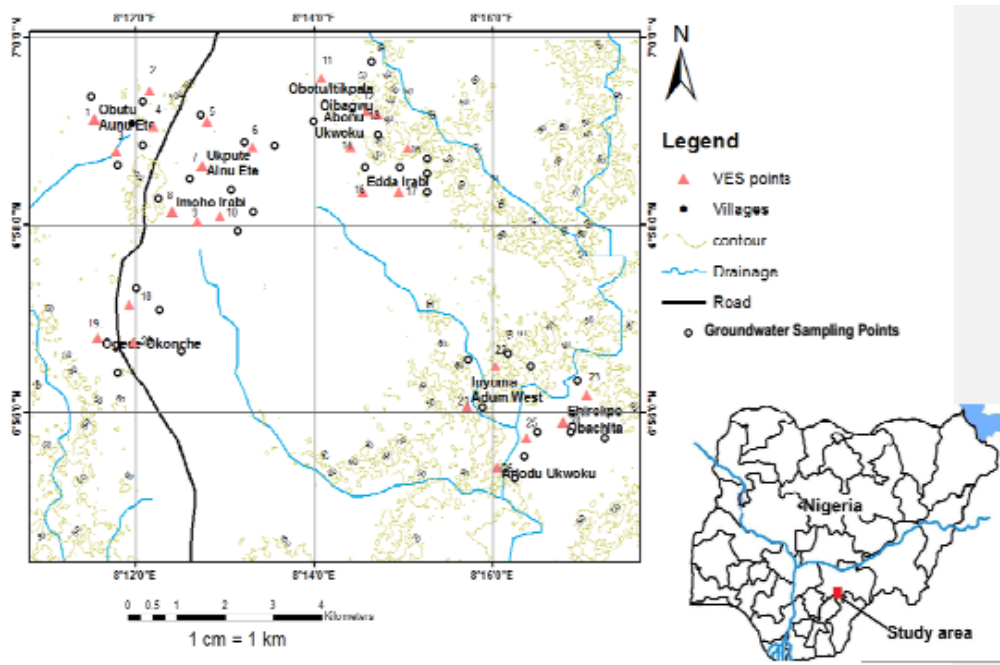

Figure 1. Modified after [16]

Figure 2. Topography Map of the study area showing VES points.

curves. The IX1D software was used to enhance VES data obtained from the field, with this we were able to generate sounding curve. Information from sounding curve was used to produce geoelectric section. According to report by [36] some parameters related to the different combinations of thickness and resistivity of the geoelectric layer are important for the analysis was used in understanding of the geologic model. The parameters are Dar Zarrouk Longitudinal conductance (*S*), Longitudinal Resistance (ρL), and Transverse Unit Resistance (*Rt*), respectively, as shown in equations 2 to 6 respectively.

$$S = \frac{h}{p} \tag{2}$$
$$T = hp \tag{3}$$

Longitudinal unit conductance (S) was calculated from the formula given below. For 'n' layers, the total longitudinal conductance is

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_i}{\rho_i} + \frac{h_2}{\rho_2} + \dots + \frac{h_n}{\rho_n} \tag{4}$$

as proposed by [22,17]

Transverse unit resistance (T) was calculated for the equation given below.

The total transverse unit resistance is

$$Rt = \sum_{i=1}^{n} h_i \rho_i = h_i \rho_i + h_2 \rho_2 + \dots + h_n \rho_n \tag{5}$$

as proposed by [17,37]

Longitudinal resistance was computed for shown below. The longitudinal resistivity is

$$\rho_L = \frac{H}{S} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{\rho_i}} \tag{6}$$

as proposed by [12]

Groundwater Sampling

Physicochemical parameters were determined using appropriate titrimetric methods described by America Public Health Association [38] standard method see Table 2. A total of 34 groundwater was randomly sampled for physicochemical properties within the study area as shown in Figure 2 and Table 5.

Table 1. Hydrogeochemical Indices

Parameters	Equation Parameters were calculated in (meq/L)	Equation Number	References
Soltan Classification	$r1 = (Na^+ - Cl^-)/SO_4^{2-}$	7a	[39]
	$r2 = [(K^+ + Na^+) - Cl^-]/SO_4^{2-}$	7b	
Gibbs Plots	Cations $Na^+/(Na^+ + Ca^{2+})$	8a	[40]
	Anions $Cl^-/(Cl^- + HCO_3^-)$	8b	
Chadba Plots	$HCO_3^- - (Cl^- + SO4^{2-} + NO_3^-)$	9a	[41]
	$Ca^{2+} + Mg^{2+}/(Na^+ + K^+)$	9b	

     17

Table 2. Method used to analyze physicochemical parameters.

S/No	Parameters	Analytical Method
1	pH	pH meter HachsensION + PH1 portable pH meter and Hachsens ION + 5050 T Portable Combination pH Electrode
2	Electrical Conductivity (EC)	HACH conductivity
3	Total dissolved solids (TDS)	TDS meters (model HQ14D53000000, USA).
4	Magnesium (Mg^{2+})	EDTA titrimetric method
5	Calcium (Ca^{2+})	Titrimetric method
6	Chloride (Cl^-)	Titrimetric method
7	Nitrate (NO_3^-)	Ion-selective electrode (Orion 4 star)
8	Sulphate (SO_4^{2-})	Turbidimetric method using a UV-Vis spectrometer
9	Potassium (K^+)	Jenway clinical flame photometer (PFP7 model)
10	Sodium (Na^+)	Jenway clinical flame photometer (PFP7 model)
11	Bicarbonate (HCO_3^-)	Titrimetric method

**Table 3.** Representative results of interpreted layer parameters from the study area

| VES	Layer resistivity (ohm-m)						Depth (m)						Curve Type	No of layers
	ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	d1	d2	d3	d4	d5	d6		
VES-01	399.9	169.5	1.21	183.9	9.3	∞	1.6	9.7	10.2	53.3	∞		H	5
VES -02	164.2	149.1	18.6	1566.9	8.5	∞	0.5	5.3	13.6	19.1	∞		QH	5
VES -03	333.6	147.5	8.2	1213.3	∞		1.4	17.0	27.1	∞			KH	4
VES-04	533.2	175.4	12.4	1229.0	690.1	∞	2.2	8.6	9.0	28.8	∞		H	5
VES-05	1488.9	540.1	125.3	319.7	2.3	∞	0.6	3.0	9.6	24.5			HK	5
VES -06	1335.4	47.7	966.9	8.4	1010.7	8.9	0.6	1.7	2.3	2.9	15.7	∞	HK	6
VES-07	3111.7	125.2	442.1	272.0	55.8	9188.6	0.6	0.9	3.8	16.2	50.1	∞	QQA	6
VES-08	313.5	24.2	1008.5	6.8	∞		2.4	6.6	15.0	∞			HK	4
VES -09	3195.5	338.6	1255.6	105.4	∞		0.8	7.1	23.23	∞			HK	4
VES -10	333.7	63.8	13.5	1850.7	∞		4.3	14.5	46.1	∞			HK	4
VES-11	1644.5	135.6	2143.9	48.0	∞		2.1	5.7	20.0	∞			HK	4
VES-12	629.0	154.2	2059.3	209.8	760.2	65.2	0.8	2.3	2.5	11.1	23.3	∞	HK	6
VES -13	1073.1	447.6	186.0	7304.9	48.8	∞	0.5	3.9	10.8	27.5	∞		HK	5
VES -14	275.5	710.2	4.8	484.9	72.6	7196.5	0.8	3.3	3.6	24.6	89.1	∞	QQ	6
VES -15	973.8	173.2	1585.0	6.8	∞		3.9	11.2	32.0	∞			HK	4
VES -16	369.9	139.6	15.3	545.6	5.7	∞	0.5	3.3	14.7	19.4	∞		H	4
VES -17	789.2	768.5	82.2	805.9	56.9	∞	1.7	5.1	8.4	26.7	∞		HK	4
VES -18	533.2	175.4	12.4	1229.0	690.1	∞	2.2	8.6	9.0	28.8	∞		H	5
VES -19	970.6	336.3	133.5	79.6	0.9	∞	1.6	2.0	11.8	56.9	∞		Q	5
VES -20	551.2	1.7	456.1	6.1	420.7	27.6	0.5	0.6	2.6	3.9	16.8	∞	HKQ	6
VES -21	1488.9	540.1	125.3	319.7	2.3	∞	0.6	3.0	9.6	24.5	∞		HK	5
VES -22	164.9	33.3	187.1	5.3	∞		0.9	19.4	43.2	∞			HK	4
VES -24	804.2	129.2	76.0	7458.1	∞		0.6	8.5	63.3	∞			QH	4
VES -25	132.8	30.1	102.6	1.0	171.9	∞	1.6	5.5	15.6	16.8	∞		HKA	5
VES -26	859.8	456.4	89.5	16183	550.6	∞	0.9	3.8	9.1	21.1	∞		H	5

3. Results

Resistivity, Thickness and Depth

Table 4. Results of Dar-Zarrouks Parameter

Sampling Code	Longitudinal conductance (S)	Transverse resistance(T)	longitudinal resistivity (ρL)
VES-01	0.16	8603.26	611.77
VES -02	0.48	103.64	3428.3
VES -03	1.33	2798.3	478.4
VES-04	0.09	26594.12	15565.67
VES-05	0.78	5677.90	215.41
VES -06	0.10	13801.	3367.05
VES-07	0.77	3352.2	1080.06
VES-08	0.18	9391.45	1398.7
VES -09	0.03	25121.55	5915.3
VES -10	2.50	2532.4	438.75
VES-11	0.03	7014.88	4058.3
VES-12	0.06	12309.7	65731.68
VES -13	0.04	125475.7	2578.36
VES -14	0.98	16892.46	2063
VES -15	0.72	22020.7	593.34
VES -16	0.05	37914.4	1148.97
VES -17	0.77	3352.2	1080.06
VES -18	0.069	18724.4	2470.81
VES -19	0.07	26594.07	15564.7
VES -20	0.05	18470.9	14789.7
VES -21	0.65	18440.5	1239.37
VES -22	0.46	6743.77	1435.01
VES -24	0.65	5234.62	407.36
VES -25	1.31	3275.07	268.07
VES -26	0.05	196417.8	17437.75
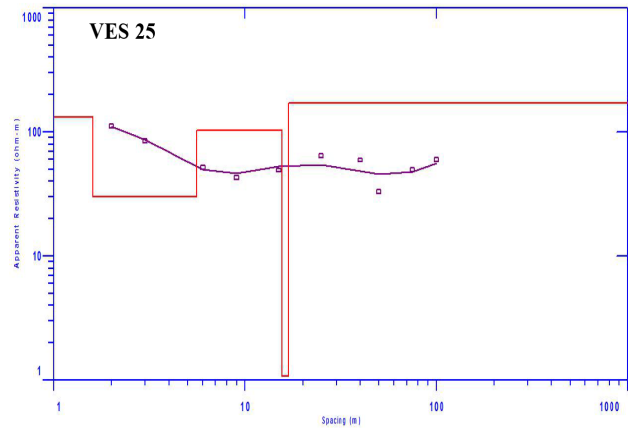
Figure 3. VES points at Ehirekpe Obachite
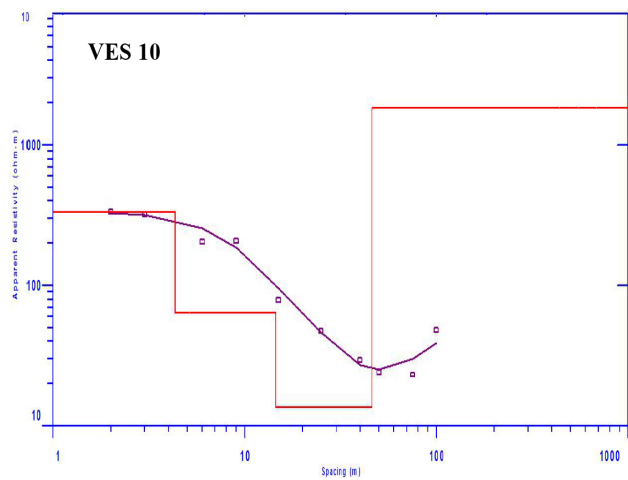
Figure 4a. VES points at Adum West
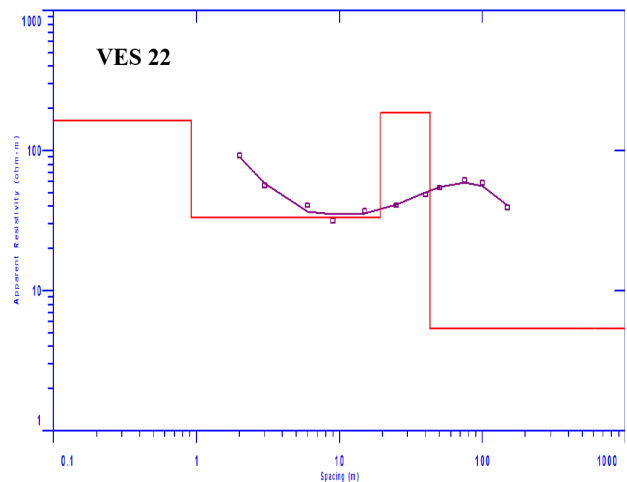
Figure 4b. VES points at Obutu Aunu Ete

Table 5. Results of physicochemical Parameters.

Sampling points	Ec (µS/cm)	pH	TDS (mg/L)	Na$^+$ (meq/L)	K$^+$ (meq/L)	Mg^{2+} (meq/L)	Cl$^-$ (meq/L)	HCO$_3^-$ (meq/L)	SO$_4^{2-}$ (meq/L)	NO$_3^-$ (meq/L)	Ca^{2+} (meq/L)
GT-1	849	6.3	264	2.11	0.09	0.68	0.01	0.02	0.00	0.01	0.30
GT-2	495	6.9	163	1.94	0.40	0.57	0.00	0.07	0.02	0.01	0.10
GT-3	693	6.5	375	0.84	0.81	0.89	0.00	0.11	0.01	0.02	0.05
GT-4	930	7.2	616	0.39	0.74	1.87	0.09	0.09	0.22	0.04	0.01
GT-5	1034	7.3	270	1.42	0.25	2.68	0.02	0.21	0.30	0.01	0.02
GT-6	442	6.2	104	2.70	0.14	1.98	0.06	0.04	0.12	0.03	0.04
GT-7	630	6.6	759	0.87	0.10	1.89	0.03	0.06	0.11	0.02	0.07
GT-8	393	7.1	1055	1.37	0.05	0.96	0.11	0.03	0.07	0.01	0.01
GT-9	701	7.3	386	1.47	0.03	0.55	0.07	0.09	0.10	0.03	0.02
GT-10	1003	7.5	200	1.58	0.07	0.71	0.21	0.23	0.04	0.04	0.08
GT-11	920	6.9	145	1.21	0.50	0.68	0.03	0.01	0.02	0.05	0.01
GT-12	829	6.5	707	1.41	0.06	0.96	0.00	0.08	0.01	0.02	0.02
GT-13	611	6.3	79	1.02	0.02	1.84	0.21	0.05	0.03	0.06	0.03
GT-14	502	6.9	546	1.07	0.08	1.65	0.20	0.14	0.06	0.04	0.04
GT-15	417	7.3	239	0.91	0.04	0.08	0.10	0.10	0.01	0.03	0.06
GT-16	696	7.0	132	1.31	0.07	0.64	0.00	0.42	0.05	0.02	0.01
GT-17	1211	6.7	435	2.17	0.02	0.78	0.05	0.41	0.08	0.03	0.03
GT-18	920	6.8	233	1.82	0.10	0.13	0.11	0.21	0.01	0.01	0.05
GT-19	834	6.9	637	0.91	0.05	0.68	0.06	0.07	0.04	0.03	0.04
GT-20	794	6.4	108	1.23	0.03	0.02	0.07	0.15	0.01	0.02	0.02
GT-21	401	6.5	113	1.47	0.06	1.96	0.04	0.06	0.06	0.13	0.01
GT-21	923	6.6	806	0.43	0.04	0.57	1.00	0.08	0.13	0.02	0.02
GT-22	581	6.8	459	1.82	0.16	0.12	0.63	0.10	0.21	0.02	0.06
GT-23	702	6.9	186	1.45	0.02	0.85	1.06	0.03	0.23	0.03	0.07
GT-24	1008	6.6	865	1.20	0.01	0.42	0.05	0.18	0.01	0.02	0.01
GT-25	933	6.9	380	0.82	0.11	1.86	0.08	0.22	0.02	0.01	0.03
GT-26	789	6.7	93	0.31	0.14	2.01	0.05	0.03	0.11	0.04	0.05
GT-27	1092	6.6	860	0.49	0.03	0.79	1.00	0.19	0.02	0.03	0.04
GT-28	1001	7.0	115	1.60	0.08	1.98	0.96	0.04	0.13	0.01	0.06
GT-29	729	7.1	329	1.82	0.10	0.64	0.06	0.02	0.02	0.03	0.02
GT-30	482	6.9	84	0.74	0.06	0.22	0.00	0.12	0.03	0.01	0.01
GT-31	509	6.5	101	1.65	0.04	1.07	0.07	0.10	0.01	0.02	0.05
GT-32	802	6.8	174	0.58	0.06	0.64	0.06	0.07	0.10	0.02	0.07
GT-33	915	6.7	108	1.04	0.14	0.12	0.64	0.18	0.11	0.01	0.01
GT-34	804	6.6	579	0.84	0.05	1.07	0.03	0.21	0.03	0.10	0.03
Min	393	6.2	79	0.31	0.01	0.02	0	0.01	0	0.01	0.01
Max	1211	7.5	1055	2.7	0.81	2.68	1.06	0.42	0.3	0.13	0.3
Stan Dev.											
WHO, 2010	1400	6.5-8.5	500	200	2.0	150	600	**	400	50	

Table 6. Computed Values of Hydrogeochemical Parameters

Sampling points	Soltan Classification		Gibbs		Chadba Plot	
	r1	r2	Cations	Anions	Cations	Anions
GT-1	0	0	0.87	0.33	-1.22	0
GT-2	1.92	117	0.95	0	-1.67	0.04
GT-3	84	165	0.94	0	-0.71	0.08
GT-4	1.36	4.94	0.97	0.5	0.75	-0.26
GT-5	1.1	5.5	0.98	0.08	1.03	-0.12
GT-6	7.63	23.1	0.98	0.6	-0.82	-0.17
GT-7	7.6	8.54	0.92	0.33	0.99	-0.1
GT-8	18	18.7	0.99	0.78	-0.54	-0.16
GT-9	14	14.3	0.98	0.43	-0.93	-0.11
GT-10	34.25	36	0.95	0.47	-0.86	-0.06
GT-11	59	84.5	0.99	0.75	-1.02	-0.09
GT-12	141	1.46	0.98	0	-0.49	0.05
GT-13	27	27.66	0.97	0.8	0.83	-0.25
GT-14	14.5	15.83	0.96	0.58	0.54	-0.16
GT-15	13.5	85	0.93	1	-0.81	-0.04
GT-16	26.2	27.6	0.99	0	-0.73	0.35
GT-17	26.5	26.75	0.98	0.1	-1.38	0.25
GT-18	1.7	181	0.97	0.34	-1.74	0.08
GT-19	0.81	22.5	0.95	0.46	-0.26	-0.06
GT-20	1.15	119	0.98	0.31	-1.22	0.05
GT-21	1.37	24.83	0.99	0.66	0.44	-0.17
GT-21	-0.7	-0.04	0.95	0.92	0.12	-1.07
GT-22	0.98	6.42	0.96	0.86	-1.8	-0.76
GT-23	0.16	1.78	0.95	0.97	-0.55	-1.29
GT-24	1.14	116	0.99	0.21	-0.78	0.1
GT-25	37	42.5	0.96	0.26	0.96	0.11
GT-26	0.15	3.63	0.86	0.62	1.61	-0.17
GT-27	-0.53	-24	0.92	0.84	0.31	-0.86
GT-28	4.92	5.53	0.96	0.96	0.36	-1.06
GT-29	88	93	0.99	0.75	-0.26	-0.09
GT-30	24.66	26.67	0.98	0	-0.57	0.08
GT-31	158	162	0.97	0.41	-0.57	0
GT-32	52	5.8	0.89	0.46	0.07	-0.11
GT-33	3.63	4.9	0.99	0.78	-1.07	-0.58
GT-34	27	28.67	0.96	0.14	0.21	0.05

4. Discussion

Previous scholars have successfully used the integration of application VES and hydrogeochemical studies in identification of aquifer's geometry, lithology and groundwater quality [42,43].

Dar-Zarrouk Parameters of the Study Area

Equations 2-6 was used to derive aquifer protective capacity and area of with high groundwater potential, estimated results obtained from aforementioned equations is presented in Table 4.

Longitudinal Conductance (*S*)

S is one of the Dar Zarrouk parameters used to determine aquifer vulnerability. According to [44] *S* evaluates the attribute of a conducting layer in contrast with the transverse resistance in determining the characteristics of resisting layer. [12] were of the view that an area with low S value signifies poor and weak aquifer protective zone and considered to be susceptible to contamination, while an area with high *S* value signifies high protective area. The highest value of *S* was observed at VES location 10 with value of 2.5 mhos and the least *S* was observed at VES location 9 with value of 0.03 mhos as shown in Figure 5. From Table 7, it was observed that 42 % of VES points fell within moderate category, 38 % fell within poor category and lastly, 20 % fell within weak category. A similar conducted by [12] at sub-urban area of Abakaliki revealed that aquifer vulnerability ranges from moderate, weak and poor. [45] were of the view that aquifer if given protection by sufficient thickness and local geology layers which is referred to protective layer.

Table 7. Aquifer protective capacity of the study area against [45]

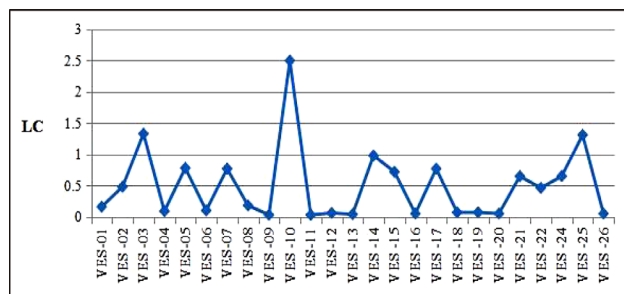| Rating	Remarks	Remarks
> 10	Excellent	
5-10	Very good	
0.2-4.9	Moderate	VES-02, 03, 05, 07, 10, 13, 14, 15, 17, 21, 22, 23, 24, 28
0.1-0.19	Weak	VES-01, 08, 12, 19, 26, 27
<0.1	Poor	VES-04, 09, 06, 11, 12, 13, 16, 18, 20, 25

Figure 5. Barchart of LC against VES points.

Transverse Unit Resistance (*Rt*)

Rt value for this study ranges from 103.64 at VES-2 to 196417.8 Ω/m^2 at VES-25 see Table 6. It has been observed that the transmissivity of water bearing unit is directly proportional to its transverse resistance. Hence, high Rt values correspond to high transmissivity values and vice versa. The high transmissivity values however, suggest that the water bearing units of the formation are highly permeable, porous and freely allow fluid movement within the aquifer, which possibly may enhance the migration and circulation of contaminants in the groundwater aquifer system while low transmissivity is suggestive of high percentage of impervious clay which retards fluid movement within the aquifer.

Longitudinal Resistance (ρL).

The estimated value of ρL ranges from 215.41 at VES location 5 to 65731.68 Ω-m at VES location 12. ρL [17] were of the view that variation in ρL value can be use to demarcates the saline, brackish and fresh water aquifers

into three different regions based on their attained magnitudes.

Hydrogeochemical Assessment of Groundwater Quality

Hydrogeochemical model such as Gibbs, Chadba and Soltan derive from equation 7 to 9 was used to characterize groundwater within the study area. According to [46] groundwater experiences series of chemical reactions and impact processes as it moves from one region to another below the subsurface, Therefore hydrogeochemical assessment of groundwater is essentially mandatory to characterize groundwater in order to know the what it can be used for.

Gibbs Plot

Gibb's plot is used to be establish the relationship and the chemical constituent of groundwater and their respective aquifer such as rock chemistry, precipitation and evaporation rate. Gibb's plot is usually a plot of cations and anions against total dissolved solid. The plot is a ratio of $[(Na^+)/ (Na^+ + Ca^{2+})]$ and other ratio for $[Cl^-/(Cl^- + HCO_3^-)]$. From Figure 6 it was observed that the major factor that influences groundwater chemistry is rock water interaction. This is in line with previous study conducted by [47] which stated rock water interaction is a major player in groundwater chemistry.

Chadba Plot

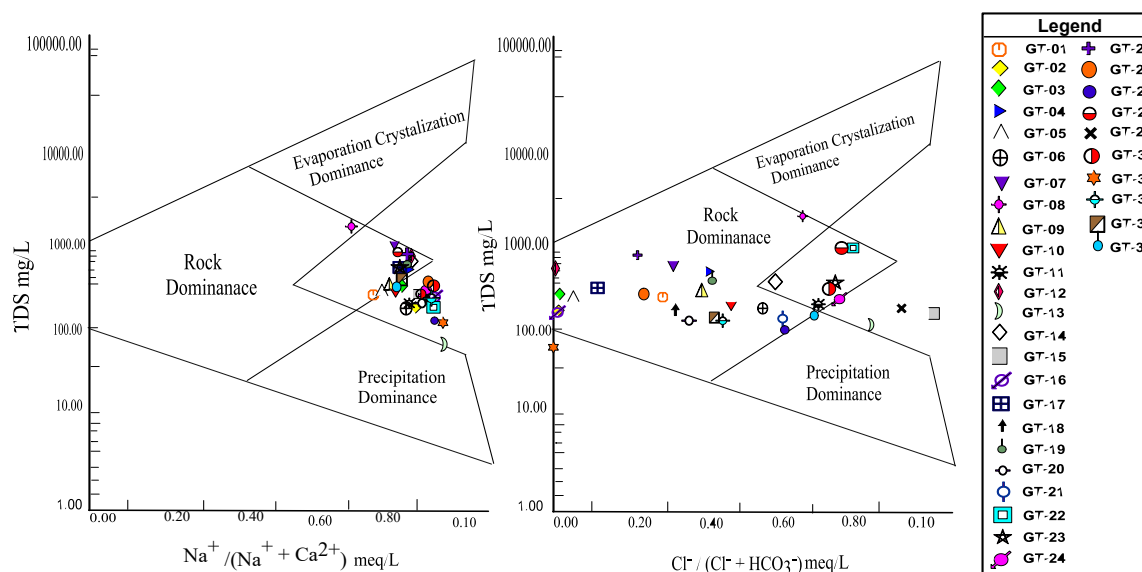[2] acknowledge that groundwater can be characterized using different kinds of hydrogeochemical model

Figure 6. Gibb's Plot of Groundwater geochemistry.

an example "the Chadba plot can be used to characterize groundwater." This plot is used in interpreting groundwater evolution trends and also aid in understanding groundwater geochemistry. It is a cross-plot such as $Ca^{2+} + Mg^{2+}$ $(SO_4^{2-} + HCO_3^-)$ versus $Na^+ + Cl^-$, $Na^+ + K^+$ versus total cation and Na^+ versus Cl^-. According to [48] the plot is used to characterize water into two major category temporary and permanent hardness. For this study groundwater fell within four categories namely; $Na^+ + HCO_3^-$, $Ca^{2+} + Mg^{2+} + HCO_3^-$, $Na^+ + Cl^-$ and $Ca^{2+} + Mg^{2+} + Cl^-$ water type as shown in Figure 7. From Figure 7 it was observed that sample locations GT- 04, 05,07, 13, 14, 17, 18, 21, 26, 27, 28 and 32 is groundwater with alkali metals exceed alkaline earth and weak acidic exceed string acidic anion. While sample locations GT-25 and 34 were classified as groundwater that showed alkaline earhs and weak acidic exceed both alkali metals and strong acidic anions'. It' is dominantly represented as $Ca^{2+} + Mg^{2+} + HCO_3^-$. Sample location GT- 06, 08, 09, 10, 11, 15, 19, 22, 23, 24 and 29 was categorize to be dominated by $Na^+ + Cl^-$. Lastly, sample locations GT-01, 02, 03, 12, 16, 20, 24, 30 and 31 is dominantly said to be of $Ca^{2+} + Mg^{2+} + Cl^-$ water type.

Soltan Classification

[39] classified groundwater based on Cl^-, $SO4_2^-$ and $HCO3^-$ concentrations. From Table 6. It was observed that sample locations GT-1, 19, 21, 22, 23, 26 and 27 were classified to be $Na^+.SO4_2^-$ water type, while ample locations GT-2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20, 21, 25, 28, 29, 30, 31, 32, 33and 34 were classified to $Na^+. HCO_3^-$ water type. Findings from Table 6 revealed that sample locations GT-1 and 21 is classified to be of deep meteoric water percolation type that implies that the groundwater is influenced by precipitation [47]. While sample locations GT-2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33 and 34 fell within shallow meteoric water.

Comparison of Groundwater Quality to WHO, (2010) Set Limit Standard

The value of Ec for this study ranges from 393 to 1211μS/cm, the highest concentrations of Ec was observed at sample location GT-17 with Ec value of 1211 μS/cm with least value of 393 μS/cm at sample location GT-8 as shown in Figure 8. The high concentration of Ec in groundwater around GT-17 can be attributed to the fact that groundwater is in contact with more dissolved inorganic constituents [48]. [49] reported that high concentration of Ec depends on temperature and type of ions present in groundwater.
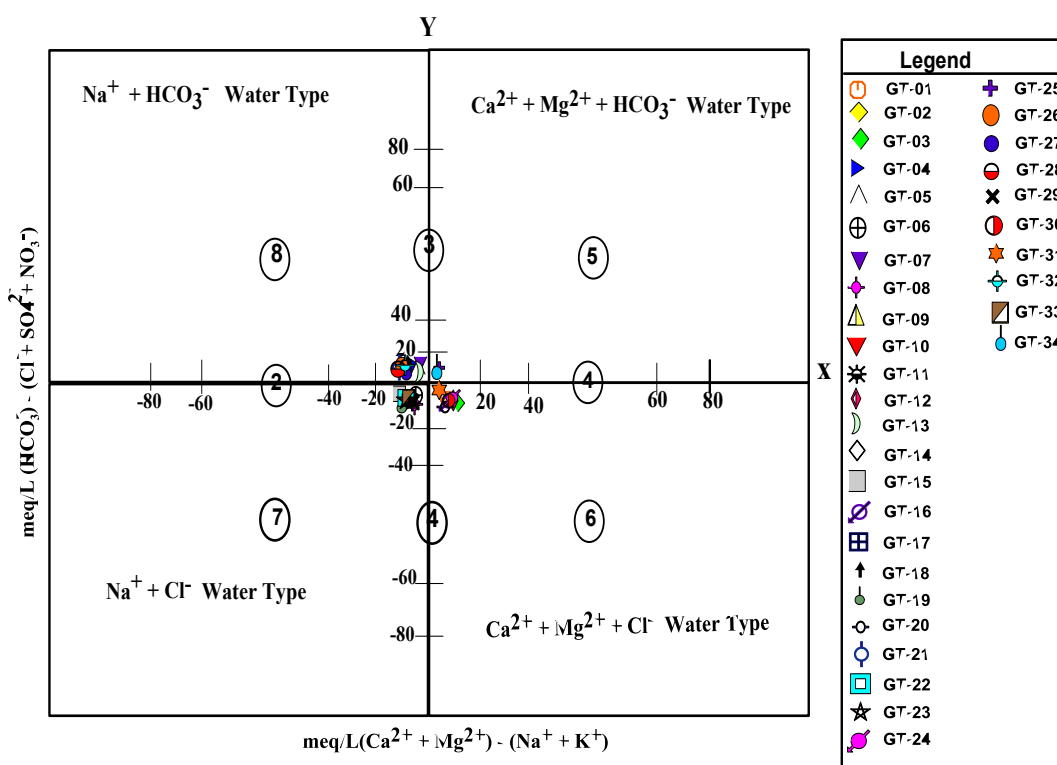

Figure 7. Chadba's diagram showing groundwater type of the study area.
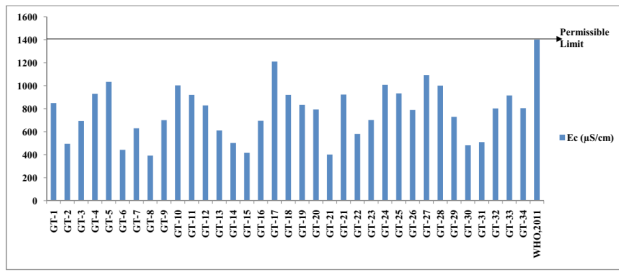
Figure 8. Plots of Ec against WHO, (2011)

pH of water is one of the major factors that provide needed information on groundwater geochemical equilibrium [50]. pH value for this study ranges from 6.2 to 7.5 with the lowest concentration of pH at sample location GT-6 with a value of 6.2.While the highest pH value was observed at sample location GT-10 with value of 7.5 as shown in Figure 9. High concentration of pH in groundwater could be attributed to aquifer configuration and other geological or anthropogenic factors [51]. pH values obtained from the study revealed that groundwater ranges from acidic to basic.
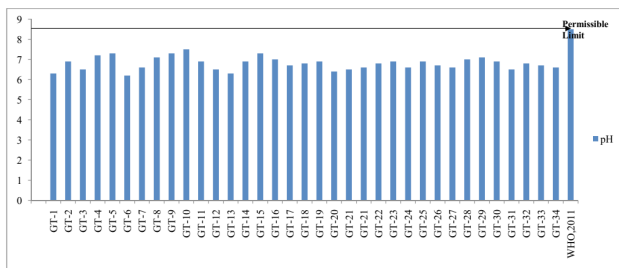
Figure 9. Plots of pH against WHO, (2011)

Total Dissolved Solid (TDS)

TDS measure the overall concentration of all mineral makeup dissolved in water. [52] reported that TDS is linked to water hardness. From Figure 10. It was observed that sample locations GT- 4, 7, 8, 12, 14, 19, 21, 24, 27 and 34 were above the [53] permissible limit. According to [54] the presence of high concentration of TDS in groundwater can be attributed to water waste discharge. Similarly, [55] further reported that high concentration of TDS in groundwater can also be attributed to geological activities, agricultural, human and industrial waste respectively.
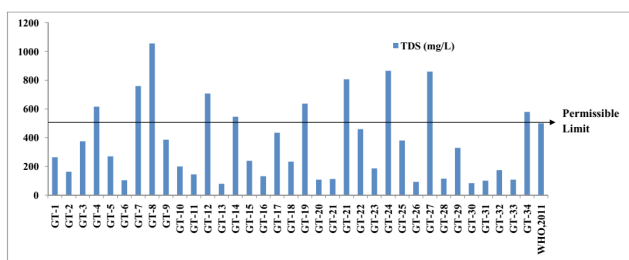

Figure 10. Plots of TDS against WHO, (2011)

5. Conclusions

Since there is a steady increase in demand for groundwater and decline on groundwater quality due to contamination that infiltrate from the surface into subsurface water (groundwater). It is of upmost importance to constantly monitor groundwater from time to time. Hence to an integrated approach was used to assess groundwater vulnerability and a major factor that influence its geochemistry. The use of VES was to determine aquifer vulnerability and groundwater potential, while hydrogeochemical studies were used to evaluate the major factors that influences groundwater chemistry and also characterize groundwater within the study area. Deduction from VES showed that the study area is underlain by four (4) to six (6) lithology. Result obtained from longitudinal conductance suggested that aquifer protective capacity fell within poor to moderate category". That implies that aquifer is considered vulnerable to contamination from the surface. Further findings suggested that VES location 2 showed more prospect of high groundwater potential when compared to other part of the study area." Findings from hydrogeochemical analysis revealed that groundwater is influenced mainly by rock water interaction. It was also observed that groundwater is characterized to be temporary to permanent hard. Findings from pH results showed that groundwater fell within slightly acidic to basic category.

References

[1] Shiklomanov, I. A. (1998). Global renewable water resources. In: Zebedi H (ed) Water: a looming crises? Proceeding of the international Conference on World water Resources at the beginning of the 21st century. Unesco/IHP, Paris, pp 1-25.

[2] Eyankware, M. O.,Aleke, C. G., Selemo, A. O. I., Nnabo, P. N. (2020a). Hydrogeochemical studies and suitability assessment of groundwater quality for irrigation at Warri and environs., Niger delta basin, Nigeria. Groundwater for Sustainable Development. DOI: https://doi.org/10.1016/j.gsd.2019.100293.

[3] Healy, R. W., Winter, T. C., LaBaugh, J. W., Franke, O. L. (2007). Water budgets: foundations for effective water-resources and environmental management. USGS Report, Circular 1308.

[4] Krishnaraj S., Vijayaraghavan, K., Murugesan V., Rajivgandhi, R., Sarma, V. S. (2011). Integrated techniques to identify groundwater vulnerability to pollution in a highly industrialize terrain, Tamilnadu, India.Environ Monit Assess 182:47-60. DOI: 10.1007/s10661-010-1857-x.

[5] De Ketelaere D, Hotzl H, Neukum C, Civita M,

Sappa G (2004). Hazard analysis and mapping. In F. Zwahlen (Ed.), Vulnerability and risk mapping for the protection of carbonate (karst) aquifers. Final report COST Action 620. European Commission, Directorate-General for Research, EUR 20912:86-105.

[6] Olayinka, A. I, Olorunfemi, M. O. (1992). Determination of geoelectric characteristics of Okene area and implication for boreholes siting. J Min Geol 28:403-412.

[7] Oladapo, M. I., Akintorinwa, O. J. (2007). Hydrogeophysical study of Ogbese Southwestern, Nigeria. Global J Pure and Applied Sci 13(1):55-61.

[8] Kai, S., Guangxu, Y., Fei W., Jian, L., Dan, L. (2020). Application of Geophysical and Hydrogeochemical Methods to the Protection of Drinking Groundwater in Karst Regions. International Journal of Environmental Research and Public Health. 17, 3627. DOI: 10.3390/ijerph17103627.

[9] Olorunfemi, M. O., Fasuyi, S. A. (1993). Aquifer types, geoelectric and hydrogeologic characteristics of part of the Central Basement Terrain of Niger State Nigeria. J Afr Earth Sci 16(1):309-317.

[10] Chambers JF, Wilkinson PB, Penn S,Meldrum PI, Kuras O, Loke MH, Gunn DA.(2013).River terrace sand and gravel depositreserve estimation using three-dimensionalelectrical resistivity tomography forbedrock surface detection. J. Appl.Geophy. 2013;93:25-32.

[11] Orlando L.(2013). Some considerations onelectrical resistivity imaging forcharacterization of waterbed sediments. J.Appl. Geophy. 2013;95:77-89.

[12] Eyankware, M.O.,Ogwah, C., Selemo, A. O. I. (2020b). Geoelectrical parameters for the estimation of groundwater potential in fracture aquifer at sub-urban area of Abakaliki, SE Nigeria. International Journal of Earth Science and Geophysics. 6:031, https: // doi: 10.35840/2631-5033/1831.

[13] Ebong, D. E., Anthony, E. A., Anthony, A. O. (2014). Estimation of geohydraulic parameters from fractured shales and sandstone aquifers of Abi (Nigeria) using electrical resistivity and hydrogeologic measurements. Journal of African EarthSciences 96: 99-109.

[14] Eduvie, M. O. (2002). Hydro-geological geophysicalevaluation of groundwater resources of the gundumiformation and around Daura, North Western Nigeria, Water Resources. Journal of Nigeria Associationof Hydro-geologist (NAH) 13: 46-49.

[15] Eyankware, M. O., Selemo, A. O. I., Obasi, P. N., Nweke, O.M. (2020c). Evaluation of groundwater vulnerability in fractured aquifer using geoelectric layer susceptibility index at Oju, Southern Benue Trough Nigeria. Geological Behavior, 4(2): 63-67.

[16] Nwajide, C. S. (2013). Geology of Nigeria"s Sedimentary Basin. CSS Bookshops Ltd Lagos, pp. 56- 98.

[17] Oli, I. C., Ahairakwem, C. A., Opara, A. I., Ekwe, A. C., Osi-Okeke, I., Urom, O. O., Udeh, H. M., Ezennubia, V. C. (2020) Hydrogeophysical assessment and protective capacity of groundwater resources in parts of Ezza and Ikwo areas, southeastern Nigeria. International Journal of Energy and Water Resources. https://doi.org/10.1007/s42108-020-00084-3.

[18] Hasan, M., Shang, Y., Akhter, G., and Jin, W. (2017). Geophysical assessment of groundwater potential: a case study from Mian Channu Area, Pakistan. Groundwater, 56, 783-796.

[19] Uma, K.O. (1989). An appraisal of the ground waterResources of the Imo River Basin. Nigerian Jour. Mining and Geol., 25:305-315.

[20] Batte, A. G., Barifaijo, E., Kiberu, J. M., Kawule, W., Muwanga, A., Owor, M., Kisekulo, J. (2010). Correlation of Geoelectric Data with Aquifer Parameters to Delineate the GroundwaterPotential of Hard rock Terrain in Central Uganda. Pure Appl. Geophys. 167, 1549-1559.DOI 10.1007/s00024-010-0109-x.

[21] Sikandar, P. and Christen, E.W. (2012). Geoelectrical sounding for the estimation of hydraulic conductivity of alluvial aquifers. Water Resources Management, 26, 1201-1215.

[22] Asfahani, J. (2013). Groundwater potential estimation using vertical electrical sounding measurements in the semi-arid Khanasser Valley region, Syria. Hydrological Sci. J. 58 (2), 468-482.

[23] Niwas, S. and Celik, M. (2012). Equation estimation of porosity and hydraulic conductivity of Ruhrtal aquifer in Germany using near surface geophysics. Journal of Applied Geophysics, 84, 77-85.

[24] Villumsen, A., Sonderskov, C. (1982). Vulnerability maps: a promising tool in groundwater protection. Aqua 5:466-468.

[25] Harter T Walker LG (2001) Assessing vulnerability of groundwater.

[26] Eyankware, M. O., Ephraim, B. E. (2021). A comprehensive review of water quality monitoring and assessment in Delta State, Southern Part of Nigeria. Journal of Environmental & Earth Sciences. 3(1); 16-28.

[27] EugeneOkorie, J. O, Obiora DN, Ibuot, JC, Desmond O. Ugbor, D. O. (2020). Geoelectrical investigation of groundwater potential and vulnerability of Oraifte, Anambra State, Nigeria. Applied Water Science, 10:223 https://doi.org/10.1007/s13201-020-01304-1.

[28] Ibuot. J. C., Okeke, F. N., George, N. J., Obiora, D. N.

(2017). Geophysical and physicochemical characterization of organic waste contamination of hydrolithofacies in the coastal dumpsite of Akwa Ibom State, southern Nigeria. Water Sci Technol Water supply 17(6):1626-1637.

[29] Obiora, D. N., Ibuot, J. C., George, N. J. (2016). Evaluation of aquifer potential, geoelectric and hydraulic parameters in Ezza North, Southeastern Nigeria, using geoelectric sounding. Int J Environ Sci Technol. 13:435-444.

[30] Alhassan, D. U., Obiora, D. N., Okeke, F. N. (2015). The assessment of aquifer potentials and aquifer vulnerability of southern Paiko, northcentral Nigeria, using geoelectric method. Global J Pure Appl Sci 21:51-70.

[31] Eyankware, M.O.,Nnajieze, V.S., Aleke, C.G. (2018). Geochemical assessment of water quality for irrigation purpose, in abandoned limestone quarry pit at Nkalagu area, Southern Benue TroughNigeria. Environ Earth Science, https://doi.org/10.1007/s12665-018-7232-x.

[32] Murat, R. C. (1972). Stratigraphy and Paleogeography of the Cretaceous and lower Tertiary in Southern Nigeria. In Proc. of the Conf. on African Geology held at Ibadan, Nigeria. Pp. 251-266.

[33] Banejree L (1980). A Sub-tidal Bar Model for the Eze-Aku Sandstone, Sediment. Geology, 25:291-309.

[34] Amajor, L. C. (1987). The Eze-Aku Sandstone Ridges Turonian of Southeastern Nigeria: A Reinterpretation of their Depositional Origin. Nig. J. of Mining and Geo, 23(1):17-26.

[35] Reyment, R. A. (1965). Aspects of the Geology of Nigeria: The Stratigraphy of the Cretaceous and Cenozoic Deposits. Ibadan University Press.

[36] Zohdy, A. A. R., Eaton, G. P., Mabey, D. R. (1974). Application of surface geophysics to groundwater investigations. Washington: United State Geophysical Survey.

[37] Nwachukwu, S. R., Bello, R., Ayomide, O., Balogun, A. O., 2019.Evaluation of groundwater potentials of Orogun, South-South part of Nigeria using electrical resistivity method.Applied Water Sci. 9:184 https://doi.org/10.1007/s13201-019-1072-z.

[38] APHA (American Public Health Association), (2003), Standard methods for examination of water and wastewater specifications, Washington DC, 6, 19th edition.

[39] Soltan, M. E. (1999). Evaluation of groundwater quality in Dakhla Oasis (Egyptian Western Desert). Eviron Monit Assess 57:157-168.

[40] Gibbs, R. J (1970) Mechanisms controlling world water chemistry. Science, v.170, pp.1088-1090.

[41] Chadha, D. K. (1999). A proposed new diagram for geochemical classification of natural waters and interpretation of chemical data. Hydrogeol J 7:431-439.

[42] Aweto, K. E. (2012).Resistivity methods in hydro-geophysical investigation for groundwater in Aghalokpe, Western Niger Delta.Global Journal of Geological Science.11; 47-55.

[43] Ryan, Michael P., Pierce, Herbert A., Johnson, Carole D., Sutphin, David M., Daniels, David L., Smoot, Joseph P., Costain, John K., Çoruh, Cahit, and Harlow, George E. (2007). Reconnaissance borehole geophysical, geological and hydrological data from the proposed hydrodynamic compartments of the Culpeper Basin in Loudoun, Prince William, Culpeper, Orange and Fairfax Counties, Virginia. [Version 1.0]: U.S. Geological Survey Open File Report 2006-1203,3-42.

[44] Yungul, S. H., (1996). Electrical methods in geophysical explorationof sedimentary basin. Chapman and Hill, U.

[45] Olusegun OA, Adeolu OO, Dolapo FA (2016) Geophysical investigation for groundwater potential and aquifer protective capacity around Osun State University (UNIOSUN) College of Health Sciences. Am. J. Water Resour. 4(6):137-143. http://article.journalofwaterresources.com/pdf/ajwr-4-6-3.pdf

[46] Ojo, A. O., Oyelami, C. A., Adereti, A.O. (2014). Hydro-geochemical and geophysical Study of Groundwater in the Suburb of Osogbo, South Western Nigeria. J Earth Sci Clim Change 5: 205. DOI: 10.4172/2157-7617.1000205.

[47] Eyankware, M.O., Nnabo, P.N., Ogwah, C. (2020d). Impact of past mining activity on water resources around active and abandoned mines in Ebonyi State, South-Eastern Nigeria- A mini review. Hydro Science and Marine Engineering, 2(2): 29-35.

[48] Eyankware, M.O., Selemo, A.O.I., Ogwah, C. (2019a). Use of modelling approach in evaluation of fractured shale aquifers for irrigation purpose; a case study of Oju, Lower Benue Trough Nigeria. Pakistan Journal of Geology. 3(1): 1-12.

[49] Adimalla N., Venkatayogi, S. (2018). Geochemical characterization and evaluation of groundwater suitability for domestic and agricultural utility in semi-arid region of Basara, Telangna State,South India. Appl Water Sci 8:44. https://doi.org/10.1007/s13201-018-0682-1.

[50] Hem, J. D. (1985). Study and interpretation of the chemical characteristics of natural water, 2nd edn. US Geol Surv Water Supply Paper, 2254:363.

[51] Prashant K., Prarabdh T., ArkoprovoB., Tapas, A. (2020). Geophysical and hydrogeological investi-

gationfor the saline water invasion in the coastal aquifers of WestBengal, India: a critical insight in the coastal salineclay-sand sediment system. Environ Monit Assess, 192:562 https://doi.org/10.1007/s10661-020-08520-x.

[52] Eyankware, M. O., Omo-Irabor, O. O. (2019b). An Integrated Approach To Groundwater Quality Assessment In Determining Factors That Influence TheGeochemistry And Origin Of Sandstone Aquifers Southern Niger Delta Region Of Nigeria. Malaysian Journal of Geosciences, 3(2): 23-32.

[53] WHO (World Health Organization). (2011). Guideline for drinking water quality Recommendations, 4th Edition. Vol 1. Pp219-230.

[54] FEPA (1991). Federal Environmental Protection Agency Guideline and Standard for Environmental Pollution Control in Nigeria. pp. 25 -26.

[55] Appelo, C.A.J., Postma, D. (2005). Geochemistry, groundwater and pollution (Amsterdam: CRC Oress, Taylor & Francis Group).