

Research Article

Application of VES and Physicochemical Analysis for the Evaluation of Dissolved Minerals in the Alluvial Aquifers of Part of Yenagoa, Bayelsa State

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Abstract

The sufficient provision and sustenance of quality water have been of a fundamental consequence in the social and economic developmental activities of humans over the years, especially in Bayelsa state and Nigeria at large, where developmental activities are on the increase. Potable water is essential to humans and animals alike, for personal, communal, industrial and societal uses. This study seeks to investigate the concentration of dissolved minerals, using an integrated approach of VES data and physicochemical analysis of ground water samples in parts of Bayelsa state, south-south Nigeria. Vertical Electrical Sounding was implemented in ten stations and interpreted using IPI2WIN software. The results from the VES interpretation revealed that the area is constituted of four to five geoelectric layers. Four distinct sounding curve types (H, HK, K and KH) were identified; with the H and K type curves being dominant. The dominant curve types show that the area has two main hydrologic regimes (of low and high Iron (Fe) concentration). The results show that in VES stations with K-type curve, the stratigraphy consists of the three to four layers, with varying thickness and corresponding resistivities; with the third or fourth layers identified as the aquifer layer. At H-type curve locations, the stratigraphy consists of the top soil, the clay layer, and the sand layer, which was identified as the aquifer. The physicochemical characteristics of water samples, collected from drilled boreholes in the vicinity of the VES locations of the study area, were analyzed for prominent physical and chemical constituents, including EC, pH, TDS, Na, K, Ca, Mg, Fe, Cl, SO, NO, and HCO. Physicochemical analysis was achieved using the standard APHA methods and compared with WHO standard. The results showed that the concentration of the chemical constituents varied spatially in the study area. The analysis revealed that 90% of the mean concentration of measured parameters were within the WHO's standard in all the samples, except for Mn (with a value of 0.532 mg/L) and Fe²⁺ (with a value of 0.88 mg/L) which was seen to be high in five of the boreholes in locations with H-type curves, hence correlating areas of high groundwater contamination to VES stations of the H-Curve type. The high Mn and Fe concentrations in the groundwater of some of the locations, makes the water unsuitable for drinking and may require treatment. Further analysis of the ground water samples, indicated that, Chloride and Sulphate are the predominant anions while, Calcium and Magnesium are the predominant cations in groundwater within the study area.

Keywords

Vertical Electrical Sounding (VES), Hydrochemical, Crystallization, Lithologic, Groundwater and Geoelectric

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1. Introduction

The sufficient provision and sustenance of quality water have been of a fundamental consequence in the social and economic developmental activities of humans over the years, especially in Bayelsa state and Nigeria at large. Potable water is essential to humans and animals alike, for personal and communal or societal uses. The largest known source of available freshwater lies beneath the surface of the ground. Proper understanding of the occurrence, extraction, and development of these water resources may be man's best bet to solving most global water issues. Around the world, water occurs in many forms such as ice caps, glaciers, ocean water, surface water, and groundwater. The continual development of groundwater resources and its extraction has been necessitated by the increase in the demand for water by humans for several purposes [1]. This is quite true of most Sub-Saharan countries, such as Nigeria where water resources are extremely limited and highly valued as a social and economic good. It is important to note that available freshwater for human consumption has become limited, the key propellant factor being the population growth of the Nigeria populace, and with this exponential growth in population comes a dramatic rise in demand for high-quality drinking water. The depletion of available freshwater resources in many parts of the World, has been documented, and for the developing countries, withdrawals are predicted to increase by 50 percent by the year 2025, while for the developed countries it is 18 percent [2]. This is mainly because an adequate supply of water is required in nearly all industrial activities and, this situation is inadvertently likely to hinder and obstruct socio-economic developments, and increase pressures on the demand for freshwater.

The relatively abundant occurrence of potable ground water is a major reason for its use as a source of water supply worldwide [3]. Available water resources continue to be depleted due to the excessive withdrawal of both surface and groundwater; this invariably will ultimately bring about water shortages which is one of the most important global problems. This of course will in turn escalate matters related to food security, international diplomacy, poverty alleviation, public health, energy production, and ecosystem protection [4, 5].

In Bayelsa State, portable water delivery is still very much insufficient, despite the many private boreholes sunk, as the main source of water for drinking and domestic usage. This is most certainly due to the heavy presence of Iron and manganese in the water [6, 7]. The investigation of groundwater potential and its pollution in Yenagoa metropolis is one way of understanding and preventing the water resource problem facing the people of the area. The overburdened issue of water

contamination due to geogenic and anthropogenic factors in the region has raised concern amongst researchers, over the years, causing for the extensive study of the region in a bid to improve the understanding of the geologic and geophysical regimes of the region.

The detection of high concentration of dissolved minerals and other contaminants, in aquifers area via Physicochemical and laboratory assessment of several water sources have raised health concerns, which has become increasingly endangering to the inhabitants of the communities.

This study, therefore, focuses on the need for accurate characterization of the subsurface for a better understanding of the groundwater architecture and how it is affected by the Iron concentration of the area to aid in the planning and development of boreholes and wells in the area.

The study will serve as a useful tool for water resource management authorities in making decisions regarding the development of the field, it shall further enhance the hydro-geologic data bank of the study area, and aid hydrogeologists in precisely identify lateral lithological variations arising from the presence of high Iron concentration in the subsurface.

1.1. The Study Area

The study area is within Yenagoa Local Government Area, which lies in the freshwater geomorphic zone in Bayelsa state; it is located between latitude 4.888235" and longitude 6.248924" to 6.336973 E" (Figure 1), [8].

1.2. Geostratigraphy of the Study Area

The geology of the area is underlain by the Coastal Plain sands, which in this area is overlain by soft-firm silty clay sediments belonging to the Pleistocene Formation [9]. According to, the Niger delta region essentially illustrates the influence of river movements from several distances inland as it drives towards the oceans [10]. The Niger Delta has three distinct lithological formation, the Akata formation, Agbada formation and the Benin formation. The Akata formation, at the basin's base, consist of Marine shale deposit, it is followed unevenly by the Agbada formation which consists of alternate Layers of Sandstone and Shale. The more recent Benin formation at the top of the basin consist of Late Eocene to recent deposits of alluvial and upper coastal plain deposits that are up to 2000 m thick, made up of unconsolidated sands with thin clay and lignite interbeds. This formation is identified as the major aquiferous formation in the Niger Delta region [10-13].

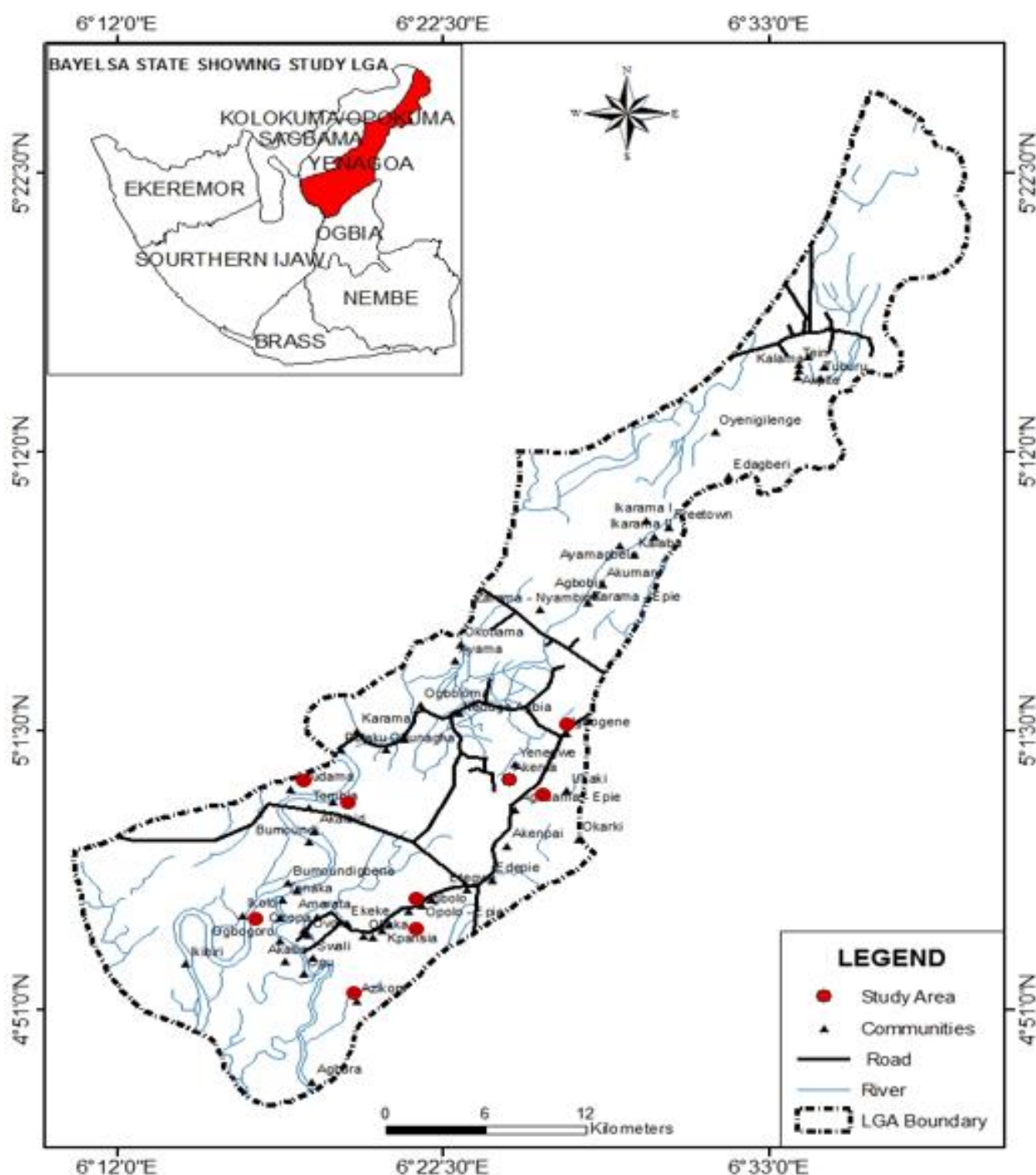


Figure 1. Map of Yenagoa LGA showing the study locations (Insert: Yenagoa in map of Bayelsa state). (modified from [8]).

1.3. Hydrogeology of the Area

Groundwater is abstracted mainly from the upper section (<300 m) of this formation. The aquifer at shallow depth (>10 m) are unconfined while the deeper aquifers are confined and isolated from the ground surface contaminant infiltration.

The study area, experiences rainfall for almost 9 months of the year, which varies from about 3500 to 2000 mm per annum, while the average specific yield of the aquifer in these

areas is estimated to be, 10,500 liter/hr/m [14]. It has been reported that transmissivity values range, from 1634.0 m²/day to 5292.0 m²/day within most parts of Yenagoa [15]. These values are typical of an unconsolidated fine-medium-coarse sand.

Water availability is directly influenced by the sources of water within an environment. Many regions of the world have varying water sources unique to such an ecosystem. The hydrologic cycle is the principle driving force behind the distribution of water on earth. However, certain factors also play

vital roles in the availability of water in an environment. These factors include climate, weather, vegetation, temperature, geologic compositions.

Climate plays a vital role in the distribution of water resources on earth, in Nigeria for instance; the climate varies from tropical in the south to semi-arid in the north [16]. This variation has been of many effects on water resources in Nigeria which are quite vast and unevenly distributed among the various hydrological areas. Recent hydrological data shows that the various regions have varying levels of precipitation in the year. The tropical rainforest regions and the Niger Delta region are said to have the highest level of precipitation of about 3000 mm/year and lengthier duration of rainfall (about six to eight months). The Savannah zone comes next with 1000 mm-1250 mm/year rainfall, and the amount of rainfall decreasing northwards. The Sahel zone has an annual precipitation of less than 750 mm/year and may drop as low as 500 mm/year in the northeastern region occasionally [16].

2. Background Theory

Surface geophysical methods have proved to be of efficient utility in regard to spatial coverage, the Electrical resistivity technique more especially, is regarded as the most efficient geophysical method for aquifer detection [17].

In and around the study area several studies have been carried out in an attempt to finding solutions to the challenges posed by shortage of potable water as well as ground water potential development. These attempts include using electrical/resistivity geophysical techniques to explore for ground water potential [18-25]. Amadi et al., and Okiongbo and Douglas investigated the hydrogeochemistry of aquifers in the study area; their study showed that dissolved iron (Fe), in groundwater had an average concentration greater than the acceptable limit provided for in the WHO standard of [18, 24, 26].

2.1. Ferrogeneous Minerals

Dissolved Iron in groundwater is usually in the reduced form of, Iron II. In this form it is soluble and usually harmless for consumption. However, when oxidation of Iron II takes place, due to its exposure to air, it forms Iron III (Fe^{3+}) ion and precipitate a rust-colored ferric hydroxide [27]. This process can also occur by the action of Iron related bacteria. Iron III forms insoluble hydroxides in water and if the Iron hydroxide deposits are produced by Iron bacteria, then they are also sticky and the problems of stain and blockage are many times worse [28]. If ferric or ferrous Iron is present in water, it develops colour, taste and Odour, which can be evidently noticed. Iron in water stains laundry, drink ware, dishes, toilets, tubs, sinks, and fixtures by leaving yellow, red, and brown spots, it reduces water flow from the borehole, blocking most pipes. Water, beverages, and food acquire a metallic taste or smell, which ruins the experience [29].

The effects can be felt through repair and replacement costs of pumps, pipes, appliances, fixtures, and sprinklers. Although the body needs Iron for certain biological processes, such as transporting oxygen in your blood, excessive intake of Iron (Fe) water leading to Iron levels being too high could damage your internal organs like the heart, pancreas, and liver causing them to fail. This is known as Iron poisoning [30].

The Niger River carries Iron loadings from the deposits of the Itakpe Iron Ore, through the processes of dispersion, advection, and inter-aquifer exchange, and then conveys the pollutants to the groundwater aquifer [31]. He also noted that the Iron concentration level in groundwater in some cities within Bayelsa State, are peculiar with most cities situated along the Niger River and its tributaries having Iron concentration values in groundwater between 1.5 mg/l and 5 mg/l.

2.2. Electrical Methods in Geophysical Studies

Electrical methods of Geophysics find wide applications in various fields including, aquifer characterization, groundwater location (water supply, drainage problems) prevention of groundwater contamination and salinity evaluation in groundwater. In characterizing and locating geological structures in near surface lithologies (pore space, faults, composition, fissures, share zones, lithologic variation), in the distinguishing and mapping of boundaries between layers having different conductivities. Furthermore, it's relevance in landfill characterization, determination of composite margins of pre-existing buried waste dumps, soil contaminant plum, tracing leachate movement and Archeological investigations, has been fully established.

In this study, the Vertical electrical Sounding technique has been employed, using the Abem Terameter SAS 1000, with it's accessories (Figure 5).

Theory of Electrical Resistivity Survey

(i). Ohm's Law and Earth Resistivity

In Ohmic materials (which earth materials are) the resistance of the conducting object is found to be directly proportional to the length, L of the object and inversely proportional to its cross-sectional area A. The constant of proportionality, in this case, is called the resistivity of the conductor [32].

The resistivity of an object is mathematically expressed as;

$$R = \rho \left(\frac{L}{A} \right) = \left(\frac{V}{I} \right) \quad (1)$$

Where, the constant 'ρ' (Rho) is the resistivity which is an intrinsic property of the material; it can then be expressed as;

$$\rho = R \left(\frac{L}{A} \right) = \left(\frac{V}{I} \right) \quad (2)$$

Equations (1) and (2) are the famous Ohm's law, which can also be given as;

$$J = \sigma E \quad (3)$$

Where J is the current density and σ , the conductivity.

(ii). Current Flow in a Homogenous Medium

As current (I) flows into the ground at fixed point C_1 it flows in a radial form from the entry point and is uniformly distributed over the hemispherical surface. The potential at a point (P) with a distance R , from the source is then given as;

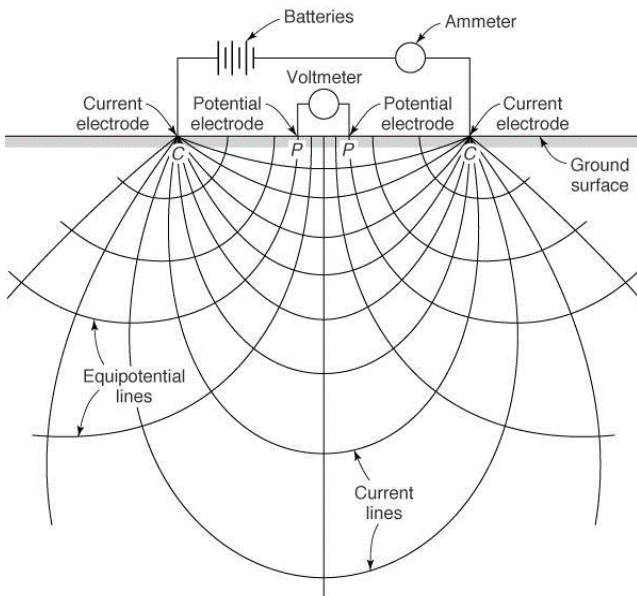


Figure 2. Electrical resistivity Current Paths into the Subsurface (after [33]).

$$V = \frac{I\rho}{2\pi R} \quad (4)$$

And

$$V_p = \left(\frac{I\rho}{2\pi}\right) \left(\frac{1}{R}\right) \quad (5)$$

(iii). Factors Affecting Resistivity of Geologic Materials

The resistivity of the subsurface depends upon, the presence of certain metallic ores and buried pipes, the temperature of the subsurface, amount of clay and other minerals, lithology of the formation, Porosity and permeability of the rock, the presence of archeological features - Graves, fire pits, post holes, amount of groundwater present, number of dissolved salts, Presence of contaminant plumes [34].

The electrical resistivity varies between different geological materials and depends mainly on variation in water contents and dissolved ion in the water (Table 2). Resistivity can thus be used to identify geologic zones with different electrical properties, which can then be referred to as different

geological strata. Resistivity is also called specific resistance which is the inverse of conductivity or specific conductance.

3. Materials and Methods

3.1. Site Selection

The study area is within Yenagoa local government area of Bayelsa state (Figure 3). Bayelsa State has been characterized to have two hydrological regimes as reported by [35]. These two regimes were identified to have low Iron (Fe) concentrations in one and higher Iron (Fe) concentrations in the other regime [36].

3.2. VES Instrumentation

The typical VES equipment used in the study is shown in the Figure 5. The Software employed in the study are Microsoft Excel, IPI2WIN (2000) and interperx IX1D Resistivity software, Surfer 15 and Rockworks 17 suite.

Table 1. Earth Materials and Their Respective Resistivity Ranges from [37].

Material	Resistivity Range
Granite	$5 \times 10^3 - 10^6$
Basalt	$10^3 - 10^6$
Slate	$6 \times 10^2 - 4 \times 10^7$
Marble	$10^2 - 2.5 \times 10^8$
Quartz	$3 \times 10^2 - 10^6$
Granite	$3 \times 10^2 - 10^6$
Granite (weathered)	30 – 500
Consolidated shale	$20 - 2 \times 10^3$
Sandstones	200 – 5000
Sandstone (weathered)	50 – 200
Clays	$1 - 10^2$
Limestone	$50 - 4 \times 10^2$
Aluminum	10 – 800
Groundwater (fresh)	10 – 100
Sea water	0.2

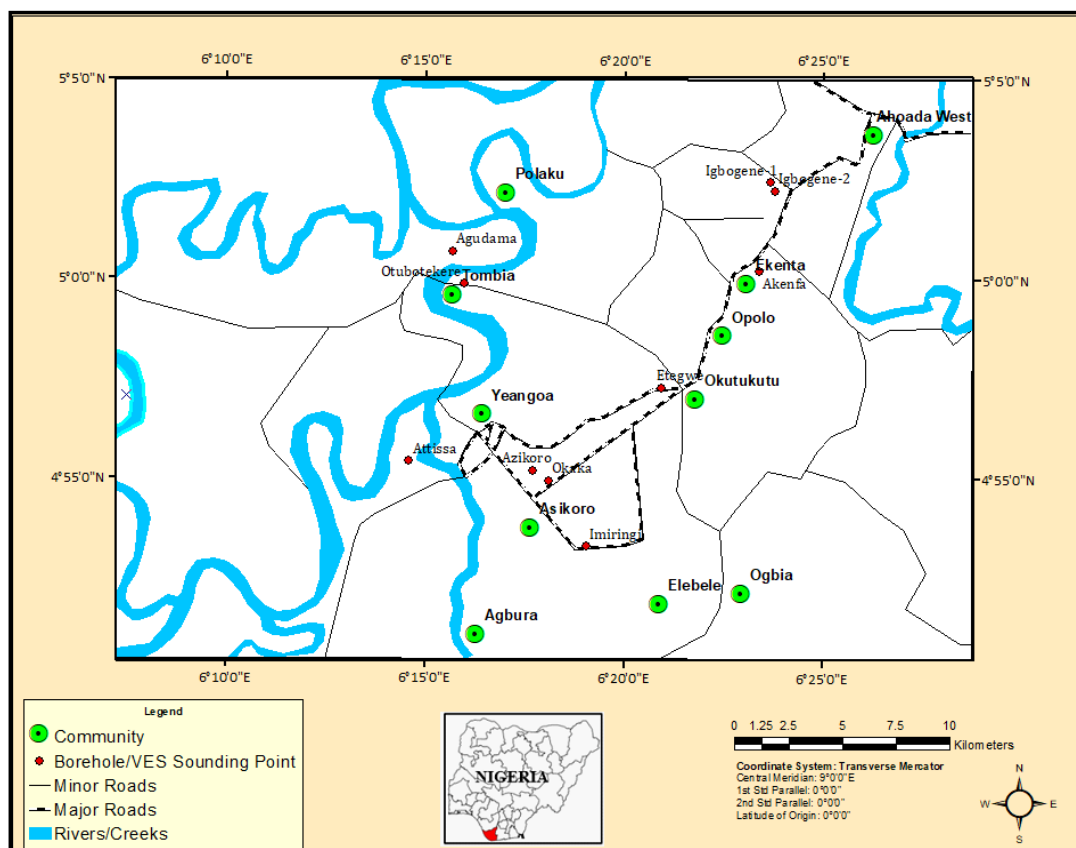


Figure 3. Map of Study Area (inset Nigeria).

3.3. The Workflow

The workflow utilized during this study is presented in Figure 4 showing the steps and methods utilized for the overall success of this research.

WORKFLOW

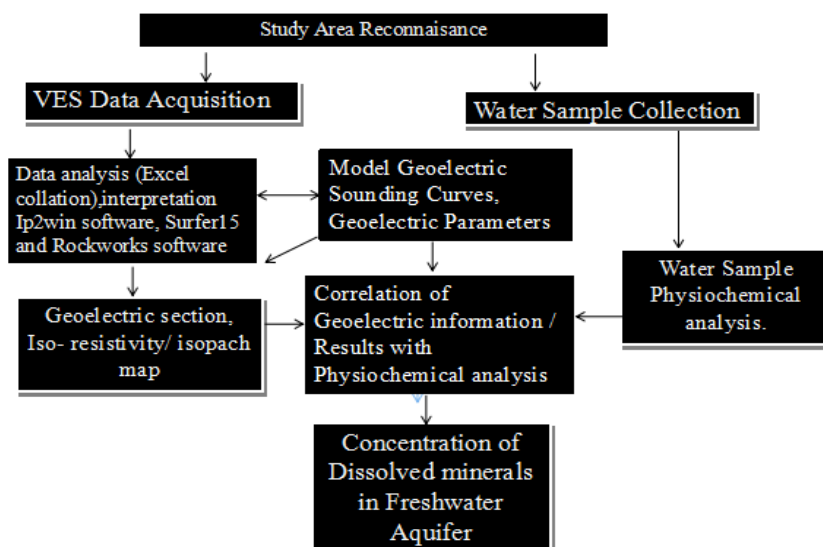


Figure 4. Workflow utilized in executing the study.

3.4. Sampling Procedure

The sampling method adopted was the Grab sampling method [38]. This method involves the collection of water samples at specific borehole locations representing conditions at only the time of sampling. At each sample point, the water samples were collected in thoroughly rinsed 100 ml sterilized polyethylene bottles. The water was allowed to run continuously for approximately 5 minutes to ensure that the piping was free of external contaminants before the actual samples

were collected. The samples were collected for analysis of physicochemical parameters and estimation of the concentration of heavy metals. The water samples were enhanced by adding few drops of diluted hydrochloric acid to stabilize them after extraction. To preserve the integrity of the collected water samples, real-time groundwater parameters such as total dissolved solids, pH and electrical conductivity were analysed in-situ. The sampling bottles were thereafter labelled accordingly and stored in a cooler before being transported to the laboratory for analysis.



Figure 5. Abem Terrameter and accessories (Abem Terrameter (SAS 1000), Garmin etrex GPS) used in the study.

3.5. Physicochemical Analysis of Groundwater Quality

Physicochemical analysis of groundwater quality entails the analytic measurement of various physical and chemical properties in an aquiferous system. These analytic measurements are made by devising and geometrically analyzing composite properties of the aquiferous system thereby providing an in-depth description of its physicochemical characteristics. Physicochemical analysis is an important method of studying systems made up of two or more components, such as natural alloys, carbides, oxides, minerals

solutions. Table 2 below shows some physicochemical parameters and their respective standard limits of [26].

Groundwater samples were collected from ten existing boreholes within the vicinity of geophysical survey stations. The samples were analyzed for pH, Electrical Conductivity (EC), Turbidity, Total Dissolved Solids (TDS), and some major ions such as Nitrate (NO_3^-), Chloride (Cl^-), Bicarbonate (HCO_3^-), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Sodium (Na^+), Potassium (K^+), Iron (Fe^{2+}) Sulphate (SO_4^{2-}) and Manganese (Mn). These boreholes had pre-existing sediment (lithologic) information which was used in the study. The sampling points (designated as BH 1- BH 10) were georeferenced using the Gamin Etrex Global Positioning System (GPS).

4. Results

The results obtained the VES, physicochemical analysis of samples and the groundwater classification, as well as the hydro chemical favors, in this study are presented here as follows,

4.1. Vertical Electrical Sounding (VES)

Ten locations were investigated using the Vertical Electrical Sounding (VES) technique. The obtained field data were interpreted and the results were used to generate geophysical models which further revealed varying VES curve types. The typical curve types identified (Figures 6 – 9) have been categorized into four groups, they are; H, HK, K and KH respectively. These curves suggest that the area is mostly underlain by four geoelectric layers of varying lithologies. There are also minor isolated cases of five geoelectric layers. The summary of the interpreted VES data is shown in Table 2.

4.1.1. VES Results of H and HK- type Curves

A representative VES interpretation of the H - curve type and HK-cure types, correlated with their borehole lithologic information, is presented in Figures 8 and 9 respectively. Table 2 shows the summary of the modelled VES parameters of locations with H and HK - curve types in the study area. The correlation between VES results and lithologic information at locations having H curve types (VES 1, 2, 3 and 4) are shown in Figures 6-9. The figures show that the stratigraphic sequence are of four to five geoelectric layers at an approximate investigation depth of ~ 0 – 50 m. The observed

resistivity values are correspondent to a typical H type curve as it shows that the resistivity of the top layer is greater than the successive second layer. This second layer identified as the clayey has a thickness range of 2.06 to 16.56 m and resistivity value of 33 to 81.94 Ωm . The resistivity value increases after this depth; this indicates the presence of aggregate materials such as fine medium sand and gravel. The third layers at VES 3 and 4, and fourth layers at VES 1 and 2 are identified as the aquifer since potential sand and gravel deposits show higher resistivity ranges showing a contrast with the surrounding clay and silt layers; the layers have their resistivity values ranging from 557.1 to 10328 Ωm and thickness of 8.85 to 14.78 m. The fourth layer at VES 3 is interpreted as a highly mineralized layer as the resistivity decreases sharply which is consistent with clay and Iron sand lenses. this layer has an undefined thickness and a resistivity of 4.66 Ωm . At VES 5 (Table 2), the observed HK – curve type reveals four layers with the top layer having a resistivity of 11.98 and thickness of 2.71 m, this layer is followed by a thick clay layer 5.94 m thick which shows a lower resistivity 8.411 Ωm than the successive fine medium sand (third layer) that constitutes the groundwater aquifer. The third layer has a thickness of 8.18 m and layer resistivity of 7296 Ωm . The lithological information across most of the identified H curve type locations are slightly different but they all show that the top soil is composed of calcareous loam mixed with organic matter. The second (near surface) layer is composed of mostly wet clay and silt; thus, this layer acts as a low permeable media over much of the aquifer within the study area. this sequence in turn stimulates Iron (Fe) mobilization into the aquifer, this is in agreement with [36, 21].

Table 2. A summary of the modelled VES parameters for all ten locations.

VES NO.	Location Name	Coordinate		Layer thickness				Resistivity					Error (%)	Curve type
		Northing	Easting	h_1	h_2	h_3	h_4	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5		
1	Agudama 1	5.01160N	6.26147E	1.11	16.56	14.78		246.2	81.94	114	557.1		1.68	H
2	Tubotekere	4.998020N	6.26635E	1.18	5.27	50.4		26	9.46	39.9	10328		4.33	H
3	Igbogene 1	5.040556N	6.394447E	0.6	2.06	8.85	12.5	42.3	33	93.4	595	1.63	2.68	H
4	Imiringi	4.887940N	6.317710E	0.918	5.21	9.19		67.2	54	983	4.66		3.34	H
5	Etegwe 1	4.9544695N	6.3488104E	2.71	5.935	8.177		11.98	8.411	7296	25.87		1.74	HK
6	Akenfa	5.003329N	6.390010E	0.86	1.32	2.75	12.7	10.4	30.3	3.62	11229	50.1	3.43	K
7	Okaka	4.915403N	6.301742E	0.1727	2.42	4.227		53.13	126.9	28.19	1731		1.5	K
8	Igbogene 2	5.03706N	6.396405E	0.325	0.419	1.35	5.38	10	34.3	8.09	1546	1.93	2.46	KH
9	Azikoro	4.919723N	6.295005E	0.6	0.654	1.37	9.07	13.7	29.5	7.99	51.6	78.2	2.54	KH
10	Attissa	4.923485N	6.243125E	0.6	2.709	36.79		29.31	770.9	97.52	146.1		0.866	KH

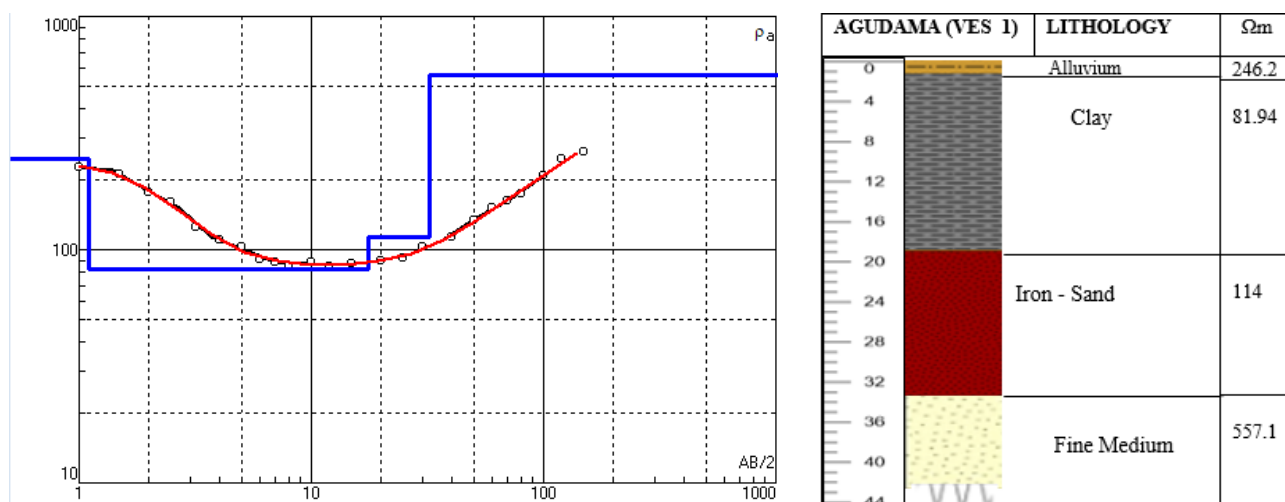


Figure 6. VES 1 curve correlated with nearby borehole data.

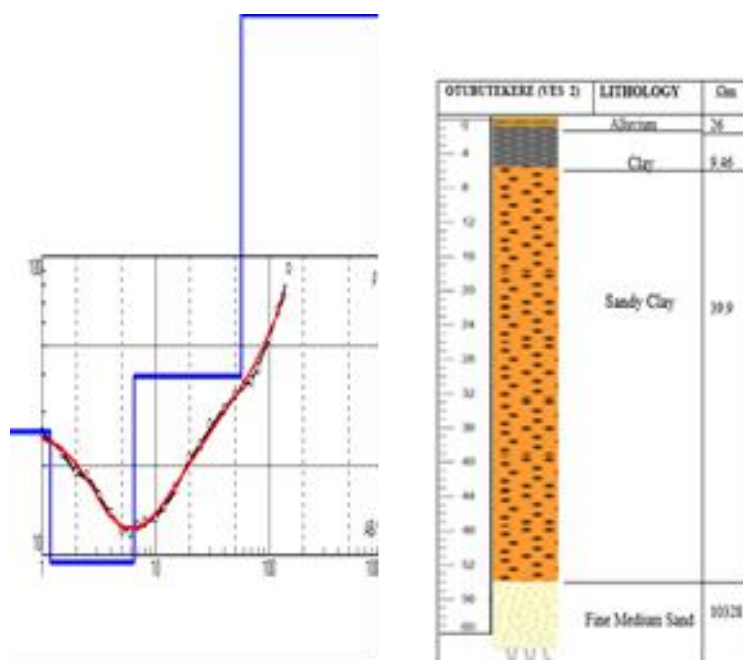


Figure 7. VES 2 correlated with nearby borehole data.

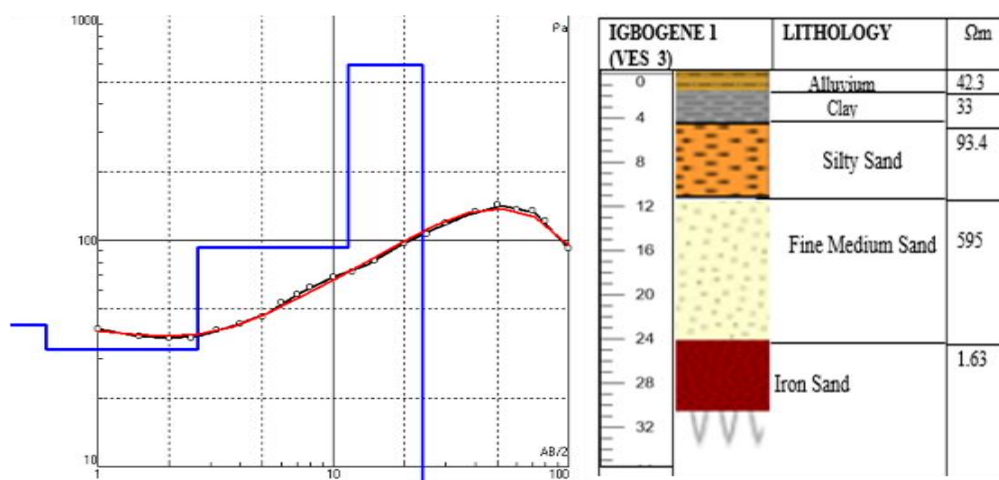


Figure 8. Modelled VES 3 (Igbogene 1) correlated with nearby borehole lithology data.

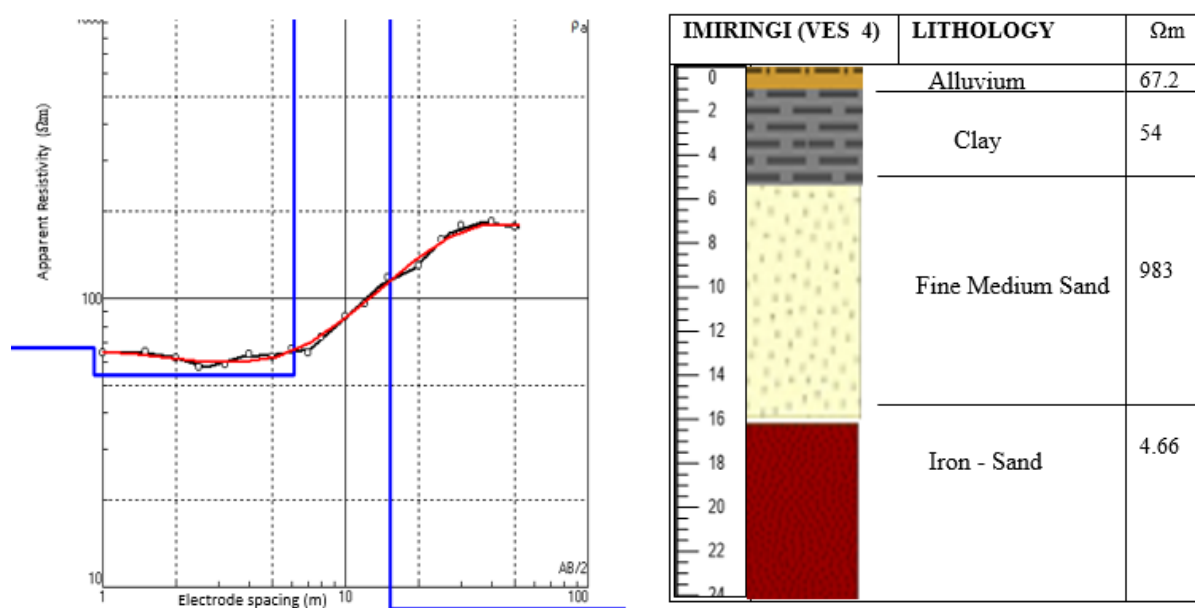


Figure 9. VES 4 curve correlated with nearby borehole data.

Table 3. A summary of the modelled VES parameters locations with H and HK Curve types.

VES NO.	Location Name	Coordinate		Layer thickness				Resistivity					Error (%)	Curve type
		Northing	Easting	h_1	h_2	h_3	h_4	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5		
1	Agudama 1	5.01160N	6.26147E	1.11	16.56	14.78		246.2	81.94	114	557.1		1.68	H
2	Tubotekere	4.998020N	6.26635E	1.18	5.27	50.4		26	9.46	39.9	10328		4.33	H
3	Igbogene 1	5.040556N	6.394447E	0.6	2.06	8.85	12.5	42.3	33	93.4	595	1.63	2.68	H
4	Imiringi	4.887940N	6.317710E	0.918	5.21	9.19		67.2	54	983	4.66		3.34	H
5	Etegwe 1	4.9544695N	6.3488104E	2.71	5.935	8.177		11.98	8.411	7296	25.87		1.74	HK

Table 4. A summary of the modelled parameters for VES locations with K and KH Curve types.

VES NO.	Location Name	Coordinate		Layer thickness				Resistivity					Error (%)	Curve type
		Northing	Easting	h_1	h_2	h_3	h_4	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5		
6	Akenfa	5.003329N	6.390010E	0.86	1.32	2.75	12.7	10.4	30.3	3.62	11229	50.1	3.43	K
7	Okaka	4.915403N	6.301742E	0.1727	2.42	4.227		53.13	126.9	28.19	1731		1.5	K
8	Igbogene 2	5.03706N	6.396405E	0.325	0.419	1.35	5.38	10	34.3	8.09	1546	1.93	2.46	KH
9	Azikoro	4.919723N	6.295005E	0.6	0.654	1.37	9.07	13.7	29.5	7.99	51.6	78.2	2.54	KH
10	Attissa	4.923485N	6.243125E	0.6	2.709	36.79		29.31	770.9	97.52	146.1		0.866	KH

4.1.2. VES with K and KH - type Curves

The summary of the VES modelled parameters with K and KH Curve types is shown in Table 4. Correlation of the in-

terpreted VES results with lithologic borehole information from the boreholes in the vicinity of locations with K and KH curve types (VES 6 to VES 10; shows that the stratigraphic sequence is composed of 4 - 5 geoelectric layers, at an ap-

proximate investigation depth of 0 – 40 m. The resistivity values observed show that the resistivity of the top layer is less than the successive second layer. The top layer has a resistivity range of 10 to 53.13 Ωm and a shallow thickness of 0.3 to 0.86 m. The second layer at VES 8 and 9, identified as the clayey layer, has a thickness range of 0.419 to 0.654 m and resistivity values ranging between 34.3 and 29.5 Ωm respectively. At VES 7 and 10, the resistivity value increases suggesting the presence of a sandy layer [36]. The layer has resistivity values of 126.9 and 770.9 Ωm and thickness of 2.079 and 2.42 m respectively. The third layers have lower resistivity signatures of suggesting clay and sandy clay lenses. The layer thickness ranged from 1.35 to 36.79 m. The fourth layers are identified as the aquifer as they exhibit higher resistivity ranges in contrast with the surrounding clay and sandy clay layers, the layers have their resistivity values ranging from 557.1 to 10328 Ωm .

The stratigraphic sections (Figures 6 - 9) show that most of the aquifers in H and HK curve type areas, have an overlying clay layer; which suggests that the Iron found in groundwater maybe influenced by certain geologic factors such as lithology and the dissolution of certain aquifer materials; as also suggested in [36, 39]

4.2. Physicochemical Analysis

4.2.1. Total Dissolved Solids and Electrical Conductivity

The electrical conductivity of the samples varied from, 338 – 2820 $\mu\text{S}/\text{cm}$, with an average of 900.4 $\mu\text{S}/\text{cm}$; nine out of the ten sampled boreholes had Electric Conductivity (EC) values within the regulatory guidelines of 1000 $\mu\text{S}/\text{cm}$, with only BH10 exceeding the WHO benchmark. Frohlich and

Urish, characterized EC as a measure of salinity, which greatly affects the taste and potability of water [40].

The values of Total Dissolved Solids (TDS) as shown in Table 5, ranged from 0.32 mg/L to 830 mg/L with a mean value of 155.5 mg/L with BH 1 – 9 having values below the stipulated limit, only BH 10 exceeded the [26] recommended standard of 500 mg/L. Generally, the EC and TDS concentrations were within the regulatory guidelines in 90% of the boreholes except BH 10 which showed elevated concentration values of both EC and TDS; this may be due to leachate infiltration into the aquiferous regions, as also suggested by Singhal and Gupta, hence the water samples may need further treatment before being considered as potable for consumption [41].

The concentration of Iron (Fe) in the groundwater samples in this study were significantly higher than the WHO recommended values; the obtained values ranging from 0.01 to 4.5 mg/L, with a mean of 0.88 mg/L. The water samples on being abstracted from the boreholes, were seen to be very clear, however, on being exposed to the atmosphere, soon became cloudy and later turning brown, due to precipitation of ferric hydroxide.

The physicochemical results of Fe concentration when correlated with the geophysical study showed that, Iron (Fe) concentration ranging from 0.01 to 0.26 Mg/L which are within permissible limit, align with VES locations with K and KH curve types (e.g VES 6 to 10) where the resistivity values range from 3.62 – 11229 Ωm ; again, Iron (Fe) concentrations in the water samples of boreholes BH1 – BH5, ranged from 0.42 – 4.5 mg/l, which are beyond the WHO standard, correlated well to the five VES stations with H and HK curve types (VES1 - VES5), with their resistivity ranging from 1.63 – 10328 Ωm .

Table 5. Statistics of Analyzed Groundwater Samples Compared with WHO Limit.

Parameter	Range of Samples		Mean	Standard Deviation	WHO Limit
	Min	Max			
pH	5.73	6.62	6.10	0.29	6.5 – 8.5
EC	79	1660	411.9	561.7	1000
Turb	0.03	36.9	10.5	14.1	-
TDS	0.32	830	155.5	246.6	500
NO ₃	0.11	0.81	0.33	0.23	50
Cl	10.5	38.7	23.12		250
HCO ₃	0.5	6.9	2.05	1.86	-
Ca	10.5	25.4	17.5	6.03	200
Mg	2.3	23	6.49	6.09	50
Na	5.5	17.9	9.30	4.56	200

Parameter	Range of Samples		Mean	Standard Deviation	WHO Limit
	Min	Max			
K	2	5.9	3.16	1.38	20
Fe	0.01	4.5	0.88	1.38	0.3
So42-	0.54	8.9	4.58	3.08	200
Mn	0.01	2.5	0.532	0.82	0.1

All parameters are expressed in mg/L, except pH, Turbidity and EC. EC is in $\mu\text{S}/\text{cm}$ while Turbidity is Nephelometric Turbidity unit (NTU).

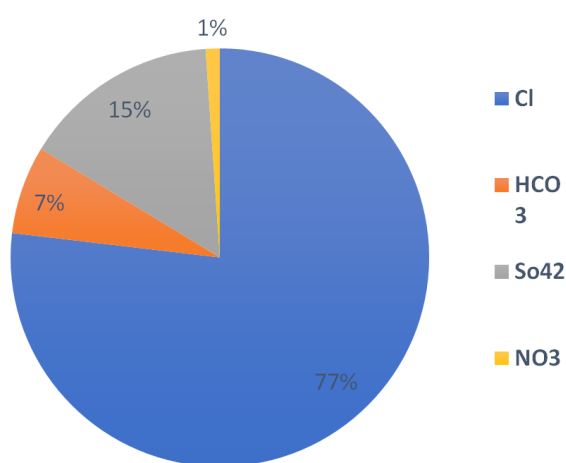


Figure 10. Mean Concentration of Anions.

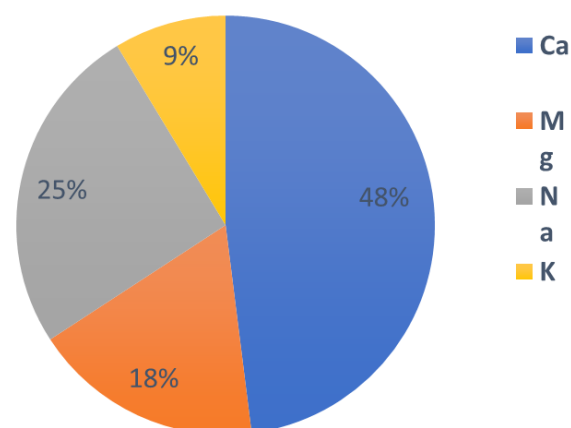


Figure 11. Mean Concentration of Cations.

Figures 10 and 11 are respectively the anion and cation average concentrations of the groundwater samples shown in percentages. Figure 10 shows that the cation, Chlorine, has the highest mean concentration with 77% while trioxocarbonate has the least mean concentration with 7%. Similarly, Moreso Figure 11 shows that Calcium cation has the highest mean concentration of 48%, while Potassium has the least mean

concentration.

4.2.2. Classification and Quality of Groundwater Hydrochemical Facies, Type

Further Analysis of the borehole samples using the Piper trilinear diagram (Figure 12) showed all the borehole samples were plotted in field I ($\text{Ca}^{2+} - \text{Mg}^{2+} - \text{Cl} - \text{SO}_4^{2+}$) for the hydrochemical facies, and field 6 ($\text{SO}_4 - \text{Cl}$ and $\text{Ca} - \text{Mg}$) for the water type classification. This suggests Calcium-Magnesium and Sulphate-Chloride rich waters. Based on the classification scheme, all borehole water falls within the $\text{Ca} + \text{Mg} + \text{SO}_4 + \text{Cl}$ hydrochemical facies. The water types are mainly Ca-Mg and $\text{SO}_4\text{-Cl}$ rich waters which indicates permanent hardness in most of the samples.

A graphical presentation of the cations and anions given in the Schoeller diagram (Figure 13) shows that Chloride and Sulphate are the predominant anions while, Calcium and Magnesium are the predominant cations in groundwater within the study area. The similarity in most of the line trends on the Schoeller diagram (BH2 - BH4, BH6 - BH10) suggests similar hydrochemical facies for most of the groundwater bodies across the study area.

Furthermore, analyzing the water samples using Gibbs's diagram (Figure 14) showed that, most of the groundwater samples plotted in the field, were of rock-weathering dominance. Hence, dissolution of the host aquiferous rock is identified as the main factor controlling the groundwater quality in the area; this corroborates with the findings of Okiongbo et al., on lithologic influence on groundwater quality [6].

Again analysis of the groundwater samples for the hydrochemical processes operational in the groundwater of the area, using the Durov plot (Figure 15), indicated that all the groundwater samples were plotted in field 4, (field of ionic exchange). The plot suggests that, sulphate and calcium are the dominant elements in the water, implying mixed water, or water exhibiting simple dissolution. The similar hydro-chemical processes acting on groundwater sources in the area suggests that, all groundwater in the area are of a common origin.

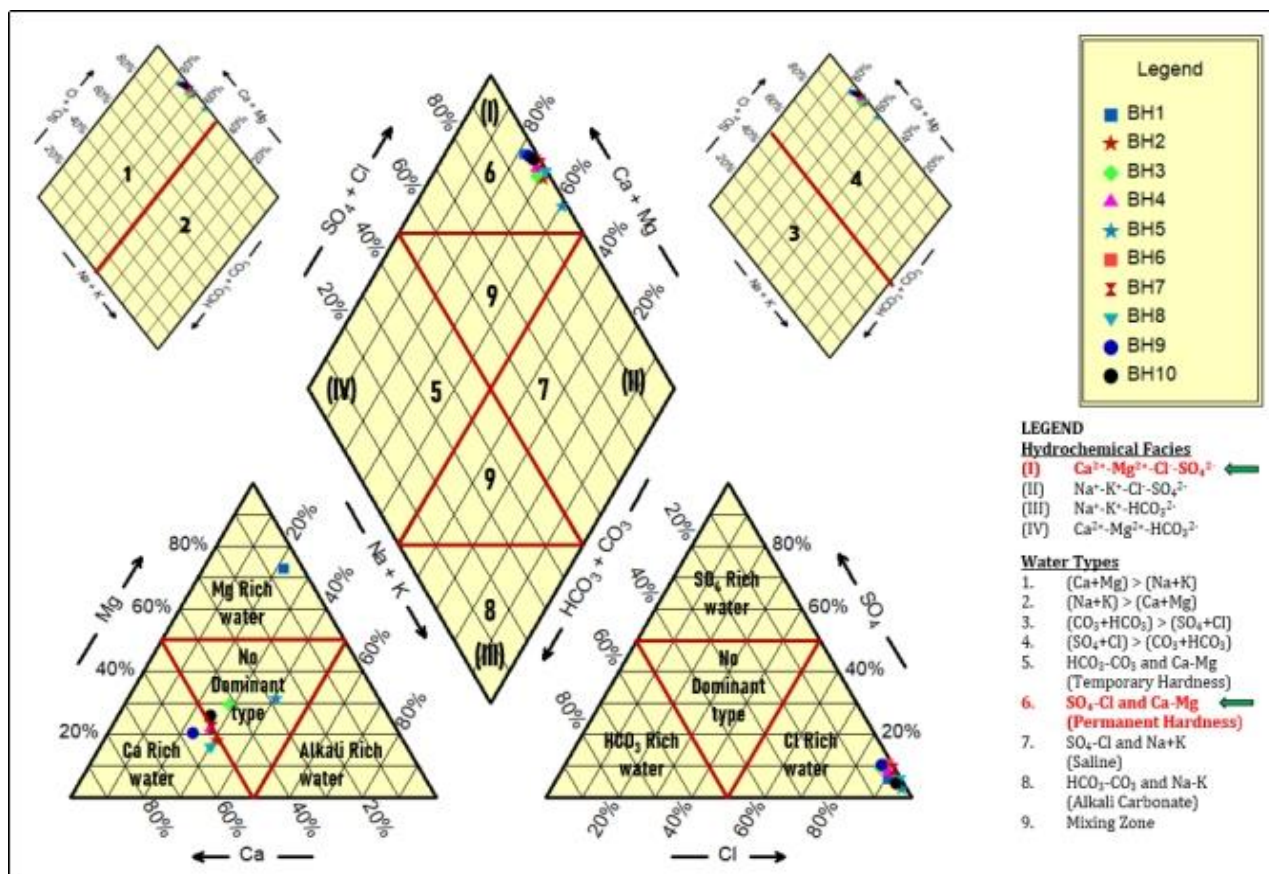


Figure 12. Piper Trilinear Diagram showing groundwater hydrochemical facies and water types across the study area [42].

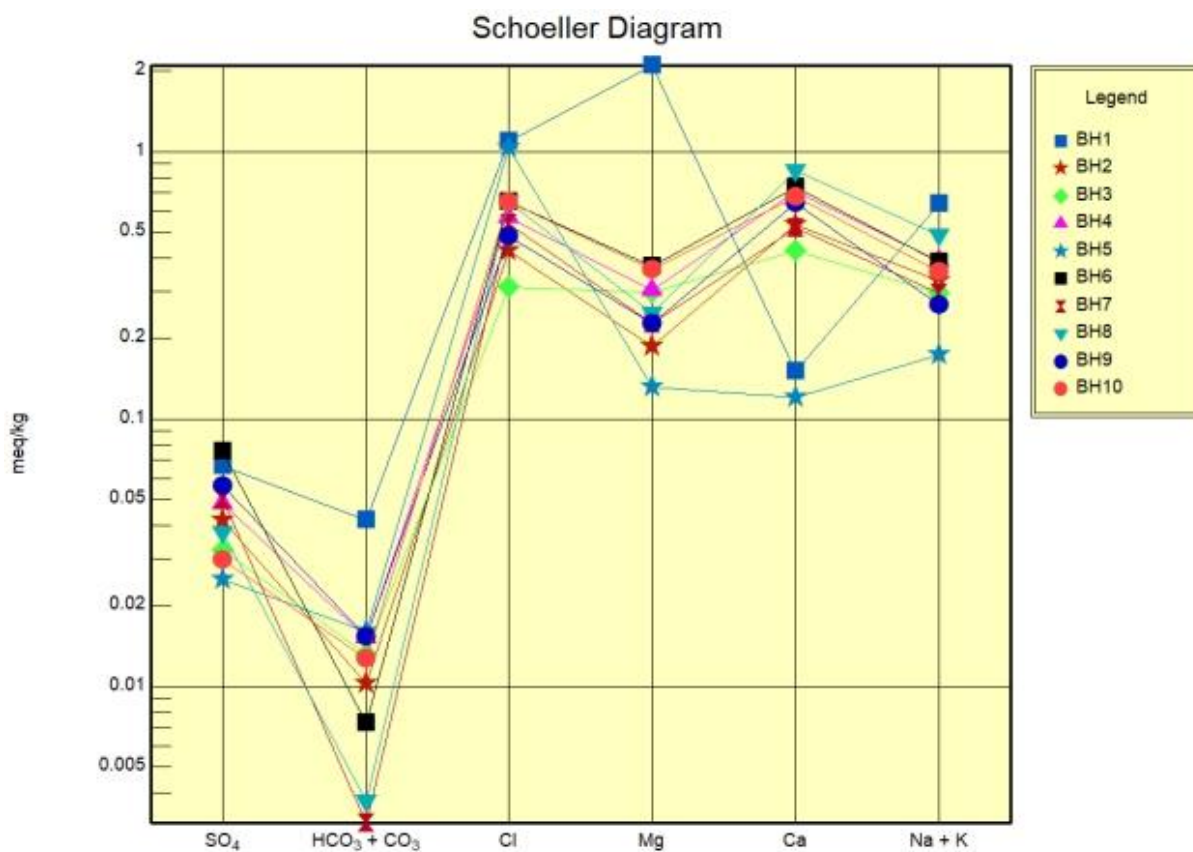


Figure 13. Scholler diagram showing the various water types [43].

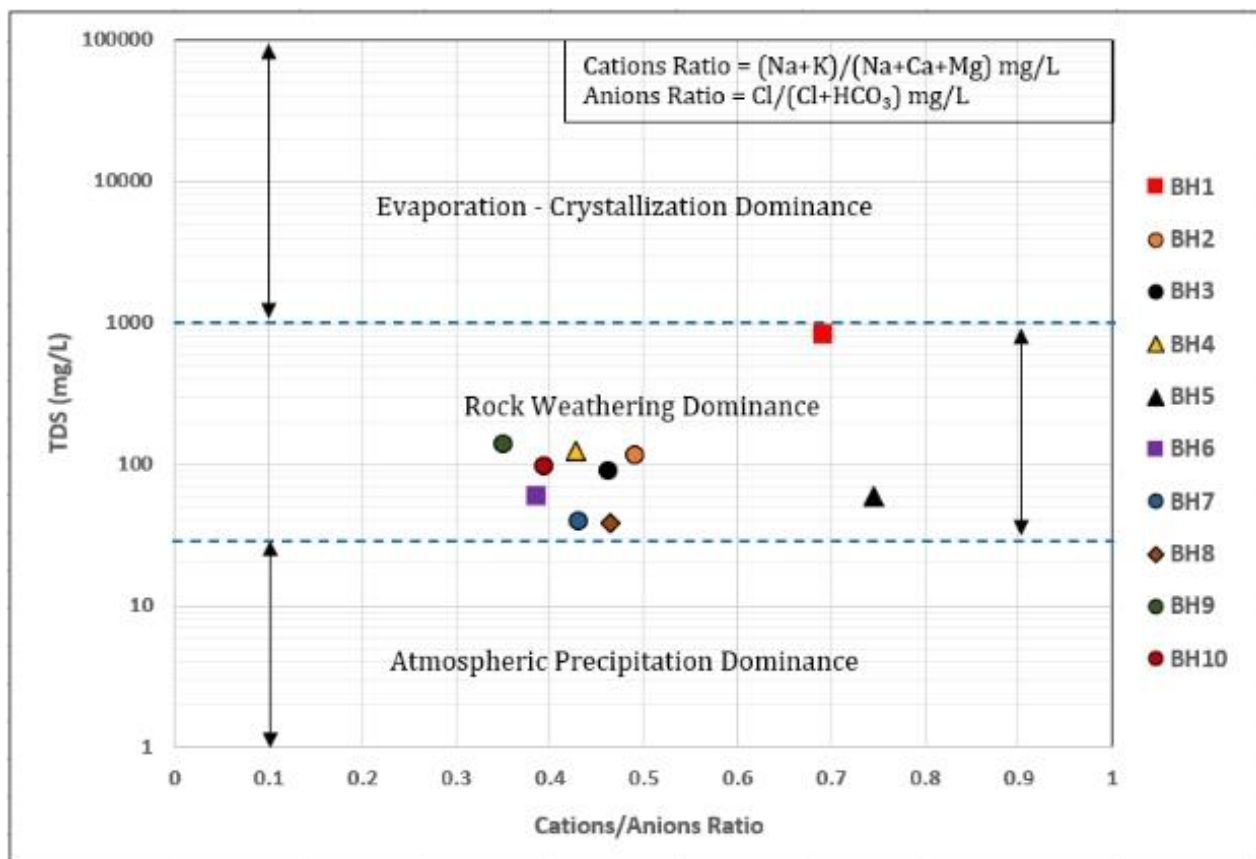


Figure 14. Gibbs energy diagrams showing the genesis of groundwater quality in the study area [44].

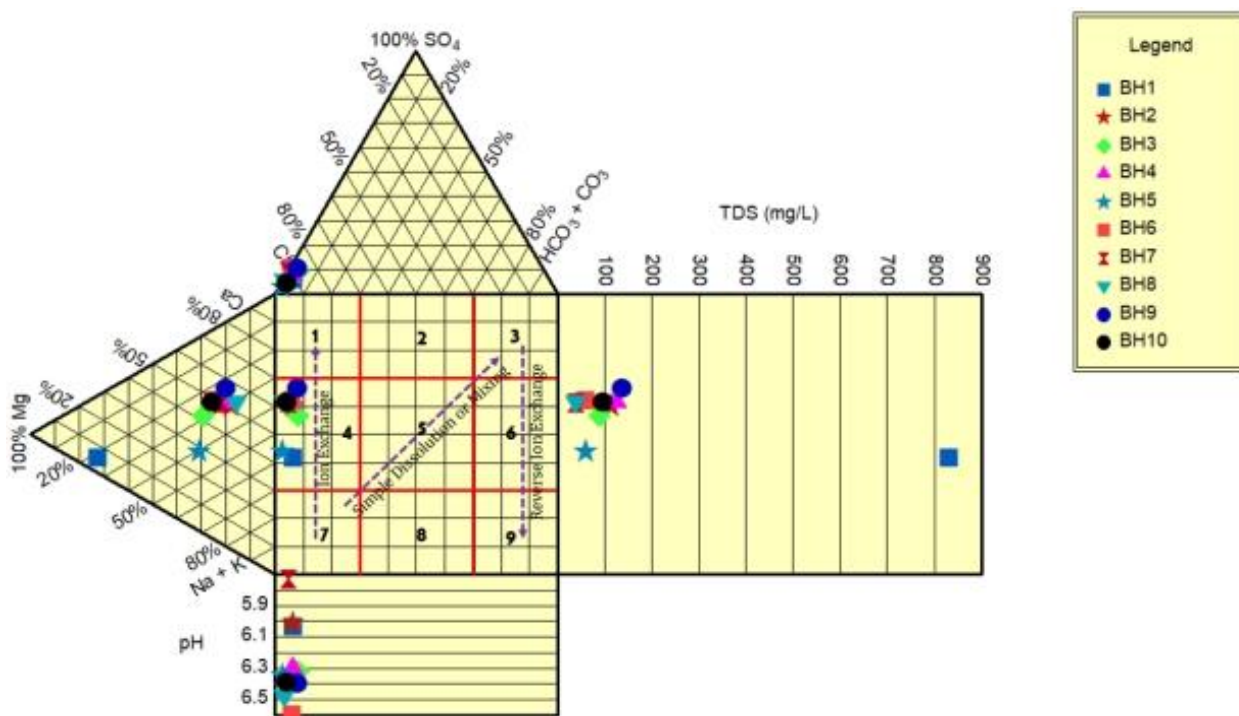


Figure 15. Durov plot depicting hydrochemical processes acting on groundwater sources in the area [After 45].

5. Conclusion

The study was carried out to evaluate groundwater minerals and to correlate the VES technique to Physicochemical approach for the estimation of groundwater mineral concentrations. The study has shown that, Iron (Fe) in the groundwater samples in the study area was significantly higher than the [26] recommended values, the obtained values ranging from 0.01 to 4.5 mg/L, with a mean of 0.88 mg/L.

The physicochemical results of Fe concentration when correlated with the geophysical study showed that, Iron (Fe) concentration align well with VES locations with K and KH curve types; While Iron (Fe) concentrations in the water samples of boreholes higher than the [26] standard, correlated well to the five VES stations with H and HK curve types (VES1 - VES5).

The study has further shown that the boreholes within the study area suggests to be rich in Calcium-Magnesium and Sulphate-Chloride.

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Conflicts of Interest

The authors declare no conflicts of interest.

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