Intrinsic Parametric Approach to Groundwater Vulnerability Assessment: A Case Study of Ijero Mining Site, Ijero-Ekiti.

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Abstract

The research was conducted to unravel the aquifer protective capacity and groundwater yield of the environment of a mining site at Ijero-Ekiti, Nigeria. The electrical resistivity method was employed and data gotten were used in combining the conventional longitudinal conductance and a new approach that indexes the resistivity and thickness considering some layers which could be protective and have low resistivity like clay material. The area is characterized by the Nigeria Basement Complex consisting of Precambrian rocks, made up of the migmatite gneiss, amphibole schist, quartzite, calc gneiss, schist biotite gneiss, biotite-schist, epidiorite, pegmatite and granite. A total of 9 points were sounded with maximum current electrode separation of 50 – 80 m. The sounding data were interpreted with the aid of partial curve-matching and computer iteration. Result of the interpretation of the geophysical data shows that the area is composed of variable subsurface layering that ranges from three to four layers. Groundwater potential zones were delineated based on the geo-electrical data. The study reveals that VES 1, 3, 4, 5 and 8 have high to medium groundwater potential. However, VES 2, 6 and 9 are characterized by low groundwater potential. The distinct aquifer protective zones identified in the study area using longitudinal conductance and geoelectric layer susceptibility indexing are poor and weak. The study has been able to detect the groundwater yield and the protective capacity of the overburden in the northeastern part of Ijero-Ekiti where a mining site is located using electrical method. Geochemical analysis of water and soil samples from the area is recommended to understand the right treatment required for some of the groundwater sources for drinking.

Introduction

Mining has proven its significant role in the global economic growth. This starts from huge benefits derived by the operating companies, a source of revenue to the government and employment generation to a large number of people. However, the negative impact of mining on the environment at local, regional and global levels continues to be a general interest (Obiora, 2015). Mining is often referred to as a practice that has negative impact on environment of both extent and diversity. Tahseen (2016) listed some of these effects to include biodiversity loss, formation of sinkhole, erosion and groundwater contamination by impurities from the mining process especially in open-pit mining.

Water is natural gift given to us by nature, a basic and a non-negotiable ingredient that supports life just like air. Water is generally defined as a universal solvent because it is a valuable natural asset, an essential necessity for human, and a prime resource (National Water Policy, 1987). According to Oladejo *et al.*, 2013; Akinrinade and Adesina, 2016; Adagunodo *et al.*, 2018; Anomohanran *et al.*, 2017; Emenike *et al.*, 2017, Water is the most vital natural resource that sustains life and could be gotten from surface flow as rivers and streams, the troposphere as rain, and subsurface flow as groundwater.

Groundwater is water that occurs in saturated zone with the source mainly from atmospheric precipitation, which has percolated down into the subsurface (Obiora *et al.*, 2015; Kwami *et al.*, 2018). Porous and fractured rock formations (aquifer) in the subsurface abhor groundwater and are identified through scientific methods before locating and extracting groundwater (Todd, 1980; Adagunodo, 2017). Naturally, Groundwater is excellent in quality, often having nothing to do with colour, pathogens, turbidity, and can be consumed/taken directly

without being treated (Jain *et al.*, 1996). It has peculiar features which makes it appropriate for public supply and therefore an indispensable resource (Offodile, 1983).

In the Basement Complex environment in Africa, groundwater exploration is often conducted using Vertical Electrical Sounding (VES) (Olasehinde and Bayewu, 2011; Oloruntola and Adeyemi, 2014, Falade *et al.*, 2019). The success rate achieved in the exploitation of groundwater within the basement complex terrain requires a comprehensive knowledge of the hydro-geological properties of the aquifer units with respect to how susceptible/vulnerable they are to environmental contamination/pollution.

Contamination of groundwater occurs when constituents or materials of different chemical composition and unhealthy benefit for human, comes in contact with groundwater and its pot-ability altered. The pot-ability of groundwater can be altered by leachate from waste sites, saline intrusion, mining activities, oil spillage, sewage (from underlined petroleum pipes, latrines and septic tanks) (Obiora *et al.*, 2015).

Groundwater vulnerability by meaning is subjective and had been defined in diverse ways; according to US National Research Council (NRC, 1993); it is the propensity and likelihood for contaminants to infiltrate the groundwater system after it has been introduced at some point in the surface. Groundwater vulnerability study is based on the relationship of the subsurface characteristics and the ease of groundwater contamination through anthropogenic activities which may be damaging to the quality of the resource. Aquifer vulnerability represents the intrinsic (natural ability of geo-materials) properties of the aquifer which determine its tendency of being affected by contaminant load imposed on it. Intrinsic aquifer vulnerability describes the relative extent of natural safety of the groundwater from contamination due to the physical properties of the surface and subsurface (Jessica *et al.*, 2011). The intrinsic vulnerability (the study focus) is recognized as the natural susceptibility to contamination based on physical parameters of the environment; in other words, the intrinsic vulnerability is the vulnerability of groundwater to contaminants/pollutants created by human activities, while considering the inherent hydrological, hydrogeological and geological properties of an area but being independent of the type of contaminants. Some of the intrinsic parameters that determine contaminants attenuation are: the thickness of the superficial deposits, the permeability and clay content of inter-granular bedrock aquifers and the depth to the water table in both superficial and inter-granular bedrock aquifers, the permeability and clay content of superficial deposits and the mode of groundwater flow in bedrock aquifers,. Vulnerability assessment is governed by the travel time of water from the surface to reach a producing aquifer and the tendency of the geo-materials (vadoze/unsaturated zone) to attenuate (filter, delay and possibly degrade by biological activity) contaminants as it is considered the first line of natural defence.

To understand the vulnerability of groundwater to contamination, the protective capacity of the aquifer must be evaluated. The measure of the protective capacity is the capability of an earth medium to impede and filter percolating fluid. However, the overburden protective capacity which is maintained by retarding and filtrating percolating pollutants is directly proportional to the thickness and inversely proportional to its hydraulic conductivity of the overburden/geo-material. Clayey material content has high protective capacity because of its characteristic low resistivity, low permeability, high longitudinal unit conductance values and low hydraulic conductivity. Hence, protective capacity is proportional to the longitudinal conductance (S). Therefore, higher longitudinal conductance of the overburden in an area leads to higher aquifer protective capacity of that area. This method thrives well when the overburden/geo-material thickness is high.

Geo-electric Layer Susceptibility Index (GLSI) (Oni *et al.*, 2017) was used in assessing the protective capacity of an overburden. The method accounts for the effectiveness of geo material like laterite that has capacity like clay to filter and degrade contaminants due to its low permeability, but highly resistive compared to clay that exhibits low resistivity.

This study focuses on understanding how to protect groundwater resources using electrical methods rather than only detecting new groundwater resources. Electrical prospecting methods, over the years have become very effective tools for distinguishing shallow geological targets, environmental and engineering applications as fluid migration, contaminant detection, structural mapping of internal landfill, imagery of faults and engineered hydraulic barriers as well as landslide investigations. Several researchers have proved the sensitivity and efficiency of electrical resistivity method in groundwater prospection and environmental investigation (Omosuyi *et al.*, 2008; Abiola *et al.*, 2009; Ariyo and Adeyemi, 2009; Mbimbe, *et al.*, 2010; Muraina *et al.*, 2012; Ogungbemi *et al.*, 2013; Obiora *et al.*, 2015; Olatunji *et al.*, 2015; Anomoharan *et al.*, 2017; Falade *et al.*, 2019; Akintorinwa *et al.*, 2020).

Location and geology of study area

The research area is located at the North-Eastern part of Ijero-Ekiti, a mining site and its environment (Figures 1 and 2). It is located between Latitudes 7° 49'36" N and 7° 49'53" N; Longitudes 5° 3'58" E and 5°4'19" E; with an elevation above sea level of 532m. It is accessible by road transport; a federal road network from Akure through Ado - Ekiti, the state capital.

Ijero-Ekiti lies in the Northwestern part of Ekiti State. The research area is largely characterized by the basement complex rocks of Southwestern part of Nigeria. It consists of the quartzite, migmatite gneiss, schist biotite gneiss, epidiorite, granite, calc-gneiss, biotite-schist, pegmatite and amphibole schist (Figure 3). Varied granitic rocks constitute about 25% of the whole area of Ijero-Ekiti, composed of fine-grained granite and medium to coarse-grained varieties with porphyritic texture while the low-lying charnockitic rocks are associated with coarse-grained porphyritic granites. Xenoliths are often formed in both charnockitic and granitic bodies. The quartzites occur as elongated bodies enclosed within the migmatitic, charnockitic and granitic rocks. Most exposed low-lying migmatites are characterized typically by foliation and intrusion of granitic and charnockitic rocks in some places.

Research Methodology

Resistivity survey was conducted by adopting the Schlumberger electrode configuration. Vertical Electrical Soundings (VES) were carried out and the apparent resistivity (ρ_a) measurements plotted against $AB/2$. The maximum electrode separation is between 50 m – 80 m. Four (4) traverses were cut and PETRO-ZENITH resistivity meter was used to acquire data in nine (9) locations (Figure 4). The parameters deemed adequate to quantify the extent of vulnerability in the area were deduced from the geo-electric parameters through the use of longitudinal conductance and GLSI.

Longitudinal Conductance

According to Henriet (1976), the extent of an aquifer protection (S) is considered to be directly related to the

$$(S = \frac{h}{\rho}).$$

ratio of the thickness and resistivity. It is often expressed as the longitudinal conductance (S) which enables to establish the protection extent in which groundwater would be protected from contaminants moving vertically from the surface. However, any overlying layer with longitudinal conductance greater than 1.0 is generally believed to offer the groundwater high protection from contamination. The thickness of this layer will increase the protection level of the groundwater and the bigger the thickness, the rate of infiltration of the contaminants will be low and it must have been greatly filtered before getting to the groundwater thereby reducing the contamination rate. Also, the more clayey of the overburden which is revealed by low resistivity (high conductivity), the less permeable the material will be (Braga *et al.*, 2006) and less contamination to the groundwater. According to Abiola *et al.*, (2009), overburden made up of clay material which offer protection to the underlying aquifer layer due to its low permeability is characterized by relatively high longitudinal conductance. The protective capacity of an area had been zoned to different categories (Table 1). The protective capacity range >10 is excellent, 5-10 very good, 0.7-4.9 good, 0.2-0.69 moderate, 0.1-0.19 weak and <0.1 poor.

The equation 1 below was utilized in determining longitudinal conductance;

$$S = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \dots + \frac{h_n}{\rho_n} \quad (1)$$

Where; h_1, h_2, h_3 and h_n represents the layer thicknesses

ρ_1, ρ_2, ρ_3 and ρ_n represents the layer resistivity parameters

S is the longitudinal conductance.

The rated longitudinal conductance protective capacity is shown in table 1.

Table 1: Modified longitudinal conductance/protective capacity rating (Oladapo *et al.*, 2007)

Longitudinal conductance (mhos)	Protective capacity rating
>10	Excellent
5-10	Very good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
<0.1	Poor

Geoelectric Layer Susceptibility Indexing (GLSI)

A hydrogeologic approach that indexes the geoelectric parameters inferred from the differences in electrical resistivity between rock sequences in the subsurface is applied in Geoelectric Layer Susceptibility Indexing (GLSI) (Oni *et al.*, 2017). It is an empirical complementary concept initiated to enhance other methods of assessing vulnerability. GLSI assigns index to each geoelectric parameter (layer resistivity and thickness) (Tables 2-4) in contrast to longitudinal conductance approach where indices were assigned to the ratios of the geoelectric parameters (layer thickness and resistivity). GLSI is determined by equation 2. GLSI accounts for the properties of lateritic materials which has low permeability (confining material) like clay but high resistivity due to the degree of induration.

$$GLSI = \frac{(\rho_{1r} + h_{1r})/2 + (\rho_{2r} + h_{2r})/2 + (\rho_{3r} + h_{3r})/2 + \dots + (\rho_{nr} + h_{nr})/2}{N} \quad (2)$$

Where; ρ_{1r} represents the first layer resistivity index rating,

h_{1r} represents the first layer thickness index rating

ρ_{2r} represents the second layer resistivity index rating,

h_{2r} represents the second layer thickness index rating

ρ_{nr} represents the nth layer resistivity index rating

h_{nr} represents the nth layer thickness index rating

N is the number of geoelectric layers overlying the Aquifer

Multi Criteria Decision Analysis (MCDA) according to Roy (1988) is adopted in GLSI. In this approach, rated parameters are assigned indices. Normalization of the assigned parameter indices are conducted by dividing them with the number of geoelectric layers (N) delineated from the resistivity curve to be above the aquifer.

Table 2: Index Rating of Resistivity Parameters Applied in GLSI

Resistivity range (Ω -m)	Lithology	Susceptibility index rating
<20	Clay/silt	1
20-50	Sandy clay	2
51-100	Clayey sand	3
101-150	Sand	4
151-400	Lateritic sand	2
>401	Laterite	1

Table 3: Index rating of Layer Thickness Applied in GLSI

Thickness(m)	Index rating
<2	4
2-5	3
5-20	2
>20	1

Table 4: Vulnerability Rating Applied in GLSI

Vulnerability Rating	Index
Low	1.0-1.99
Moderate	2.0-2.99
High	3.0-3.99
Extreme	4.0

Results And Discussion

Geo-Electrical Characterization and Groundwater Potential: The geophysical data obtained were presented in Table 5 and the results of the interpreted vertical electrical soundings (VES) data are presented in Table 6. The interpreted vertical electrical sounding data show that the study area is characterized with 3-layer to 4-layer geo-electric sections. From the table, the three layer geo-electric section is observed at only one point and the four-layer type was noticed at all other points. Five sounding curve types or signatures are observed namely K-type curve, HK-type curve, AA-type curve, KH-type curve and AH-type curve as shown in Figure 5a to 5i and Figure 6. Their frequencies of occurrence are shown in Figure 6. These curve types revealed that the study area has low to medium groundwater potential.

Table 5: Results showing the apparent resistivity for each VES points

VES NO AB/2	1	2	3	4	5	6	7	8	9
1	685.21	204.73	302.51	405.44	208.38	64.73	116.38	88.35	346.69
2	618.6	237.54	297.86	491.16	264.68	54.55	211.65	81.94	386.08
3	510.13	281.65	324.07	481.29	290.13	61.64	274.3	102.93	410.98
4	454.46	313.7	410.22	528.86	266.44	68.03	314.7	126.69	396.14
6	459.23	334.81	373.27	608.6	305.2	87.72	377.8	164.17	438.37
6	524.84	325.76	334.81	616.4	291.82	102.94	211.63	275.99	380.06
8	585.17	394.13	888.81	665.6	309.68	80.92	764.13	203.09	438.37
12	728.51	409.23	737.49	742.01	318.24	77.5	1251	223.09	456.97
15	628.11	393.94	1484.6	763.51	319.9	93.94	243.47	193.87	422.43
15	781.18	484.26	1028.61	805.92	93.15	48.42	431.24	533.74	710.84
20	640.97	500.21	986.6	804.35	232.95	88.01	508.33	222.15	1410.1
30	838.75	913.66	1086.2	607.07	293.31	115.05	659.95	202.82	635.12
40	1013.51	1509.59	1622.16	430.08	379.91	631.07	1000.79	695.39	590.69
40	833.67	1437.78	2091.32	1779.63	228.08	160.8	1890.23	995.39	1648.92
50	918.49	2749.25	1618.13	645.62	797.28	315.7	1618.13	382.85	4194.57
60	989.09	1060.54	1106.89	684.44	840.35	550.4	1272.35	263.89	
70		721.36	670.67	769.45	995.68	676.12	1375.09	2248.37	

The Subsurface Sequences: Table 5 above presents the summary of interpreted geo-electric section. Four geo-electric sections were drawn along traverses 1, 2, 3 and 4. Traverses 1, 2 and 3 trends NW-SE while traverse 4 trends E-W direction. The geo-electric section along traverses 1-4 in Figure 7a - 7d shows four distinct layers namely topsoil lateritic layer, weathered layer delineated as aquifer and partly weathered basement. The geo-electric parameters obtained from depth sounding on VES1, VES3, VES4, VES5, VES6, VES7 and VES9 classified the area into four geo-electric layers. On VES1, 3, 4, 5, 6, 7 and 8 the top soil resistivity value ranges from 60 - 686 ohm-m with thickness ranging from 0.8 - 2.1m. The resistivity value of the second layer ranges between 71 - 997 ohm-m and 622 ohm-m with thickness range between 4.2 and 7.6m and is interpreted as lateritic layer. The third layer is the weathered layer delineated as the aquifer with resistivity range 91 - 1389 ohm-m. The last layer has resistivity value ranging from 468 - 6834 ohm-m interpreted as partly weathered basement. VES2 is interpreted as 3 layers. The aquifer thickness ranges between 4.9 - 23m. VES 6 is 4.9 m thick and Ves4 23 m thick. It is considered fairly thick to harbor groundwater development. Others; VES1, 3,5,7,8 and 9 has thickness 19.2m, 22m, 9.3m, 19.1m, 22.2m and 11.8m respectively. The total overburden thickness ranges between 4.9-9.2m. The overburden is considered generally thin.

Table 6: Summarized interpreted result of the study area

VES NO	h1 (m)	h2 (m)	h3 (m)	ρ_1 (Ω m)	ρ_2 (Ω m)	ρ_3 (Ω m)	Curve Type
VES 1	1.2	4.2	19.2	687	402	991	HA
VES 2	5	39	-	247	1389	758	K
VES 3	1.9	4.7	22	298	421	1905	HK
VES 4	2.1	7.1	23	417	997	470	KH
VES 5	1.2	3.7	9.3	208	433	129	KH
VES 6	1.5	6.6	4.9	60	71	91	AA
VES 7	0.8	7.6	19.1	104	720	807	AA
VES 8	1.7	6.6	22	82	306	169	KH
VES 9	1.9	6.4	12	373	419		AA

Depth to Bedrock (Overburden Thickness): The depth to bedrock is the total thickness of all the overlying layers above the fresh basement rock. Thickest overburden is found around VES 2, 3 and 4 with an overburden thickness of about 22 m. The thinnest overburden is found around VES 5 with overburden thickness of about 10m. Figure 7a - 7d shows the overburden thickness in all the VES points. Overburden thickness is one of the parameters on which groundwater potential evaluation is based. Areas that are characterized with thin overburden are zones of probable low groundwater zones and those areas with thick overburden are zones of probable high groundwater zones.

Vulnerability Assessment/Protective Capacity Evaluation

Longitudinal Conductance (LC): The vulnerability of the study area is considered generally high (Figure 8). Based on longitudinal conductance model, VES 6 is considered weak having longitudinal conductance 0.12 while other areas (VES) have longitudinal conductance value less than 0.1 and therefore categorized as poor protective capacity. Poor longitudinal conductance is observed from southern to the northern part of the study area is indicative of poor protective capacity while the southwestern part (VES6) indicated weak protective capacity. The average vulnerability of the area is high because the geo-materials provide little protection to the underlying aquifer.

Geoelectric Layer Susceptibility Indexing (GLSI): The map shown in figure 9 reveals the vulnerability index based on the lithology and vadoze zone thickness of the study area. The impact of vadoze zone thickness in assessing the vulnerability of an aquifer is highly essential because a great thickness of the vadoze zone can sufficiently delay contaminants from traveling to the aquifer layer, thereby reducing the rate of contamination. These parameters were combined and used to generate GLSI overlay index map. The map indicates low vulnerability (1.0-1.99) at the southern part of the study area, medium vulnerability (2.0-2.99) at the northeastern and northwestern part of the study area and high vulnerability zones (3.0-3.99) at the southwestern part of the area. The entire study area could be classified between medium to high vulnerability, which suggest that the aquifer system in the study area has poor protective capacity.

Conclusion

Hydrogeophysical study was conducted with the objective of categorizing the groundwater potentials and to unravel the aquifer protective capacity in the vicinity of mine at the North eastern part of Ijero Ekiti. Geo-electrical parameters show that the area is characterized with 3-layer to 4-layer subsurface sequences. The 4-layer type constitutes the dominant layer type and is observed at five (5) VES points. The layers of the subsurface include topsoil, weathered/fractured layer and the fresh bedrock. Areas where thick overburden and low resistivity values were observed constitute zones of high longitudinal conductance; this parameter was used as a standard for rating the aquifer protective capacity. Three zones were distinctly defined as weak, poor and moderate aquifer protective capacity zones. The zones that are vulnerable to surface contaminant sources are termed as poor and weak zones and are found mostly in the southwestern and Northeastern part of the study area. Three groundwater potential zones were also delineated in the research area; the classification criteria used includes the resistivity and thickness of the weathered layer, overburden thickness and bedrock resistivity. Because of the instability in the basement relief and the local and discontinuous nature of the basement aquifers, the three zones vary from place to place. Areas of high aquifer protective capacity coincide with areas of poor groundwater potential; the former increases as the clay content of the overburden increases while the latter decreases with increase in the overburden's clay content.

Declarations

Conflict of Interest

The authors declared that they have no conflict of interest.

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Availability of data and material

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Figures

Figure 1

Map of Ijero - Ekiti

Figure 2

Base map of the study area showing the VES Points

Figure 3

Geological Map of Ijero-Ekiti (Romanus 2014).

Figure 4

Base map showing the traverses and VES points

Fig. 5a

Fig. 5b

Fig. 5c

Fig. 5d

Fig. 5e

Fig. 5f

Fig. 5g

Fig. 5h

Fig. 5i

Figure 5

a: Resistivity Profile for VES 1 b: Resistivity Profile for VES 2 c: Resistivity Profile for VES 3 d: Resistivity Profile for VES 4 e: Resistivity Profile for VES 5 f: Resistivity Profile for VES 6 g: Resistivity Profile for VES 7 h: Resistivity Profile for VES 8 i: Resistivity Profile for VES 9

Figure 6

Frequency Distribution of Curve Types

Fig. 7a

Fig. 7b

Fig. 7c

Fig. 7d

Figure 7

a: Geo-electric section of traverse 1 showing VES1, VES3 and VES7 b: Geo-electric section of traverse 2 showing VES2, VES8 and VES9 c: Geo-electric section of traverse 2 showing VES6, VES7 and VES8 d: Geo-electric section of traverse 4 showing VES2, VES8 and VES9

Figure 8

Longitudinal conductance map of the study area

Figure 9

GLSI Map of the study area.