REVIEW ARTICLE

GEOPHYSICAL EVALUATION OF SUBSURFACE PROTECTIVE CAPACITY AND GROUNDWATER PROSPECT IN A TYPICAL SEDIMENTARY ZONE, EASTERN DAHOMEY BASIN USING ELECTRICAL RESISTIVITY TECHNIQUE

Kayode Festus Oyedele^a, Olawale Babatunde Olatinsu^{b*}

^a Department of Geoscience, Faculty of Science, University of Lagos, Akoka, Lagos, Nigeria.

^b Department of Physics, Faculty of Science, University of Lagos, Akoka, Lagos, Nigeria.

*Corresponding Author Email: oolatinsu@unilag.edu.ng

This is an open access article distributed under the Creative Commons Attribution License CC BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

ARTICLE DETAILS

Article History:

Received 17 September 2021

Accepted 20 October 2021

Available online 01 November 2021

ABSTRACT

Subsurface protective capacity evaluation is important in groundwater prospecting. With the aid of Dar-Zarrouk parameters which show direct relationship with contaminants infiltration time and transmissivity, joint interpretation of vertical electrical sounding (VES) and 2-D resistivity imaging were employed to evaluate overburden protective capacity and groundwater potentials at Mowe in Obafemi-Owode LGA, southwest Nigeria. Total longitudinal conductance S , total transverse resistance T , longitudinal resistivity ρ_L and transverse resistivity ρ_T were computed. Sand/clayey sand was delineated at 70% of the area either as confined aquifers (78%) or unconfined aquifers (22%). S values in 87% of locations has moderate protective rating (0.2071 - 0.5630), one location has good protective rating (0.7736), others have weak protective ratings (0.1053 - 0.1814). The entire area is characterized by low overburden thickness H (7.9 - 25.6 m), which agrees with a correlation coefficient of 0.58 between S and H . T values is in the range 235 - 2046 Ωm^2 with high values indicating high transmissivity zones, suggesting high probability of pollutant contamination of aquifer, also agreeing with moderate correlation coefficient of 0.69 between T and H . The study area was grouped into three regions on the cross plot of T versus S : low S and high T - poor protection and high contaminant transmission; moderate/good S and low T - good protection with low contaminants transmission; moderate/low S and low T - weak protective capacity and poor transmissivity. Excellent correlation (0.99) exists between ρ_L and ρ_T , with ρ_T slightly higher than ρ_L , and low ρ_L signifying the presence of conductive clayey materials in the overburden.

KEYWORDS

Overburden, resistivity, Dar-Zarrouk parameters, correlation, evaluation

1. INTRODUCTION

A thorough inventory of groundwater and surface water use has revealed the worldwide importance of groundwater in human existence (Maduabuchi, 2004; Turner and Wurster, 2017; Walker et al., 2019). Several reasons account for the advantages of groundwater over surface water: (i) its existence relative to where water is demanded; (ii) its superior intrinsic state, generally satisfactory for potable supplies for most uses; (iii) where high purity level is required, treatment is usually minimal; and (iv) the rather low capital cost for commercial processing and production. Furthermore, the development phases, to square up with increasing consumer needs, is usually more readily accomplished for groundwater than for surface water (Cosgrove and Loucks, 2015). However, most often the importance of groundwater in the water supply programme is greatly underestimated. In most countries across the globe, groundwater resources are being seriously and rapidly degraded in terms of quality and quantity primarily due to human activities, ecosystem and landscape changes, sedimentation, pollution, over-abstraction and climate changes (Vandas et al., 2002; BGS, 2008; Nel et al., 2009; Khatri and Tyagi, 2015; Zereg et al., 2018). In many countries around the world, population growth, economic and technological advancement etc., have activated unconventional variations in the condition of groundwater systems, which

has excited an increasing consciousness in the finiteness and susceptibility of this vital natural endowment (Bovolo et al., 2009; Döll, 2009).

The foremost position of groundwater resources is incontrovertible, and by extension, their continual preservation and utilization are, therefore, of crucial importance to human survival and multifarious activities. The medium that hosts the resource (groundwater), the aquifer, has an important role to play in its protection and conservation. In some geological environments, aquifers that can provide sustained economic quantity of freshwater are usually located within formations at depths of less than a few hundred meters beneath the ground surface. Also, the variability in the nature and characteristics of the aquifer and the covering sedimentary materials above it have a strong impact on the quality and quantity of groundwater for the various human needs (Konikow and Neuzil, 2007). In sedimentary terrain, a contaminant can enter a network of conduits in an aquifer and become a widespread health problem. A large number of reports of diseases can be traceable to or caused by contaminated groundwater.

The electrical resistivity technique offers a reliable and relatively low-cost approach to hydrogeological investigation and subsurface characterization (Christensen and Sørensen 1998; Olayinka and

Quick Response Code

Access this article online

Website:
www.mjgeosc.com

DOI:
10.26480/mjg.02.2021.85.92

Yaramanci, 2000; Sørensen et al., 2005; Gupta et al., 2015). It has been used extensively in groundwater mapping for investigation of the vulnerability of aquifers to possible contamination (Mousatov and Ryjov, 2005; Worall and Kolpin, 2003; Machiwal et al., 2018; Oroji, 2018; Ayuk, 2019). This technique is also capable of mapping both low and high resistive formations, thereby making it a valuable tool for studies relating to groundwater protection (Braga et al., 2006, 2008; Casa et al., 2008; Ayuk, 2019; Hasan et al., 2019).

Several authors have established the application of Dar Zarrouk parameters, longitudinal unit conductance (S), and transverse unit resistance (T), in aquifer protection studies as well as for the evaluation of hydrogeologic and hydrogeophysical characteristics of aquifers (Zohdy, 1965, 1974; Henriot, 1976; Singh et al., 2004; Braga et al., 2006; Batayneh, 2013). Henriot suggested the possibility of direct proportionality between the protective capacity of a clayey aquifer overburden and its longitudinal unit conductance (Henriot, 1976). Salem employed the correlation between fluid transmissivity (product of layer thickness and permeability) and electric transverse unit resistance (product of layer thickness and resistivity) to delineate zones of high potentials in aquifers and hydrocarbon reservoirs (Salem, 1999). The protection of aquifers against the infiltration of contaminants, is closely related to the heterogeneous properties of clay cover which acts as a cap or seal. The resistivity of formation can be greatly affected by the proportion of clay (clay content). While permeable formation containing clayey materials manifests low resistivities, those with sandy permeable usually have moderately high resistivities (Archie, 1942).

Maillet proposed the term "Dar-Zarrouk" (D-Z) parameters into the geophysical literature on electrical prospecting to establish the relationships between subsurface layer resistivity and thickness to define the longitudinal unit conductance (Maillet, 1947).

$$S_i = h_i / \rho_i \quad (1)$$

and the transverse resistance

$$T_i = h_i \rho_i \quad (2)$$

where ρ_i and h_i are the electrical resistivity and thickness of the i^{th} layer, respectively.

From Equations (1) and (2), for $n-1$ layers (excluding the aquifer), the total longitudinal conductance and the total transverse resistance respectively are:

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

$$T_t = \sum_{i=1}^{n-1} h_i \rho_i \quad (5)$$

The longitudinal resistivity in the direction parallel to the subsurface layers and the transverse resistivity in the perpendicular direction to the subsurface layers are:

$$\rho_L = \frac{H}{S_t} \quad (6)$$

$$\rho_T = \frac{T_t}{H} \quad (7)$$

where $H = \sum_{i=1}^{n-1} h_i$.

Henriot established the direct applications of the D-Z parameters in the investigation of aquifer protection and hydrologic/hydrogeologic characteristics of aquifers (Henriot, 1976). Other workers have also confirmed the implications of D-Z parameters on the hydrological attributes of aquifers in several geologic formations (Niwas and Singhal, 1981; 1985; Khalil, 2009; Mondal et al., 2013). Several studies aimed at aquifer protection studies and groundwater prospect evaluation have been executed in both sedimentary and basement complex regions in Nigeria. Due to the need to establish certain facilities such as automobile

mechanic village, abattoir and meat processing factory at Aboru residential estate in Lagos, Nigeria, necessitated a geophysical study aim at using longitudinal unit conductance to ascertain the vulnerability of the subsurface aquifers in the study area against the expected long-term anthropogenic impacts of the proposed facilities on the groundwater system (Ayuk, 2019). The total longitudinal unit conductance was found to be in the range 0.0164 - 0.1168 mhos indicating a poor/weak protective capacity rating across the study area. As such, the establishment of the proposed service facilities in the study area was not recommended due to the possible long-term effects of their operations on aquifer system. Total longitudinal conductance obtained from VES interpretations conducted near forty well bores was used to evaluate the overburden protective capacity and corrosion index in a crystalline basement complex of Ogbomoso North, southwestern Nigeria (Adabanija and Ajibade, 2020). Results obtained from the study revealed a broad range of overburden protective capacity from excellent to good, fair and poor ratings. In addition, based on Langelier saturation index (LSI) and aggressive index (AI), areas where the groundwater is strongly corrosive and non-corrosive were clearly delineated. Umar and Igwe evaluated the characteristics of granular sandstone aquifers within Lafia, North Central Nigeria for groundwater supply (Umar and Igwe, 2019). It was found that the groundwater resources in about 82% of the area was not fit for human consumption due to high corrosive content. In this present study, computed D-Z parameters were employed to delineate the overburden protective capacity ratings and possible aquifer units at the study location. The study area and its environs is socially and economically active, and fast developing. Thus, there is the necessity to meet up with this vast and rapid development in terms of making available fresh and potable water supply for human consumption and other domestic needs.

2. DESCRIPTION OF THE STUDY AREA

The study area is located within Redemption Camp, in Mowe town, Ogun State, southwest Nigeria. Ogun State lie within Latitudes 6° 41' N - 7° 9' N and Longitudes 3° 16' E - 3° 41' E in the humid tropical rain forest region of Nigeria characterized by two climatic seasons; rainy season (March - October) and dry season (November - February). The average annual rainfall is about 1300 mm; annual evapo-transpiration is about 188 mm with elevation ranging from 40 m in the South to 154 m in the North. Mowe town lies approximately 45 km North-East of Lagos and it is accessible through the Lagos-Ibadan expressway. It shares a boundary with Ibafo in the west and Shagamu in the east. The geologic units of Ogun state comprise of the crystalline basement rocks and sedimentary rocks of the wide-ranging Dahomey Basin. The geographic extent of the Dahomey Basin covers the area from southeastern Ghana across Republics of Togo and Benin to the western fringes of the Niger Delta towards the East. (Jones and Hockey, 1964; Reymont, 1965; Ogbe 1972; Omatsola and Adegoke, 1981). The basin is edged on the west by faults and some tectonic structures directed toward the land and stretches into the Romanche fracture zone (Adegoke et al., 1981). Similarly, its eastern border is inscribed by the Benin Hinge line. It is also a significant fault structure ending the western margin of the Niger Delta Basin (Omatsola and Adegoke, 1981; Whiteman, 1982). The Tertiary sediments of the Dahomey Basin decreases and are particularly separated from the deposits of the Niger Delta Basin next to the Okitipupa ridge of the Basement Complex (Omatsola and Adegoke, 1981). Stratigraphic units of the eastern Dahomey Basin consist of the late Cretaceous mainly sandy strata of the Abeokuta Group as the oldest. The overlying Tertiary strata encompasses limestone of the Ewekoro Formation, shale of the Akinbo Formation, mudstones/shale of the Oshosun Formation, and sandstone of the Ilaro Formation (Figure 1). Other younger strata are the Oligocene to Recent continental sands of the Benin Formation as well as recent alluvial sediments (Russ, 1924; Adegoke 1969; Omatsola and Adegoke, 1981). Sandstone, limestone and sandy sediments are the aquifer units within these geologic formations. The high annual rainfall usually experienced in the state suggests regular recharge of these aquifer units. While major segment of the study area is underlain by the Abeokuta Group, some segments fall within the transition zone (Figure 1).

Figure 1: Geological map of Ogun State showing the study location falls within the Oshosun Formation.

3. METHODOLOGY

3.1 Data Acquisition

The geophysical survey carried out at the study site involved the integration of 2-D constant separation traversing (CST) and the vertical electrical resistivity (VES) techniques since both respond favorably to measurable parameters that can easily assist in distinguishing an aquifer from other formations. The PASI terrameter was used for the data acquisition and the survey was carried out along five traverses with a maximum spread of 200 m (Figure 2). The Wenner array was employed for the 2-D resistivity imaging and the Schlumberger array for the VES. Measurements were taken at an electrode separation of 10 - 60 m for the 2-D resistivity imaging. Six (6) VES sounding points were occupied at distances 60, 75, 90, 105, 120, and 140 m along each traverse line, thereby making a total number of thirty (30) sounding points altogether (Figure 2).

Figure 2: Data acquisition map showing the VES data point outlined on the CST traverses. 6 VES arranged on each of the 5 traverses.

3.2 Data Processing and Interpretation

The VES data were interpreted with the aid of both semi-qualitative and quantitative procedures. The quantitative interpretation method facilitates the computation of the resistivity and thickness of the subsurface layers through partial curve matching method with master curves designed for stratified and multi-layered Earth models while the qualitative interpretation entails the use of software, correlation of anomalous resistivity curves, and classification of the different curves based on the resistivity of the subsurface layers. The interpretation was enhanced with the use of computer iteration software "WinResist". The VES results as output from the processing software were used to produce

a geoelectric section for each of the VES data points to represent the variations in the thickness of overburden materials vertically. Samples of curves obtained from iterated VES data are presented in Figure 3. For the CST data, apparent resistivity values were calculated manually using Excel software and processed using Dipwin software. The software assigns the bulk data into a set of horizontal and vertical rectangular blocks, with some records in each box. The resistivity of each block is then calculated to generate an apparent resistivity pseudo-section.

Figure 3: Samples of VES curves obtained as the output of computer iteration using WinResist software.

4. RESULTS AND DISCUSSION

4.1 Result

The summary of computed Dar-Zarrouk parameters (S , T , ρ_L and ρ_T) obtained from VES analysis is presented in Table 1. Geoelectric sections developed from the interpreted VES data and the inverted 2D resistivity structure from CST profiling are presented in pairs in Figures 4 - 8. In each pair, the first figure (upper) shows the respective sequence of subsurface layer with resistivity and thickness/depth along with a legend depicting the constituting geologic materials. While the second figure (lower) displays the colour-coded lateral and vertical resistivity distribution of the subsurface layer along with colour scale bar. Good agreement exists between the two techniques in all the five traverses investigated. Across the traverses, the aquifer unit is delineated in the last subsurface strata either as the third or fourth layer with indeterminable thickness since current was terminated in this region.

Figure 4: Geoelectric section and 2D resistivity structure along Traverse 1 consisting of VES 1 - 6

Table 1: Summary of computed Dar-Zarrouk parameters from VES analysis

VES	Overburden Longitudinal Conductance S (mho)	Overburden Transverse Resistance T (Ωm^2)	Overburden materials without topsoil	Longitudinal Resistivity ρ_L (Ωm)	Transverse Resistivity ρ_T (Ωm)	Overburden thickness H (m)	Inferred Aquifer Type
1	0.2360	734	Clayey sand	53.81	57.80	12.7	Sand
2	0.6560	1136	Sandy clay	39.02	44.40	25.6	Sand
3	0.3952	398	Clayey sand	30.61	32.85	12.1	Clayey sand
4	0.3460	369	Clayey sand	32.08	33.27	11.1	Clayey sand
5	0.2272	1508	Clayey sand	80.53	82.40	18.3	Sandy clay
6	0.5029	862	Sandy clay	41.36	41.43	20.8	Sandy clay
7	0.2061	366	Sandy clay	41.72	42.56	8.6	nil
8	0.2693	427	Sandy clay	38.99	40.67	10.5	nil
9	0.5921	235	Clay	19.76	20.08	11.7	Sandy clay
10	0.4317	356	Clay	28.49	28.94	12.3	Sandy clay
11	0.2071	530	Clayey sand	47.79	53.52	9.9	Sand
12	0.2161	643	Clayey sand	52.74	56.42	11.4	Sand
13	0.5705	410	Clay	26.64	26.94	15.2	Clayey sand
14	0.1814	616	Sandy clay	57.87	58.62	10.5	Clayey sand
15	0.2893	2046	Clayey sand	84.00	84.22	24.3	Sand
16	0.2489	755	Clayey sand	54.25	55.93	13.5	Sand
17	0.1486	438	Clayey sand	53.17	55.38	7.9	Sand
18	0.3383	1150	Clayey sand	57.95	58.65	19.6	Sand
19	0.3850	679	Sandy clay	41.82	42.18	16.1	nil
20	0.4016	644	Sandy clay	39.84	40.25	16	nil
21	0.1248	572	Clayey sand	67.29	68.10	8.4	nil
22	0.2490	734	Sandy clay	54.21	54.33	13.5	Clayey sand
23	0.4196	1316	Sandy clay	56.00	56.00	23.5	Sand
24	0.5630	727	Sandy clay	35.70	36.16	20.1	Sand
25	0.2725	932	Clayey sand	57.24	59.76	15.6	Sand
26	0.3718	273	Clay/Clayey sand	26.90	27.30	10	Sand
27	0.7736	466	Clay	24.43	24.63	18.9	Clayey sand
28	0.4417	740	Sandy clay	40.75	41.11	18	Clayey sand
29	0.1053	1143	Clayey sand	103.48	104.84	10.9	Clayey sand
30	0.4945	811	Sandy clay	40.44	40.55	20	Clayey sand

Figure 5: Geoelectric section and 2D resistivity structure along Traverse 2 consisting of VES 7 - 12.

Figure 6: Geoelectric section and 2D resistivity structure along Traverse 3 consisting of VES 13 - 18.

Figure 7: Geoelectric section and 2D resistivity structure along Traverse 4 consisting of VES 19 - 24.

Figure 8: Geoelectric section along and 2D resistivity structure along Traverse 5 consisting of VES 25 - 30

5. DISCUSSION

5.2.1 Aquifer potentials

The characteristics of any subsurface medium that would serve as an

aquifer largely depend on its nature (i.e. constituent geologic material) and geometry. Porous and permeable subsurface materials such as sand give the idea of the water storage capacity of the aquifer as well the capacity to transmit water. But porosity can be greatly reduced with the presence of materials such as clay, silt, etc. (Konikow et al., 2001). In this study, sand and clayey sand were delineated as the last subsurface layer in 12 (40%) and 9 (30%) respectively, of the traverses, with the indeterminable thickness (invariably due to current electrode spread used) is presumed as the aquifer. Tables 2 gives the summary of the description of these aquifers across the traverses. The remaining 9 (30%) of the traverses are underlain by either sandy clay or clay as the last subsurface medium and are not recognized as an aquifer, even though porous, cannot transmit water.

With respect to the overburden materials, the aquifers delineated in the study location can be categorized into either unconfined or confined aquifers. An aquifer is said to be confined, if it has layers of aquitard e.g. clay, both above and below, causing it to be under pressure (Neuman, 1972; Parsons, 2004). When a borehole well is drilled into such an aquifer, water is expected to accumulate until it gets to the top of the aquifer. An impermeable formation such as an aquitard possesses very low or zero permeability, hence, low hydraulic conductivity, and has the capacity to restrain groundwater flow. Aquitards are usually composed of unconsolidated, very fine-grained sediments like clay, silt or unbroken rock fragments such as shale, quartz, or basalt (Parsons, 1995). They screen against any infiltration from the Earth's surface into groundwater network and can protect confined aquifers from surface contamination (Neuman, 1972; Nacht, 1983). In contrast, an unconfined aquifer or water table aquifer, usually very close to the land surface is typically overlain by the unsaturated zone and stretches from the top of the water table at atmospheric pressure, down to an impervious aquitard surface (Wilson, 1983; Gardner, 1999; Winter, 1999; Parsons, 2004). Since unconfined aquifers have no impervious barriers above their surface, they are often expose to contamination from the surface. Table 2 gives a summary of delineated sand/clayey sand aquifers.

Table 2: Summary of aquifer types with range of resistivity values and depth

Traverses	VES	Resistivity range (Ωm)	Depth range (m)	Comment
Sand				
1	1, 2	141-230	12.7-25.6	VES1 unconfined/ VES2 confined
2	11, 12	170-172	9.9-11.4	Both unconfined
3	15, 16, 17, 18	125-478	13.5-31.9	unconfined
4	23, 24	116-128	20.1-23.5	Both confined
5	25, 26	140-150	15.6-20.0	VES25 unconfined/VES26 confined
Clayey sand				
1	3,4	66-67	18.3-20.8	Both unconfined
2	nil	-	-	-
3	13, 14	58-80	10.5-15.2	Both confined
4	22	22	13.5	confined
5	27, 28, 29, 30	64-80	10.9-20.0	VES27, 28 & 30 confined VES29 unconfined

5.2.2 Overburden protective capacity

The total longitudinal conductance S has been shown to have a direct relationship with the overburden capacity ratings of geologic materials (Henriet, 1976). Based on this fact, overburden protective capacity ratings inferred from the computed values of S , indicates that the overburden materials above the preferred sand/clayey sand aquifers in most locations provide moderate protective rating viz: 0.3460 - 0.6560 along TR1; 0.2071 - 0.2161 along TR2; 0.2489 - 0.3383 along TR3; 0.2490 - 0.5630 along TR4 and 0.2725 - 0.7736 along TR5. Only VES27 along TR5 has a fairly good

protective capacity (0.7736) against infiltration of contaminants from the surface. Weak protective capacity characterizes VES14 (0.1814) and 17 (0.1486) along TR3, VES21 (0.1248) along TR4, and VES 29 (0.1053) along TR5. Overburden containing clayey materials usually protects the underlying aquifer. The low values of protective capacity may be due to the generally low overburden thickness, 7.9 - 25.6 (Table 1) across all the traverses in the study area. Also, the cross plot of S against H (Figure 9) shows a coefficient of correlation of 0.58, implying a fair dependence of S on H .

Table 3: Overburden protective capacity rating (Henriet, 1976)

Total longitudinal conductance (S)	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

The total transverse resistance, T , which depicts varying thickness of a high resistivity material and the variation in the hydraulic conductivity values varies from a minimum of 235 Ωm^2 at VES9 to a maximum of 2046 Ωm^2 at VES15. Increasing T has a correlation with an increase in the thickness of highly resistive materials. High values of T are indicative of zones with high transmissivity and thereby suggests a high probability of the underlying aquifer becoming contaminated by infiltrating pollutants from the surface. The cross plot of T against H (Figure 10) shows a coefficient of correlation of 0.69 indicating a moderate correspondence between T and H . Also, any location with a combination of low overburden protective capacity rating (low S) and high transmissivity (high T) (oval region I in Figure 11) will probably favour contaminant leaching and migration into the underlying aquifer system. Oval region II of moderate/good S and low T will offer some degree of protection to the underlying aquifer with low transmission of surface contaminants. The locations lying within oval region III with moderate/low S coupled with low T has weak protective capacity and low transmissivity.

The variations of ρ_L and ρ_T at the VES points are noteworthy. ρ_L ranges from 19.76 - 103.48, while ρ_T ranges from 20.08 - 104.84, showing that ρ_T is slightly higher than ρ_L at each of the VES points in agreement with Flathe, which confirms that current flow and mean hydraulic conduction parallel to geologic boundaries (longitudinal) are greater relative to those normal to the boundary plane (Flathe, 1955). A maximum difference of 5.72 occurs at VES13 and a difference of approximately 0.00 at VES25 (Table 1). The cross plot of ρ_T against ρ_L (Figure 12) support the linear relationship between the two parameters with a coefficient of correlation of 0.99. Furthermore, at 57% (17) of the VES points, the difference is < 1 and at 40% (12) of the VES points, it is > 1. The lower longitudinal resistivity values are a confirmation of the presence of conductive clayey materials in the overburden (Keller, 1982).

Figure 9: Cross plot of total longitudinal conductance (S) against overburden thickness (H).

Figure 10: Cross plot of total transverse resistance (T) against overburden thickness (H).

Figure 11: Cross plot of total transverse resistance (T) total longitudinal conductance (H).

Figure 12: Cross plot of total transverse resistivity (ρ_T) and against longitudinal resistivity (ρ_L).

6. CONCLUSION

Groundwater studies have been carried out within a fast-growing and developing community at Mowe, Southwest Nigeria using electrical resistivity techniques that involved VES and 2-D profiling techniques. The protective capacity ratings of geological materials overlying the aquifers and potential groundwater aquifer for groundwater development have been evaluated. Sand and clayey sand presumed as the aquifer

(confined/unconfined) have been delineated as the last subsurface layer in 12 (40%) and 9 (30%) respectively, of the sampled locations. The remaining 9 (30%) of the traverses are underlain by either clay or sandy clay as the last subsurface layer. Of these aquifers, 78% are confined, while 22% are unconfined.

Overburden protective capacity rating inferred from the computed values of total longitudinal conductance S , shows that the overburden materials above the preferred sand/clayey sand aquifers in most locations provides moderate protective rating along all the traverses except for VES27 along TR5 which has a fairly good protective capacity (0.7736) and can shield against the infiltration of contaminants from the surface. Two locations along TR3, one location along TR4 and TR5 respectively are characterized by weak protective capacity ratings (0.1053-0.1814). Conventionally, overburden with clayey materials is expected to provide a good protective capacity rating, low values of protective capacity defined in the study area are possibly due to the generally low overburden thickness, 7.9 - 25.6. The coefficient of correlation of 0.58 between S and H attests to this fact.

The total transverse resistance, T , which depicts varying thickness of a high resistivity material and the variation in the hydraulic conductivity values varies from a minimum of 235 Ωm^2 at VES9 to a maximum of 2046 Ωm^2 at VES15. Increasing T has a correlation with an increase in the thickness of highly resistive materials. High values of T are indicative of zones with high transmissivity, thereby suggesting a high probability of the underlying aquifer becoming contaminated by infiltrating pollutants from the surface (moderate correlation coefficient of 0.69). Locations characterized by low overburden protective capacity rating and high transmissivity will support contaminant leaching and migration in the groundwater supply system.

Excellent correlation (0.99) was established between ρ_L and ρ_T and with ρ_T slightly higher than ρ_L at all the VES points which confirms preferential longitudinal conduction path. The lower longitudinal resistivity is evidence of the presence of more conductive clayey materials in the overburden.

CONFLICT OF INTEREST

The authors of this article declare that there is no conflict of interest in any in relation to the work carried out in the research.

AUTHOR CONTRIBUTION

Professor K.F. Oyedele supervised the project from conceptualization to execution. Dr. O.B. Olatinsu developed the article for publication.

COMPLIANCE WITH ETHICAL STANDARDS

This article does not contain any studies involving life, whether animal or human, performed by any of the authors.

FUNDING

No funding was received to accomplish this study.

ETHICAL CONDUCT

The authors have conformed with all ethical conducts required in a work like this.

ACKNOWLEDGEMENT

The authors wish to express their gratitude to Mr. Samuel Udofia, GIS Unit, Geography Department, University of Lagos, for assisting with the maps.

REFERENCES

- Adabanija, M.A., Ajibade, R.A., 2020. Investigating groundwater corrosion and overburden protective capacity in a low latitude crystalline basement complex of southwestern Nigeria. *NRIAG Journal of Astronomy and Geophysics*, 9 (1), Pp. 245-259. <https://doi.org/10.1080/20909977.2020.1723867>.
- Adegoke, O.S., 1969. Eocene Stratigraphy of Southern Nigeria. Colloque sur Eocene Vol. III Bur. Rech. Geol. Min. Mem., 69, Pp. 23-48.
- Adegoke, O.S., Jeje, L.K., Durotoye, B., Adeleye, D.R., and Ebukanson, E.E., 1981. The Geomorphology and Aspects of Sedimentology of Coastal Region of Western Nigeria. *J. Min. Geol.*, 17 (2), Pp. 217-223.

- Archie, G.E., 1942. The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics. *Trans.*, 146 (01), Pp. 54-62. Paper Number: SPE-942054-G <https://doi.org/10.2118/942054-G>
- Ayuk, M.A., 2019. Groundwater Aquifer Vulnerability Assessment using a Dar-Zarrouk Parameter in a Proposed Aboru Residential Estate, Lagos State, Nigeria. *J. Appl. Sci. Environ. Management*, 23 (12), Pp. 2081-2090.
- Batayneh, A.T., 2013. The estimation and significance of Dar-Zarrouk parameters in the exploration of quality affecting the Gulf of Aqaba coastal aquifer systems. *Journal of Coastal Conservation*, 17, Pp. 623-635. <https://doi.org/10.1007/s11852-013-0261-4>.
- Bovolo, C.I., Parkin, G. and Sophocleous, M., 2009. Groundwater resources, climate and vulnerability. *Environ. Res. Lett.* 4, Pp. 035001.
- Braga, A.C.O., Filho, W.M., Dourado, J.C., 2006. Resistivity (DC) method applied to aquifer protection studies. *Brazilian Journal of Geophysics*, 24, Pp. 573-581.
- Braga, A.C.O., 2008. Estimation of the natural vulnerability of aquifers: a contribution from the resistivity and longitudinal conductance. *Brazilian Journal of Geophysics*, 26 (1), Pp. 61-68
- Braga, A.C.O., Francisco, R.F., 2014. Natural vulnerability assessment to contamination of unconfined aquifers by longitudinal conductance - (S) method. *Journal of Geography and Geology*; 6 (4), Pp. 68-79.
- British Geological Survey. 2008. Groundwater Information Sheet: The Impact of Industrial Activity, Pp. 6.
- Casas, A., Himi, M., Diaz, Y., Pinto, V., Font, X. and Tapias J.C.A., 2008. Assessing aquifer vulnerability to pollutants by electrical resistivity tomography (ERT) at a nitrate vulnerable zone in NE Spain. *Environ. Geol.*, 54, Pp. 515-520. DOI 10.1007/s00254-007-0844-1
- Christensen, N.B., Sørensen, K.I., 1998. Surface and Borehole Electric and Electromagnetic Methods for Hydro-Geophysical Investigations. *European Journal of Environmental and Engineering Geophysics*, 3, Pp. 75-90.
- Cosgrove, W.J., Loucks, D.P., 2015. Water management: Current and future challenges and research directions, *Water Resour. Res.*, 51, Pp. 4823-4839, doi:10.1002/2014WR016869.
- Döll, P., 2009. Vulnerability to the impact of climate change on renewable groundwater resources: a global-scale assessment. *Environ. Res. Lett.*, 4, Pp. 035006.
- Flathe, H., 1955. Possibilities and limitations in applying geoelectrical methods to hydrogeological problems in the coastal area of northwest Germany. *Geophysical Prospecting*, 3, Pp. 95-110. DOI: <https://doi.org/10.1111/j.1365-2478.1955.tb01363.x>.
- Gardner, K.M., 1999. The importance of surface water/groundwater interactions - Report EPA-910-R-99-013, Environmental Protection Agency, Seattle.
- Hasan, M., Yanjun, S., Weijun, J., Gulraiz, A., 2019. Assessment of aquifer vulnerability using integrated geophysical approach in weathered terrains of south China. *Open Geosciences*, 11 (1), Pp. 1129-1150. <https://doi.org/10.1515/geo-2019-0087>.
- Henriet, J.P., 1976. Direct application of the Dar-Zarrouk parameters in groundwater survey. *Geophysical Prospecting*, 24, Pp. 344-353. <https://doi.org/10.1111/j.1365-2478.1976.tb00931.x>.
- Gupta, G., Patil, S.N., Padmane, S.T., Erram, V.C., Mahajan, S.H., 2015. Geoelectric investigation to delineate groundwater potential and recharge zones in Suki River basin, north Maharashtra. *J. Earth Syst. Sci.*, 124 (7), Pp. 1487-1501. DOI: 10.1007/s12040-015-0615-4.
- Jones, H.A., Hockey, R.D., 1964. The geology of part of south western Nigeria. *Geol. Survey. Nigeria, Bull.*, 31, Pp. 1-101.
- Kampsax-Kruger and Sshwed Associates, 1977. Underground water resources of the Metropolitan Lagos", Final Report to Lagos State Ministry of Works, Pp. 170.
- Keller, G.V., 1982. Electrical properties of rocks and minerals: In: Handbook of Physical Properties of Rocks (ed.) Carmichael R.S., CRC Press, Pp. 217-293.

- Khalil, M.H., 2009. Hydro geophysical assessment of Wadi El-Sheikh aquifer, Saint Katherine, South Sinai, Egypt. *J. Environ. Eng. Geophys.*, 14 (2), Pp. 77-86. <https://doi.org/10.2113/JEEG13.2.77>.
- Khatri, N., Tyagi, S., 2015. Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas, *Frontiers in Life Science*, 8 (1), Pp. 23-39, DOI: 10.1080/21553769.2014.933716.
- Konikow, L.F., August, L.L., Voss, C.I., 2001. Effects of clay dispersion on aquifer storage and recovery in coastal aquifers. *Transport in Porous Media*, 43, Pp. 45-64. <https://doi.org/10.1023/A:1010613525547>.
- Konikow, L.F., Neuzil, C. E., 2007. Method to estimate groundwater depletion from confining layers. *Water Resources Research*, 43, Pp. W07417. doi:10.1029/2006WR005597.
- Machiwal, D., Kumarjha, M., Singh-V.P., Mohan, C., 2018. Assessment and mapping of groundwater vulnerability to pollution: Current status and challenges. *Earth-Science Reviews*, 185, Pp. 901-927. <https://doi.org/10.1016/j.earscirev.2018.08.009>.
- Maduabuchi, C.M., 2004. Surface and groundwater resources monitoring and management in Nigeria United Nations/Austria/ESA Symposium on Space Applications for Sustainable Development, Graz, Austria, 13-16 September.
- Maillet, R., 1947. The fundamental equations of electrical prospecting. *Geophysics*, 12, Pp. 529-526. <https://doi.org/10.1190/1.1437342>.
- Mondal, N.C., Singh, V.P., Ahmed, S., 2013. Delineating shallow saline groundwater zones from southern India using geophysical indicators. *Environ. Monit. Assess.*, 185, Pp. 4869-4886. <https://doi.org/10.1007/s10661-012-2909-1>.
- Mousatov, A., Ryjov, A., 2005. Geoelectrical Characterization of Oil Contaminated Site in Tabasco, Mexico. *Geofis. Int.*, 44 (3), Pp. 251-263. DOI:10.22201/igeof.00167169p.2005.44.3.197
- Nacht, S.J., 1983. Groundwater monitoring system considerations. *Groundwater Monitoring and Remediation*, 3 (2), Pp. 33-39. <https://doi.org/10.1111/j.1745-6592.1983.tb01197.x>.
- Nel, J., Xu, Y., Batelan, O., Brendonck, L., 2009. Benefit and Implementation of Groundwater Protection Zoning in South Africa. *Water Resources Management*, 23, Pp. 2895. <https://doi.org/10.1007/s11269-009-9415-4>.
- Neuman, S.P., 1972. Theory of flow in unconfined aquifers considering delayed response of the water table. *Water Resour. Res.*, 8 (4), Pp. 1031-1045. doi:10.1029/WR008i004p01031
- Niwas, S., Singhal, D.C., 1981. Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *J. Hydrol.*, 50, Pp. 393-399. [https://doi.org/10.1016/0022-1694\(81\)90082-2](https://doi.org/10.1016/0022-1694(81)90082-2)
- Niwas, S., Singhal, D.C., 1985. Aquifer transmissivity of porous media from resistivity data. *J. Hydrol.*, 82, Pp. 143-153. [https://doi.org/10.1016/0022-1694\(85\)90050-2](https://doi.org/10.1016/0022-1694(85)90050-2)
- Ogbe, F.G.A., 1972. Stratigraphy of strata exposed in the Ewekoro quarry, Western Nigeria. In: T. F. J. Dessauvage and Whiteman (Eds) *African Geology*, University Press, Nigeria, Pp. 305- 322.
- Olayinka, A.I., Yaramanci, U., 2000. Assessment of the reliability of 2D inversion of apparent resistivity data. *Geophys. Prospec.*, 48, Pp. 293-316.
- Omatsola, M.E., Adegoke, O.S., 1981. Tectonic Evaluation and Cretaceous Stratigraphy of the Dahomey Basin. *Journal of Mining and Geology*, 18 (1), Pp. 130-137.
- Oroji, B., 2018. Assessing groundwater vulnerability by pollution mapping in Iran: Case study Hamadan – Bahar plain. *Geofisica Internacional*, 57 (3), Pp. 161-174. DOI: 10.22201/igeof.00167169p.2018.57.3.2108
- Parsons, R.P., 1995. A South African aquifer system management classification; WRC report KV 77/95, Water Research Commission, Pretoria.
- Parsons, R., 2004. Surface Water – Groundwater Interaction in a Southern African Context Prepared for the Water Research Commission WRC Report No. TT 218.
- Reyment, R.A., 1965. Aspects of the Geology of Nigeria Ibadan University Press. Ibadan. Pp. 145.
- Russ, W., 1924. The phosphate deposits of Abeokuta Province. *Geol. Surv. Nigeria, Bull.*, 7, Pp. 1 – 43.
- Salem, H.S., 1999. Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurements. *Hydrology and Earth System Sciences*, 3 (3), Pp. 421-427. DOI: 10.5194/hess-3-421-1999.
- Singh, U.K., Das, R.K., Hodlur, G.K., 2004. Significance of Dar-Zarrouk parameters in the exploration of quality affected coastal aquifer systems. *Environ Geol.*, 45, Pp. 696-702. <https://doi.org/10.1007/s00254-003-0925-8>.
- Sørensen, K.I., Auken, E., Christensen, N.B., Pellerin, L., 2005. An Integrated Approach for Hydro-geophysical Investigations: New Technologies and a Case History. In: Butler, D.K. (Ed.).
- Turner, N., Wurster, F., 2017. Water Resource Inventory and Assessment Summary Report – FY17 Northeast Region, Pp. 91.
- Umar, N.D., Igwe, O., 2019. Geo-electric method applied to groundwater protection of a granular sandstone aquifer. *Appl water Sci.*, 9, Pp. 112. <https://doi.org/10.1007/s13201-019-0980-2>.
- Vandas, S.J., Winter, T.C., and Battaglin, W.A., 2002. Water and the Environment. American Geosciences Institute Environmental Awareness Series, Pp. 42-44.
- Walker, D.B., Baumgartner, D.J., Gerba, C.P., Fitzsimmons, K., 2019. Chapter 16 - Surface Water Pollution, Environmental and Pollution Science (Third Edition), Pp. 261-292. <https://doi.org/10.1016/B978-0-12-814719-1.00016-1>.
- Whiteman, A.J., 1982. Nigeria: Its petroleum geology, resources and potentials. Graham and Trotman, London, U.K, (1) 176, Pp. 238.
- Wilson, L.G., 1983. Monitoring in the vadose zone: Part 3. *Groundwater Monitoring Review*, 3 (1), Pp. 155-166.
- Winter, T.C., Harvey, J.W., Franke, O.L., Alley, W.M., 1999. Ground water and surface water – a single resource; USGS Circular 1139, United States Geological Survey, Denver. <https://doi.org/10.3133/cir1139>
- Worrall, F., Kolpin, W., 2003. Direct assessment of groundwater vulnerability from single observations of multiple contaminants *Water Resources Research*, 39 (12), Pp. 1345, doi:10.1029/2002WR001212, 2003.
- Zereg, S., Boudoukha A., Benaabidate, L., 2018. Impacts of natural conditions and anthropogenic activities on groundwater quality in Tebessa plain, Algeria. *Sustainable Environment Research*, 28 (6), Pp. 340-349. <https://doi.org/10.1016/j.serj.2018.05.003>,
- Zohdy, A.R., 1965. The auxiliary point method of electrical sounding interpretation and its relationship to the Dar Zarrouk parameters. *Geophysics*, 30, Pp. 644-660. <https://doi.org/10.1190/1.1439636>.
- Zohdy, A.R., 1974. Use of Dar Zarrouk curves in the interpretation of vertical electrical sounding data. United States Geological Survey Bulletin 1313-D, 41, Pp. 4. <https://doi.org/10.3133/b1313D>.