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EVALUATION OF THE OVERBURDEN PROTECTIVE CAPACITY OF AQUIFER-AQUITARD SYSTEMS IN AGBARA TOWN, SOUTHWESTERN NIGERIA USING ELECTRICAL RESISTIVITY TECHNIQUES

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ABSTRACT

This study utilized electrical resistivity techniques to assess the protective capacity of overburden materials within Agbara industrial area in southwestern Nigeria. Forty vertical electrical sounding (VES) stations and six 2-D traverses were occupied using Schlumberger and Wenner configurations, respectively. Both techniques suggest the existence of a multi-layered aquifer-aquitard systems, characterized by a lithological sequence presumably composed of sand and clayey sand, of moderate resistivity, alongside clay of low resistivity and high-resistivity hard clay. At most locations, thin unconfined phreatic sand or clayey sand aquifers were identified at shallow depths less than 5 m. Seasonal variations in groundwater volume and quality usually render phreatic aquifers unsuitable for long-term sustainable groundwater development. Much deeper sand/clayey sand aquifers (5.0 - 68.0 m) were identified at seventy percent of the surveyed locations. At twenty VES stations, impermeable subsurface zones were delineated: clay layers with resistivity in the range 29 - 71 Ωm and thickness range of 2.5 -10.0 m and hard clay medium with resistivity range of 818 - 2557 Ωm and thickness range 1.4 - 52.4 m. Clay materials are common aquitard which act as lithological barriers since they can impede the movement of contaminants into groundwater. In contrast, if the clay is hard, compacted, and consolidated, cracks can quickly allow water and dissolved pollutants to enter aquifer systems. Computed values of overburden protective capacity (longitudinal conductance) portrayed significant variations with twenty-seven (67.5%) locations showing poor ratings (0.0027 - 0.0813 S); nine locations (22.5%) exhibiting weak ratings (0.1044 - 0.1824 S); and only four (10%) indicating moderate ratings (0.348 - 0.472 S). Moderate to very high overburden transverse resistance (filtration coefficient) values (544 - 81105 Ωm^2) also support these ratings. The findings indicate that the aquifers in these areas are vulnerable to contamination, which should be a critical concern in groundwater projects in this area.

Keywords: electrical resistivity assessment, subsurface protective capacity, aquifer, aquitard, Agbara Town, fracture.

INTRODUCTION

Groundwater as an essential and abundant natural resource has continued to face many threats from the effects of industrialization, urbanization and population growth. Its steady and continuous availability is critical and indispensable for energy, food security, human health, population and socioeconomic growth, ecosystems, marine preservation and conservation (Foster *et al.*, 2013; Gleeson *et al.*, 2015, 2020; Lee and Kim, 2021). Several factors affecting groundwater availability and use are both natural and man-made. These include climate, geology, aquifer pollution, over-abstraction, and supply and distribution infrastructure limitations. Beyond present discovery, exploration and exploitation, the sustainability of groundwater resource is also very crucial to meet current and future beneficial uses without causing unacceptable environmental or socioeconomic consequences (Alley *et al.*, 1999; Gleeson *et al.*, 2010; Smith *et al.*, 2016; Thomas *et al.*, 2017). To ensure the long-term sustainability of aquifer yields and availability of water, there is need for wholesome consideration of protection and preservation from contamination.

Classification of groundwater systems as renewable or non-renewable is often based on natural fluxes of recharge or on estimates of aquifer volume storage and groundwater residence time (Cuthbert *et al.*, 2023). Although the rate of groundwater replenishment and renewal varies significantly depending on geological and environmental conditions, groundwater is in some respects a renewable resource (Altchenko and Villholth, 2015; Loucks and van Beek, 2017; Jasechko *et al.*, 2024). As a significant part of the water cycle, the renewal process is facilitated in part by the infiltration and percolation of water from rivers, runoff, and precipitation. The vast majority of people on the planet depend on groundwater for drinking and other household purposes. The greater number of people in rural, peri-urban, and urban settlements use it for irrigation and household needs (Howard *et al.*, 2003; Shah *et al.*, 2003; Lapworth *et al.*, 2017a, 2017b; Li *et al.*, 2021; Murei *et al.*, 2023; Lee *et al.*, 2024). In addition to this fundamentally growing use, the current global issues brought on by the effects of climate change have increased the significance and demand for groundwater resources (Holman, 2006; Dragoni and Sukhija, 2008; Villholth, 2009; Stigter *et al.*, 2023). It is becoming increasingly apparent that climate change has the potential to impact and disrupt human survival and existence by endangering the stability of our food, energy, and water systems. (Carter and Parker, 2009; FAO, 2015; Suri, 2024).

Groundwater protection has now become a worldwide issue due to growing concerns about possible contamination with the consequential deterioration in groundwater quality (Jones, 1997; Sophocleous, 2000; Nair and Indu, 2021). The heavy reliance on groundwater has been attributed to a number of advantages over other sources of water for human consumption. Groundwater is generally of high quality in its natural, unaltered state and is fit for human consumption even in the absence of treatment. In addition, Groundwater can be exploited inexpensively and delivered close to the point of use, thereby saving on the cost of transporting water over long distances. In numerous communities where rural inhabitants depend on private wells and public water sources, groundwater frequently constitutes the sole available water supply. Recent available data has shown that groundwater consumption is increasing at twice the rate of surface water consumption (Fienen and Arshad, 2016; Kourakos *et al.*, 2019; Pointer, 2022). Furthermore, it is anticipated that this trend will persist due to the projected increase in future water demand (Boretti and Sosa, 2019). Therefore, safeguarding the quality of current, future and prospective groundwater supplies is a critical issue that requires immediate attention. Any groundwater development and protection plan, as well as the methods used, are greatly influenced by the geological and physical features of the aquifer formation and its immediate surroundings. An aquifer unit can be a layer of gravel, sand, or other subsurface materials, or it can be a piece of bedrock with water-flowing fractures. Urbanization, industrialization, agriculture, mining, and exploration activities are all posing a growing threat to surface and groundwater pollution (Biswas, 1991). However, there are several ways in which groundwater pollution differs from surface. The majority of the time, pollutants enter surface water directly, but those that infiltrate groundwater must first pass through certain soil materials above aquifers. Because of this, things like chemicals, medications, fuel, fertilizer, road salt, bacteria, viruses, etc. can be found in groundwater close to underground oil and gas tanks, septic tanks, landfills, and industrial facilities, among other places (Brindha and Schneider, 2019).

Numerous places in Lagos and Ogun States, the two main industrial nerve centers in Nigeria, are home to industrial estates and parks that are both prominent and bustling. These locations include Sagamu, Sango-Ota, and Agbara in Ogun State, and Ilupeju, Ikeja, Apapa, and Ikorodu in Lagos State. The rapid urbanization of Agbara Town has led to an increase in waste generation, primarily from manufacturing industries. As a result, the area is characterized by household waste, large amounts of industrial waste, and sewage from treatment plants. Toxic components in the effluents released from industrial plants have caused groundwater pollution in multiple locations as a result of flagrant disregard for pollution reduction and abatement measures. If buried underground storage tanks leak or leachate from decomposed waste dumps seeps into the groundwater resource in industrial areas, the groundwater resource could become contaminated (Hudak *et al.*, 1999; Olukoya *et al.*, 2016; Zhang *et al.*, 2016; Sharma *et al.*, 2018; Naveen and Malik, 2019; Ogunlaja *et al.*, 2019; Siddiqua *et al.*, 2022). Therefore, to ascertain the degree of protection of the hydrogeologic and aquifer systems within any industrial zone, it becomes necessary to conduct a scientific evaluation of the protective capacity of the overburden materials above potential aquifer zones in the area. Geophysical studies are among the best, easy to execute, implement and less expensive methods for carrying out the assessment without intruding into the hydrogeologic settings. Because aquifers, aquitards, sediments, and bedrock frequently exhibit different resistivity or conductivity, a variety of geophysical survey, especially the electrical (geoelectrics) and electromagnetic methods, are commonly used to investigate groundwater conditions as well as aquifer structure and geometry (Buselli and Lu, 2001; Karlik and Kaya, 2001; Paepen *et al*., 2020). The techniques used in these two categories are typically non-invasive, reasonably priced, and provide quantitative description and evaluation capabilities (Flathe, 1955. Keller and Frischknecht, 1966; Zohdy, 1969; Zohdy *et al*., 1974; Roy and Elliot, 1980; Fitterman and Stewart, 1986, Goldman and Neubauer, 1994; Sikandar and Christen, 2012). To evaluate groundwater potential and the protective capacity rating of subsurface materials covering aquifer units within the Agbara industrial zone, an electrical resistivity survey was carried out using vertical electrical sounding and 2-D imaging techniques. The objective was to provide geoscientific data that will greatly assist in the planning, development, and management of groundwater resources in the area.

LOCATION AND GEOLOGY OF THE STUDY AREA

Agbara Town, located in the Ado-Odo/Ota local government area, is roughly 25 km west of metropolitan Lagos. It is currently the primary industrial hub in West Africa, where trade, residential structures, and manufacturing industries coexist. Situated between Lagos and Ogun States, it is a highly industrialized place that is home to several domestic and international manufacturing companies. Additionally, the Industrial Estate is near two residential estates, Agbara and OPIC Estates, as well as Agbara Parks. The environment will definitely face some challenges due to industrial and human waste emanating from industries and estates. There are also numerous economic pursuits being carried out especially by artisans and technicians within the community such as in wood mills, automobile mechanic workshops, solid waste combustion site as well as farming sites. It is probable that these actions will lead to the release of anthropogenic substances and pollutants into the environment.

Geographically, the community is an expanse of land that lies on latitude $6^0\,28'\,13''$N and longitude $3^0\,28'\,30''$N. It falls within the eastern segment of the Dahomey Basin (Figure 1), which stretches from southern Ghana through southern Togo and southern Benin Republic (Dahomey) to southwest Nigeria (western flank of the Niger Delta Basin). The western border between Nigeria and the Benin Republic is where the basin's axis with the thickest sediments is located (Adegoke, 1969, 1972; Okosun, 1990). To the west, faults and other tectonic features enclose the basin. The Benin Hinge, a significant fault structure at the western end of the Niger Delta Basin, marks the eastern boundary. To the west of the Benin Hinge line is the Okitipupa Ridge (Adegoke, 1969; Adegoke, 1977). The Maastrichtian onshore is the Dahomey Basin's oldest sedimentary sequence (Stansky, 1962; de Klasz, 1978). Boreholes data has also revealed some older sediments offshore (Billman, 1976). These oldest pre-Albian sediments are folded, non-fossiliferous rocks with an unknown thickness. Pleistocene to Recent stratigraphic layers is the youngest. The lithology and texture of the sediment within the eastern Dahomey Basin vary greatly; surface observations in some areas of the study area reveal primarily lowly rusty red soil (lateritic soil), whereas high-level ground is clayey with a small number of sandy areas (Billman, 1976; Omatsola and Adegoke, 1981). Agbara's identified stratigraphy revealed that the area is primarily made up of five subsurface layers: sandy ferruginous top soil (Reddish clay) makes up the first two layers; clayey units/soil make up the third layer; sandy aquifers make up the fourth layer; and grayish dark clay makes up the fifth and last layer. The area is characterized by two distinct seasons: a short dry season (October to March) and a long-wet season (April to October), with an annual rainfall of about 1,783 mm. The relative humidity ranges from 57.6% to 82.1%, while the temperature ranges from 22.3 °C to 29.5 °C.

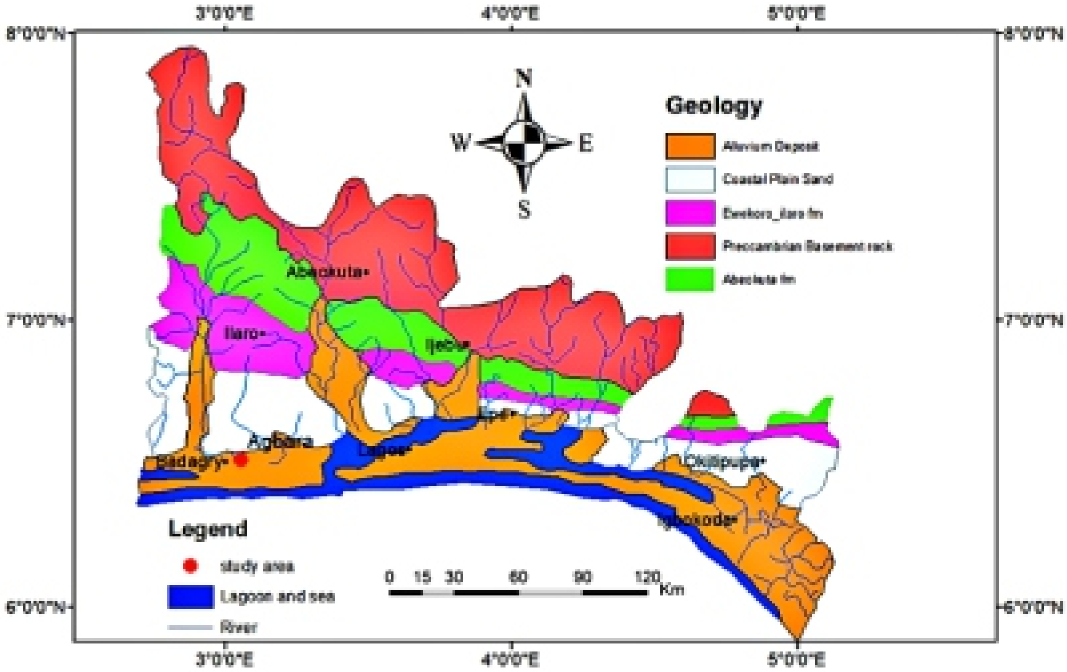

Figure 1: Agbara Town's location on a geology map of the Eastern Dahomey Basin. Adapted from the work of Aladejana *et al.* 2020.

MATERIALS AND METHODS

Data Acquisition

The field survey was conducted using a PASI resistivity meter and its accessories along six traverses for 2-D electrical imaging and Vertical Electrical Sounding (VES) techniques. At various locations along the six traverses, forty VES stations were occupied (Figure 2). The Garmin 12 Global Positioning System was used to acquire the VES stations' coordinates for potential future precise georeferencing. Current electrode separation (AB) at the different locations ranged from a minimum of 2.0 m to a maximum of 700 m using the Schlumberger configuration for VES data acquisition. The VES electrodes are oriented and positioned throughout the traverses in both west-east and north-south directions. For the 2-D resistivity imaging technique, the Wenner array electrode configuration was employed. By deploying this technique, many data points can be recorded simultaneously for each current injection with this electrode configuration, which is ideal for field data acquisition systems with constant separation traverse (CST) approach. Profile spacing for the six distinct profiles was determined by the field's accessible points (Figure 2). Due to the limitation of comparatively shorter profiles possible within the study location, measurements were taken at 10 m intervals using four electrodes for traverses in order to obtain high-quality data.

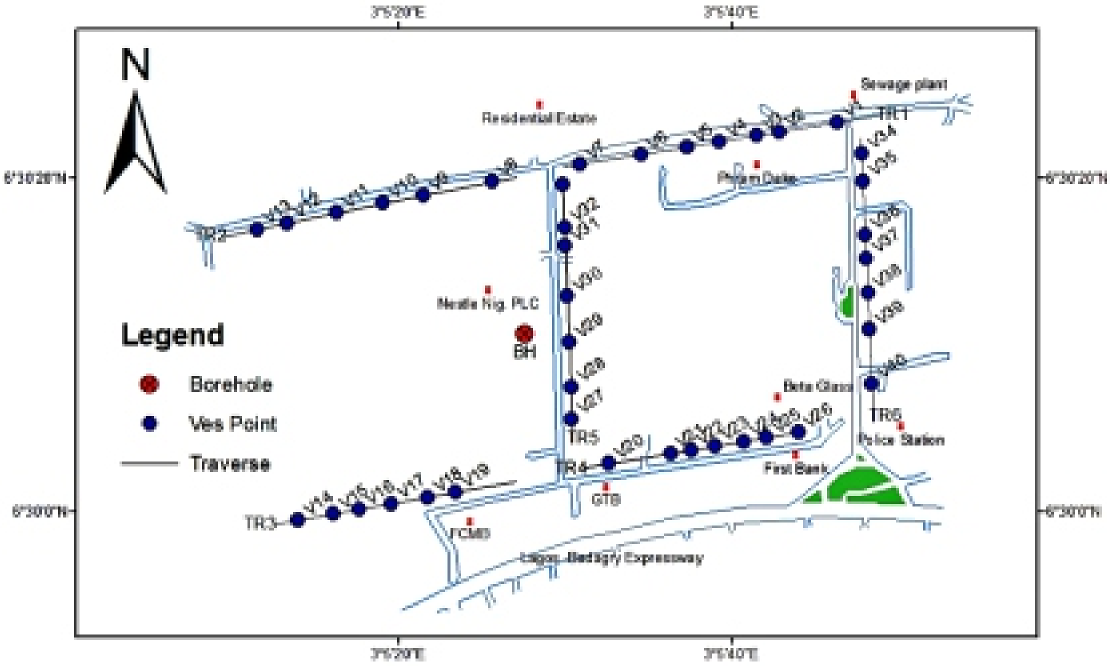

Figure 2: Map displaying the study location data acquisition setup, including the locations of one borehole, 2D traverses, and VES stations.

Data Processing and Interpretation

The first step carried out in processing the VES field data was to multiply the resistance readings taken straight from the resistivity meter by the appropriate geometric factor to get the apparent resistivity values. The WinGLinK software (SLB) was used to import the sets of calculated apparent resistivity values and half-electrode spacing (AB/2) for every VES station. By removing the superimposed random noise, this software, which has strong workflows for data visualization and editing, map attribute construction, model building, and inversion, assisted in smoothing the apparent resistivity field data curve (Zohdy, 1989; Ward, 1990). With the aid of the geological and available borehole data in the study area, the WinGLinK output was used as the initial model parameters (thicknesses and corresponding resistivities) for the delineated subsurface layers. The WinResist modeling program was then used to enter the initial model parameters for further processing (Vander Velpen, 2004). To find the best fit between the calculated field curve and the smoothed one, quick computer iterations were performed using the WinResist software. The final models' root mean square (RMS) errors varied from 0.5 % and 2.4 %. The sounding curves and summary of layer resistivities and thicknesses obtained for the final models were imported into the MATLAB program platform for presentation (Figure 3). Using ArcGIS software (ESRI Inc.), geoelectric sections were created using the summary of results from VES interpretation (layer resistivities and thicknesses) for the study site with the help of the borehole log data (Figure 4).

The protective capacity rating of the subsurface geological materials covering the aquifer unit beneath the VES stations was based on the Dar-Zarrouk parameters, namely the longitudinal conductance and the transverse resistance. These were computed for the sequence of geoelectric layers starting with the first layer (topsoil) to the layer directly above the delineated aquifer at each VES station (Maillet, 1947; Keller and Frischknecht, 1966; Zohdy *et al.*, 1974; Henriet, 1976; Ward, 1990). The apparent resistivity values from the 2-D resistivity data acquisition were also processed using forward modeling with the aid of Dipro software. The smoothness-constrained least squares method is the mathematical foundation of this program. The bulk data is separated by the Dipro program into a number of rectangular blocks that are both horizontal and vertical, with several records in the blocks. Apparent resistivity pseudo sections were then created by computing the resistivity of each block. For consistency, the pseudosection and the real measurements were then compared and contrasted. The forward model is deemed erroneous and is rejected if there is a substantial difference between the processed pseudosection and the measured one.

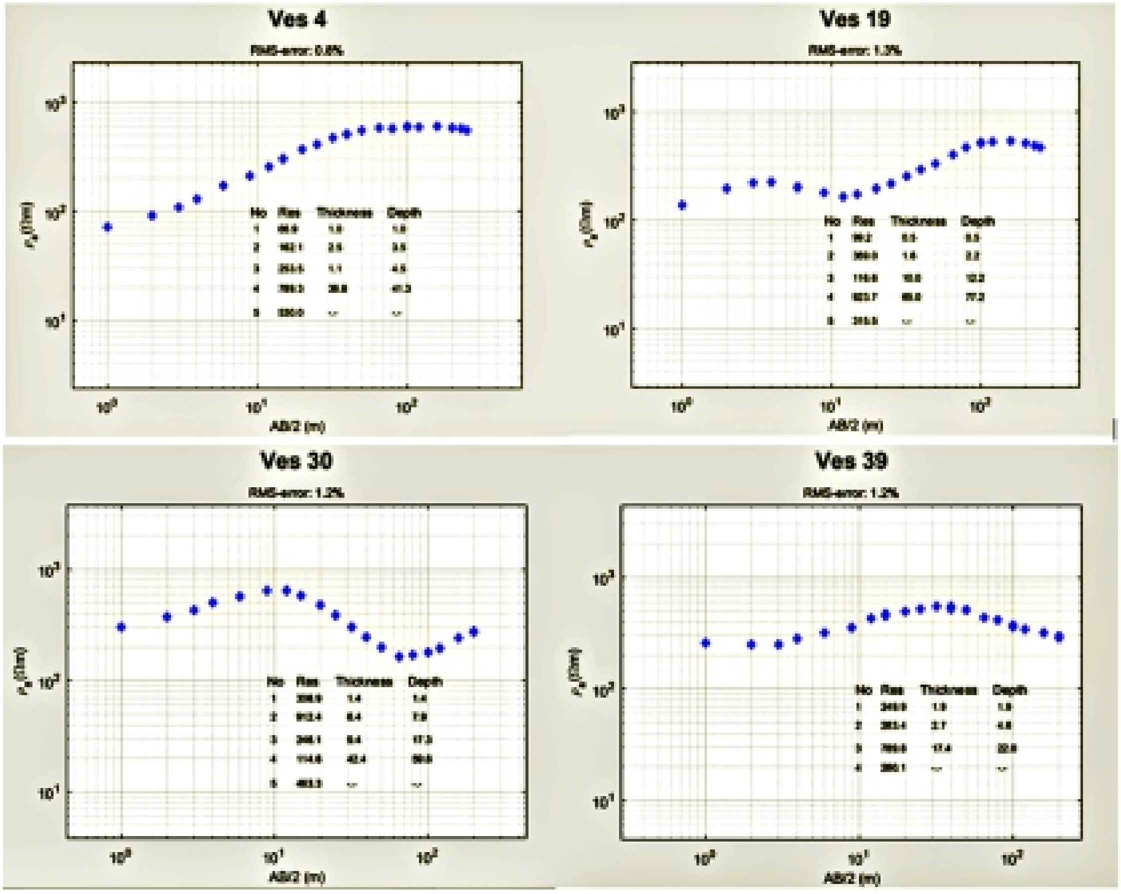

Figure 3: Representative resistivity (VES) curves produced by processing data with WinResist and WinGLink software in MATLAB format.

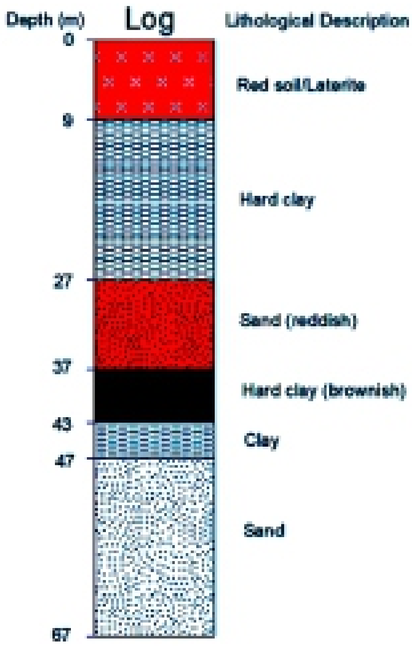

Figure 4: The borehole log used for correlation of VES and 2-D data analysis and interpretation.

RESULTS AND DISCUSSION

The results of this study are presented as: (i) 1-D vertical representation of stratified layers (geoelectric cross-sections which show the apparent resistivities and depths/thicknesses) derived from the VES interpretation in combination with the available borehole data (Figure 4) for a site within the study location that served as the interpretation control (Figures 5–10); (ii) 2-D resistivity structures which show both vertical and lateral resistivity distributions (Figures 11–16); (iii) a table of summary which shows the details of the VES interpretation (Table 1); and the cross plots of longitudinal conductance versus overburden thickness, transverse resistance versus overburden thickness, and transverse resistance versus longitudinal conductance (Figures 17–19). Overburden protective capacity rating was classified based on Henriet (1976) scale (Table 2) using the computed longitudinal conductance in conjunction with the transverse resistance (filtration coefficient) values derived from the layer resistivities and thicknesses of the subsurface strata beneath the sounding stations.

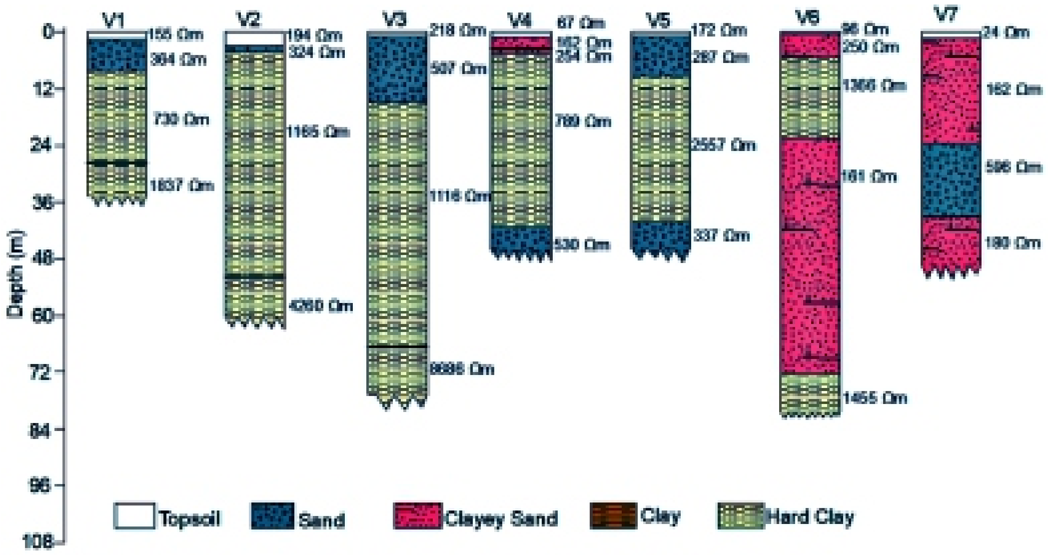

Figure 5: Infered geological sections (VES 1-7) across Traverse 1. Shallow depth sand (phreatic) aquifer are recognizable across the traverse at depth less than 5 m below the topsoil. Confined sand/clayey sand aquifers ((hard clay cover) at moderate depth present beneath VES 4, 5, and 6 and the unconfined aquifers at VES 7.

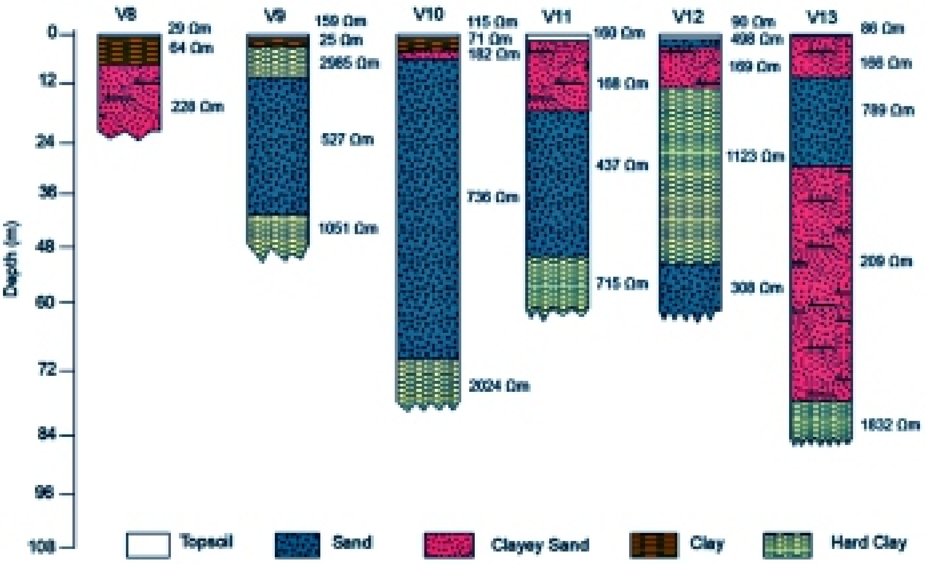

Figure 6: Infered geological sections (VES 8-13) across Traverse 2. Confined (clay cover) sand/clayey sand aquifer at VES 8, VES 9 (with additional hard clay cover) and VES 10. Very deep sand aquifers (VES 12); low depth unconfined sand/clayey sand (phreatic) aquifer (VES 11, 12 and 13).

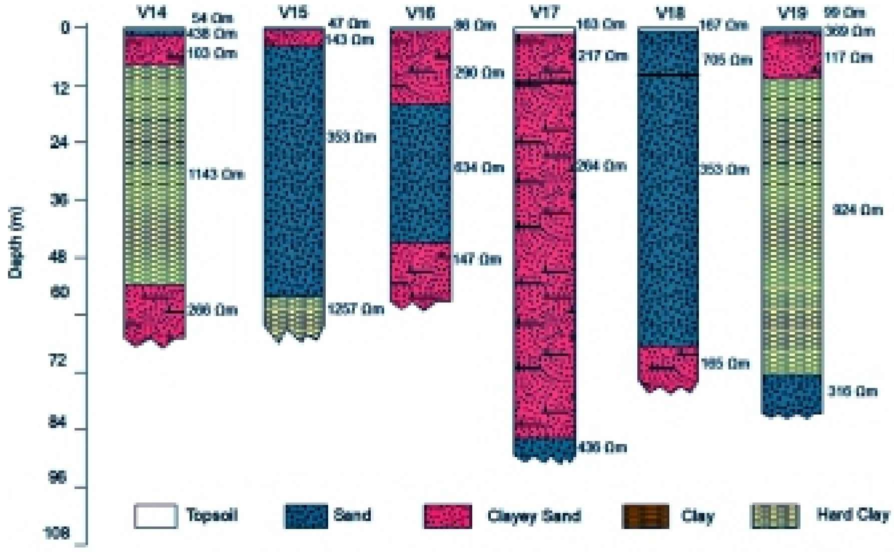

Figure 7: Infered geological sections (VES 14-19) beneath Traverse 3. Phreatic sand and clayey sand aquifers delineated across the entire traverse; deep confined clayey sand (VES 14) and sand zones (VES 19).

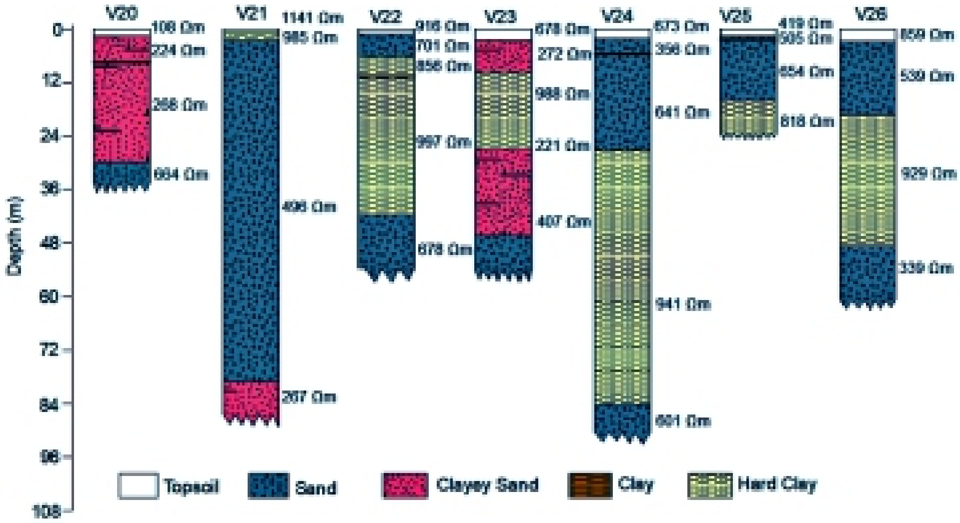

Figure 8: Infered geological sections (VES 20-26) across Traverse 4. Water table (phreatic) aquifer delineated at all the stations except at VES21 with a confined aquifer covered by a very thin hard clay medium at shallow depth. Deep lying confined aquifers depicted at VES 22, 23, 24 and 26.

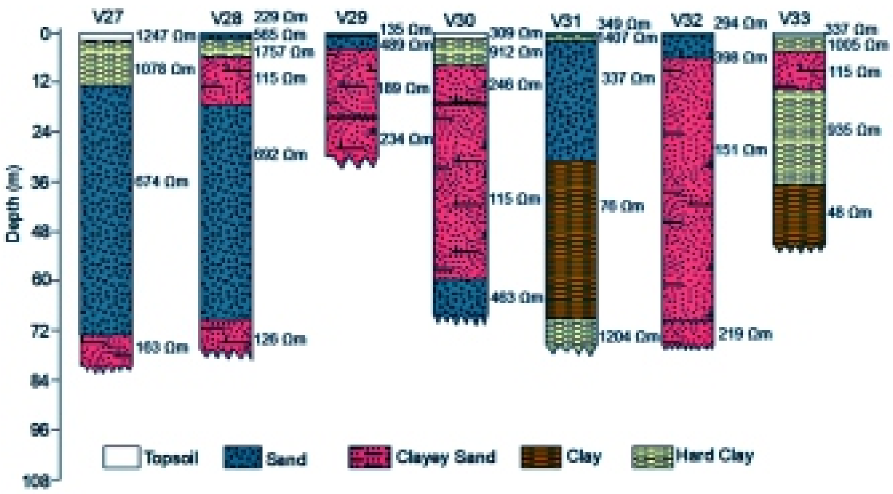

Figure 9: Infered geologic sections (VES 27-33) across Traverse 5. Confined aquifer with hard clay cover at VES 27, 28 and 30 at moderate depth and VES 31 at shallow depth. Phreatic (exposed) aquifer also delineated at VES 29, 31 and 32.

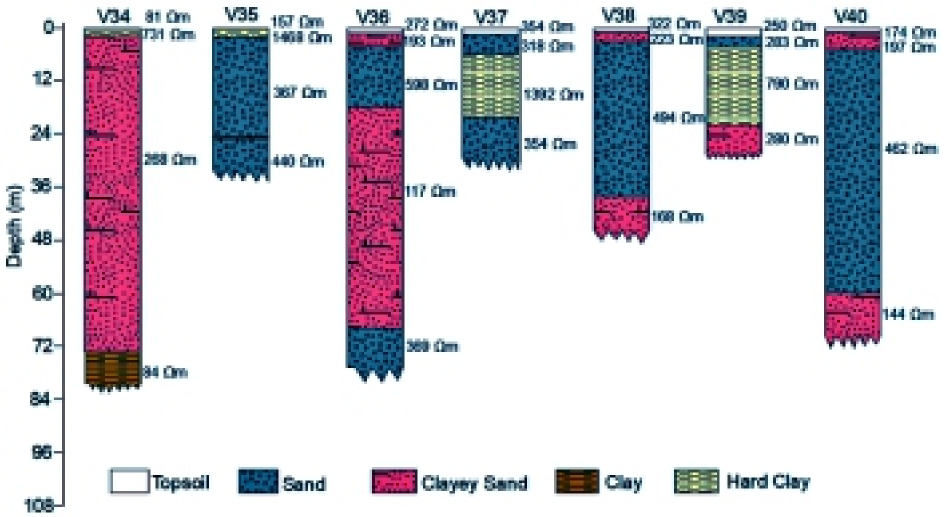

Figure 10: Infered eologic sections (VES 34-40) across Traverse 6. Phreatic (exposed) aquifer (sand/clayey sand) across all the VES stations. Shallow confined sand and clayey sand aquifers mapped at VES 37 and VES 39, respectively.

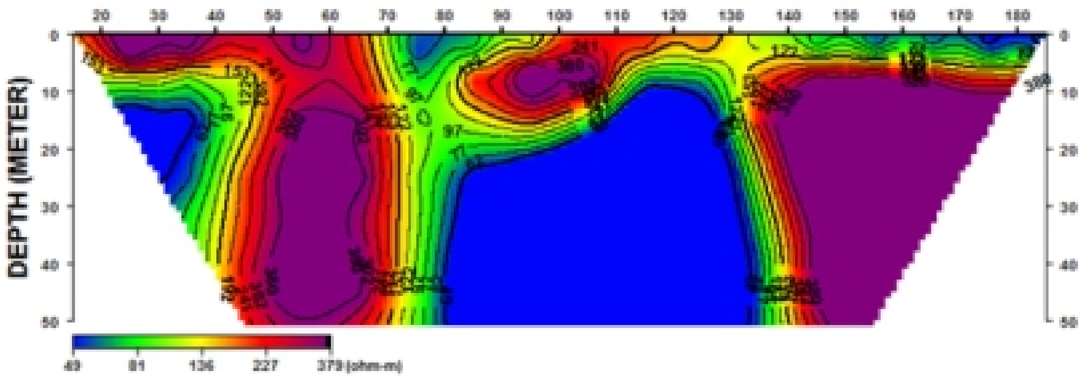

Figure 11: Traverse 1 Resistivity-Depth Structures. Phreatic water table aquifers are located at lateral distances of 20 to 60 meters and 95 to 105 meters at depths below 10 meters. Fairly deep sand aquifers are located at depths above 10 meters (purple region). The traverse's starting and middle sections are clay zones.

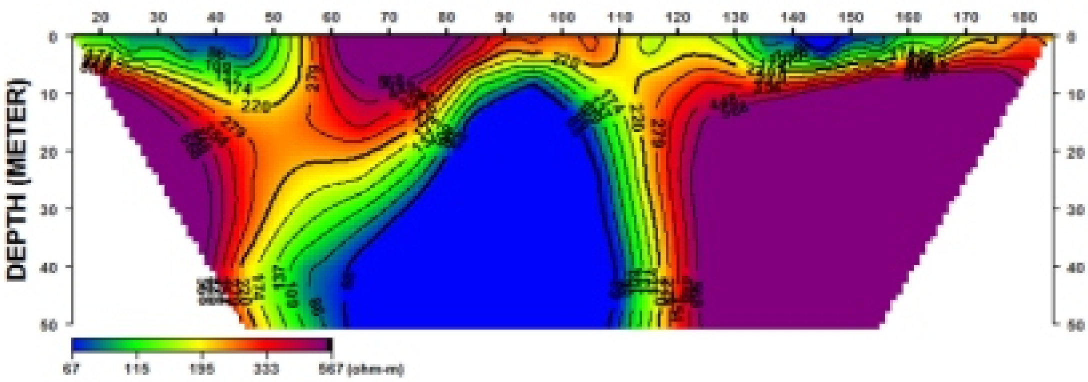

Figure 12: Traverse 2 Resistivity-Depth Structures. Phreatic aquifer was found at a depth of less than 10 meters at a lateral distance of 60 to 80 meters. Confined (thin hard clay layer) aquifer was found at a lateral distance of 125 to 180 meters down to a depth of 50 meters. A clay zone is shown in the direction of the traverse's center.

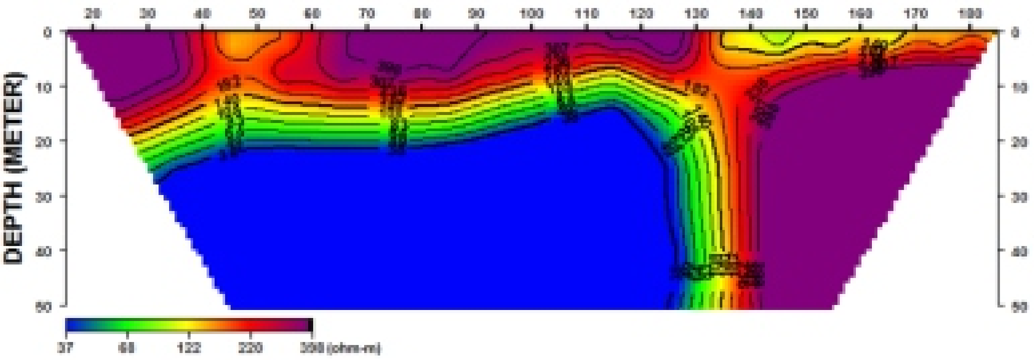

Figure 13: Traverse 3: Resistivity-Depth Structures. Spread of clay zone aquifers from 140 to 180 m., 65-130 m., and 0 to 37 m phreatic aquifers to a lateral distance of roughly 120 m.

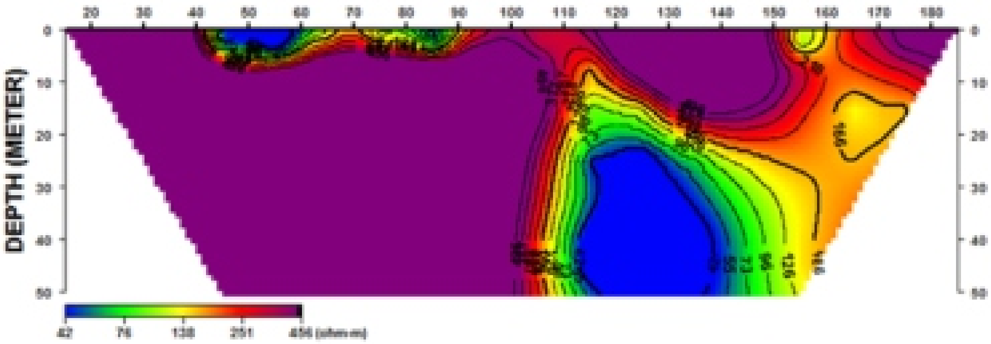

Figure 14: Traverse 4: Resistivity-Depth Structures. Phreatic aquifer 0–40 m, 120–150 m, and 170-180 m. Deeper aquifer up to 100 m down to a depth of roughly 50 m. Clay zone at a depth of roughly 20 m down to 110–140 m lateral distance.

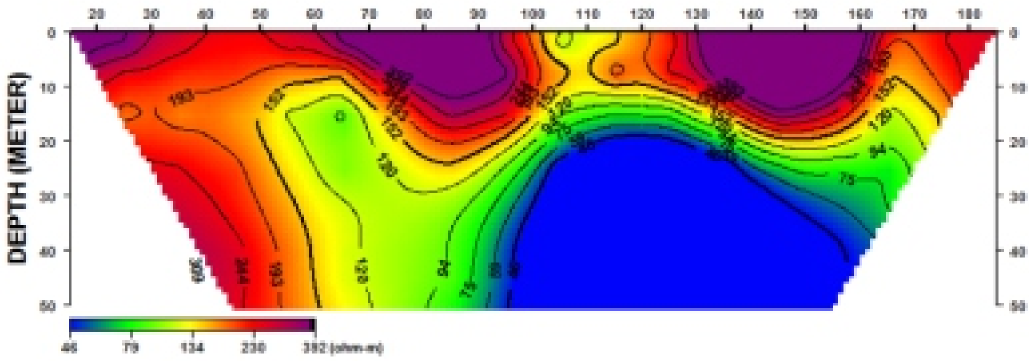

Figure 15: Traverse 5 resistivity-depth structures. A phreatic aquifer sits on top of fairly deep aquifers at lateral distances of 0 to 30 m, 63 to 94 m, and 130 to 160 m. clay.

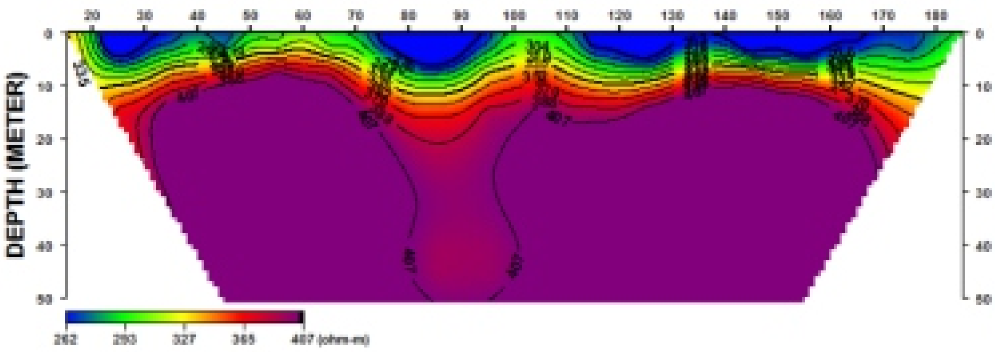

Figure 16: Traverse 6: Resistivity-depth structures. The aquifer spreads 10 meters below the surface of the traverse. Several traverse sections have clay zones at the top. The whole spread has deep aquifers.

Table 1: Summary of subsurface parameters interpreted from resistivity sounding. The last layer that current penetrates has an unknown thickness, as indicated by the (-) in the aquifer thickness column. Protective capacity rating is not a function of aquitard (clay) thickness alone. It also depend on the resistivity. A combination of high thickness and low resistivity gives better rating. Thin subsurface cover containing clay/hard clay above an aquiferous zone at shallow depth will exhibit poor protective capacity rating. High resistivity and fracturable hard clay whether thin or thick poses low protective capacity rating. Fracture provides high potential for water movement.

VES station	Depth to Aquifer (m)	Aquifer thickness (m)	Clay/hard clay in overburden and thickness (m)	Longitudinal conductance (siemens)	Transverse resistance (ohm-m^2)	Protective capacity rating
1	8.3	27.7	nil	0.0288	2686	Poor
2	2.8	4.2	nil	0.0144	544	Poor
3	0.9	14.8	nil	0.0041	196	Poor
4	41.3	-	nil	0.0813	29797	Poor
5	40.1	-	Hard clay/30.7	0.0466	81105	Poor
6	22.6	49.6	Hard clay/17.5	0.0358	25117	Poor
7	23.7	39.1	nil	0.1824	3660	Weak
8	7.7	-	Clay/10.0	0.0121	548	Poor
9	10.6	40.6	Clay/1.8 & Hard clay/8.1	0.0830	24381	Poor
10	5.0	71.5	Clay/2.5	0.0520	597	Poor
11	17.4	49.8	nil	0.1044	2935	Weak
12	51.5	-	Hard clay/38.5	0.1083	45885	Weak
13	8.6	29.0	nil	0.0538	1399	Poor
14	59.2	-	Hard clay/50.4	0.1200	59078	Weak
15	5.6	65.5	nil	0.0413	769	Poor
16	18.4	51.2	nil	0.0676	5227	Poor
17	88.4	-	nil	0.3480	22582	Moderate
18	12.5	58.2	nil	0.0213	8312	Poor
19	77.2	-	Hard cly/65.0	0.1660	61847	Weak
20	29.9	-	nil	0.1230	7501	Weak
21	2.5	76.5	Hard clay/1.8	0.0024	2571	Poor
22	41.6	-	Hard clay/52.4	0.0446	39158	Poor
23	46.3	-	Hard clay/26.7	0.1360	24862	Weak
24	84.1	-	Hard clay/51.2	0.1070	70179	Weak
25	2.2	13.6	nil	0.0050	982	Poor
26	48.6	-	Hard clay/29.3	0.0655	38497	Poor
27	12.9	60.1	Hard clay/11.1	0.0118	14336	Poor
28	17.7	51.5	Hard clay/4.4	0.1090	9807	Weak
29	20.5		nil	0.0980	5206	Poor
30	59.6	-	Hard clay/6.4	0.4200	13444	Moderate
31	2.0	29.0	Hard clay/1.4	0.0027	2179	Poor
32	69.6	-	nil	0.4370	12037	Moderate
33	4.4	9.6	Hard clay/3.3	0.0055	3687	Poor
34	1.9	71.4	Hard clay/1.2	0.0103	933	Poor
35	24.9	-	Hard clay/1.8	0.0652	11068	Poor
36	67.9	-	nil	0.4720	14880	Moderate
37	20.3	-	Hard clay/14.3	0.0287	21858	Poor
38	3.2	35.1	nil	0.0131	803	Poor
39	22.0	-	Hard clay/17.4	0.0392	14983	Poor
40	4.9	59.8	nil	0.0257	939	Poor

Table 2: Longitudinal conductance/protective capacity rating (Adapted from Henriet, 1976)

Total longitudinal conductance/mhos	Soil protective capacity classification
>10.00	Excellent
5.00 – 10.00	Very good
0.70– 4.90	Good
0.20 – 0.69	Moderate
0.10 – 0.20	Weak
<0.10	Poor

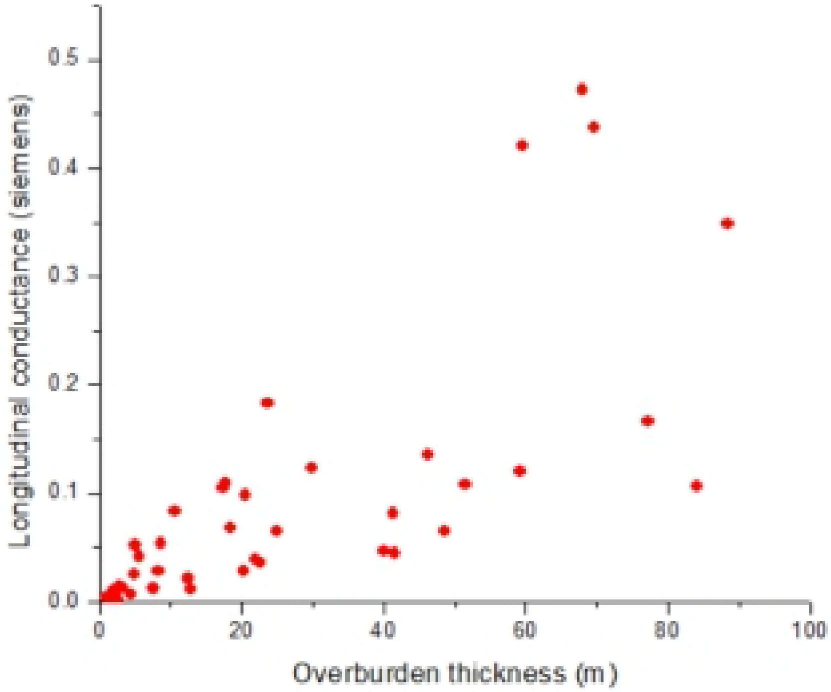

Figure 17: Cross plot of longitudinal conductance versus overburden thickness.

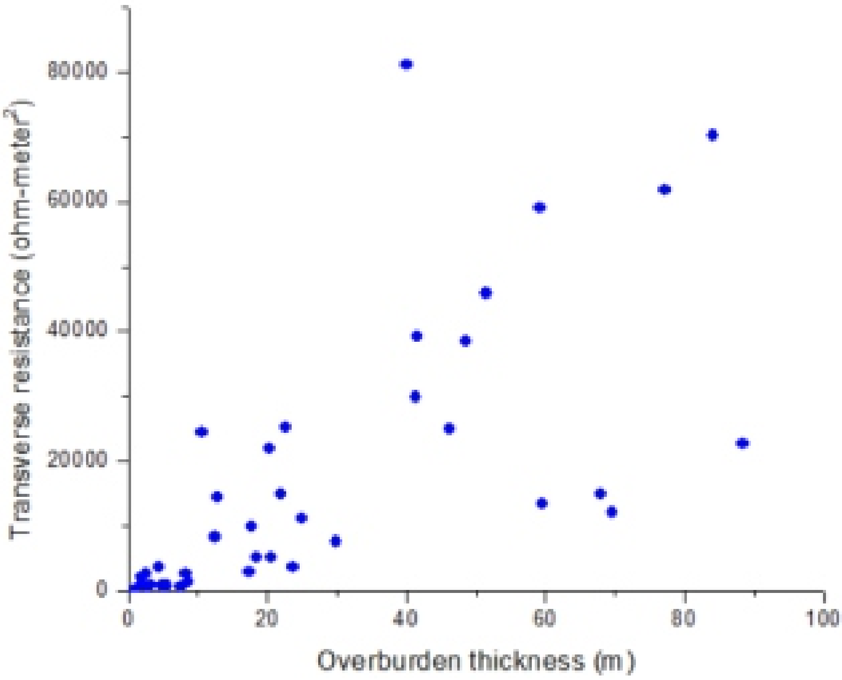

Figure 18: Cross plot of transverse resistance versus overburden thickness.

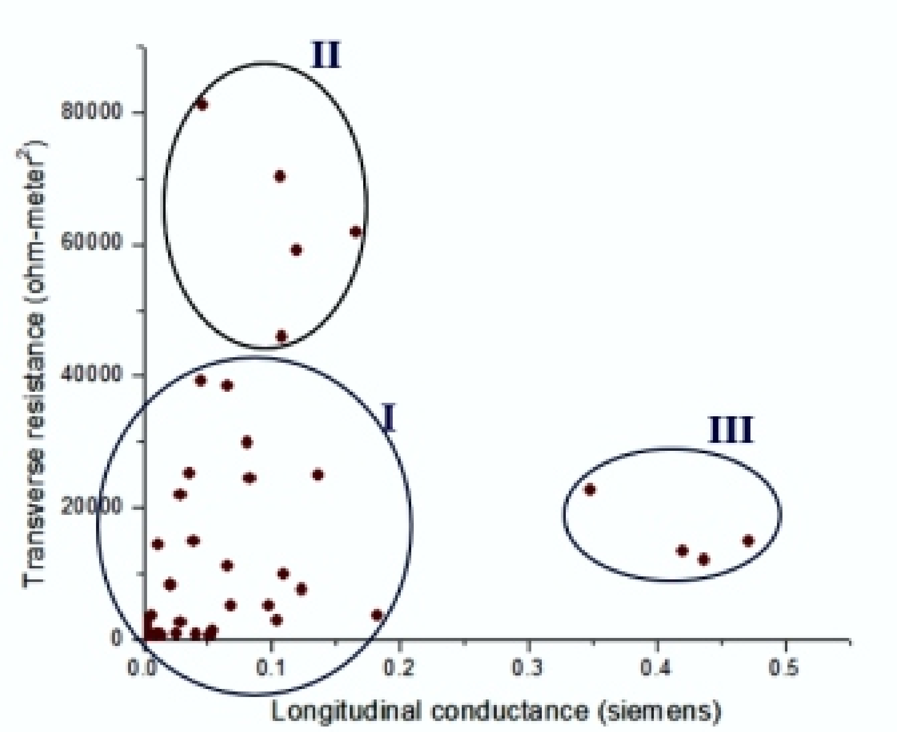

Figure 19: Cross plot of transverse resistance versus longitudinal conductance. Ellipses I, II and III show a region of poor overburden protection/high aquifer vulnerability, weak overburden protection/medium aquifer vulnerability and moderate overburden protection/low aquifer vulnerability respectively.

Understanding soil characteristics is crucial for assessing aquifer and groundwater protection, as well as evaluating potential contamination risks in any geological environment. Overburden materials can retain water in soil pores, release it to plant roots or the atmosphere, or allow it to percolate into the aquifer. Several factors, including the thickness, composition, texture, and geoelectric properties of the overburden, influence its protective capacity. Groundwater contamination can occur when recharge water from the surface or other sources transports pollutants down to the water table and further into an aquifer. Pressure gradients within the aquifer can cause the recharge water to travel in a horizontal direction once it reaches the aquifer.

The borehole log depicted in Figure 4 reveals the depth and outline of the lithological succession in the study area. This clearly shows two aquifers at depths 27 m and 47 m. The possibility of overburden protection by hard clay layer (thickness 18 m) which lies above the first aquifer is high. The very thin layer of clay (thickness 4 m) overlying the deeper aquifer from depth of 43 m to 47 m is only complementary. For a clay layer to be a filter or protective, it should be about 15 m thick. The hard clay layer of thickness 18 m has the protective capacity for transverse/vertical flow which should also protect the second aquifer. However, the first hard clay layer's protective capacity is guaranteed in the absence of the occurrence of fracture which is a possibility.

Depth to Aquifer Unit

According to the findings from the VES and 2-D imaging techniques, the aquifer systems at the study site are a typical multi-layered aquifer-aquitard system, characterized by intercalations of clay, hard clay, clayey sand, and sand, as much as possible at the respective locations. Both the geoelectric cross-sections (Figures 5-10) from the VES technique and the 2-D resistivity structures (Figures 11-16) show the presence of sand (resistivity, 316-789 Ωm) and clayey sand (resistivity, 103-272 Ωm) aquifers at both shallow (i.e. water table or phreatic aquifers) and moderate depths across all traverses. In groundwater development and protection projects, the depth to aquifer (overburden thickness) is crucial primarily because it helps to determine the volume or extent of subsurface materials a contaminant must travel through before coming into contact with an aquifer. As groundwater depth decreases, there will be less soil to block or filter the flow of pollutants and hence fewer chances for contaminant adsorption or degradation before reaching an aquifer. Additionally, this decrease in depth and thickness also establishes the duration of a contaminant's interaction with the soil. The filtration, sorption, biodegradation, and volatilization processes are thought to function well in relatively deep soil. In contrast, only a certain volume of pollutants can be absorbed by shallow soil layers. The likelihood of pollution rises in areas where the water table is close to the surface or where the underlying soil or bedrock is permeable and the sequence of subsurface layers covering the aquifer is thin. To safeguard groundwater in regions where the aquifer is shallow and near the surface, additional precautions must be taken. This study found that 13 (32.5%) VES stations had low depth to aquifer or total overburden thickness (< 5.0 m), while the remaining 27 (67.5%) sounding stations had moderate to high depth to aquifer (5.0 – 68.0 m) as indicated in Table 1. As shown by the geoelectric cross-sections and 2-D imaging structures, the phreatic zone (unconfined aquifers) spread across the study area. Their greater capacity for renewal and lower exploitation costs makes them preferred over the much deeper confined aquifers and they are primarily exploited in communities. But seasonal fluctuations impact a great effect on the volume as well as the quality of groundwater in the phreatic zone.

Overburden Lithological Characteristics

Assessing the index or degree of aquifer vulnerability and groundwater exposure to possible contamination depends significantly on the overburden's subsurface composition. The texture of a subsurface medium is determined by the relative proportions of sand, silt and clay. (i.e. either fine or coarse). Since soil texture affects pore size and total surface area, it then means that it will also affect the movement of liquid through soil. Large pores and low surface areas in sandy soils enable quick drainage of liquid. As a result of this, some contaminants might leach away quickly into groundwater zones. Particles of clay can provide a large surface area for sorption to occur. Consequently, clay soils have a lower likelihood of leaching, or percolation through soil. About twenty VES locations in the study area showed the presence of clay or hard clay in the overburden above the depicted aquifer units. While only three locations have clay layers with a resistivity range of 29 - 84 Ωm and a thickness range of 2.5 - 10.0 m, eighteen locations have hard clay substrata with resistivity in the range of 818 - 2557 Ωm and thickness of 1.4 - 52.4 m in the overburden. The protective capacity of compacted and consolidated hard clay is uncertain and may be greatly reduced in the event of fracturing or fissuring (Bezuijen and van Tol, 2011; Dashko and Kotiukov, 2018; Young and Ospina, 2023). Fracture can also occur in certain sedimentary deposits with a high degree of lithification as it is common with magmatic or metamorphic rocks in crystalline formations. Through these fissures, water can swiftly pass through a medium that would otherwise be almost impervious (Young and Ospina, 2023).

Overburden Geoelectric Attributes

The ability of the overburden rock unit to naturally filter and impede percolating dissolved pollutants is usually evaluated using the protection capacity rating derived from longitudinal conductance (Henriet, 1976; Wood, 1990; Braga, 2006). Furthermore, the permeability of the lithological sequence in the overburden that covers an aquifer like sand, gravel, etc. will also determine whether water and dissolved pollutants will seep into the groundwater region. Since clay is typically less permeable and prevents water from moving freely, estimating the volume of clay in near-surface formations is important for geotechnical, hydrogeological, and oil contamination studies (Shevnin *et al.* 2007). Where geologic layer permeability is high, groundwater quality is most at risk. In hydrogeology, a number of investigators have found a connection between soil transverse resistance and hydraulic conductivity (filtration coefficient), which is helpful for groundwater protection, groundwater management, and the prediction of the movement of contaminants (Ponzini *et al.*, 1984; Kelly, 1985; Shevnin *et al.*, 2006; Sinha *et al.*, 2009; Sinha and Singhal, 2009). Table 1 indicate that most of the delineated lithological sequence has an unfavourable overburden protective capacity rating: twenty-seven locations (67.5%) have poor ratings (0.0027 - 0.0813 S); nine locations (22.5%) have weak ratings (0.1044 - 0.1824 S); and only four locations (10%) have moderate ratings (0.348 - 0.472 S). The longitudinal conductance distribution with overburden thickness is displayed in Figure 17. The high likelihood of pollutants migrating into groundwater resources at the study site is indicated by these ranges of values. The generally moderate to high values of transverse resistance (filtration coefficient), which indicate a high likelihood of contaminant plumes passing through the overburden and into the underlying aquifer, also serve as some sort of confirmation for the low protective capacity rating. The distribution of transverse resistance with overburden thickness shown in Figure 18, also follows a similar pattern to that of Figure 17. Figure 19 shows the cross plot to illustrate the relationship between longitudinal conductance and transverse resistance and it reveals three distinct and separate regions. These are: (i) a region of weak overburden protection and medium aquifer vulnerability; (ii) a region of moderate overburden protection and low aquifer vulnerability; and (iii) a region of poor overburden protection and high aquifer vulnerability as represented by the ellipses I, II, and III, respectively. The order of the decrease in spread and coverage (i.e. III < II < I) of the three regions is a representation of the overall protective capacity of the study location.

CONCLUSION

Using VES and 2-D imaging techniques, electrical resistivity assessments of the groundwater potential and overburden protective capacity of subsurface materials beneath sites near Agbara Industrial Estate have been conducted. A typical multi-layered aquifer-aquitard systems, depicting an intercalation of geoelectric layers likely composed of sand, clayey sand, clay, and hard clay, is revealed by the two resistivity survey techniques. In majority of the sites, shallow unconfined sand/clayey sand aquifers (water table or phreatic aquifers) identified at depths less than 5 m are not appropriate for long-term and sustainable groundwater exploitation, despite being more common and expected to have lower exploitation costs. Seasonal fluctuations generally affect the amount (volume) as well as quality of groundwater in phreatic aquifers. Much deeper aquifer of sand and/or clayey sand (5.0 – 68 m) were delineated in about 67.5% of the sounding stations. Approximately twenty VES locations showed the presence of impermeable soil strata in the overburden, such as hard clay with resistivity in the range 818 - 2557 Ωm and thickness range 1.4 - 52.4 m, and clay with resistivity range 29 - 71 Ωm and thickness range 2.5 - 10.0 m. However, there is a high likelihood of fracturing or fissuring in hard, compacted impermeable clay which can create pathways for dissolved pollutants to quickly and easily migrate into aquifers. Three different overburden protective capacity ratings have been deciphered in the study area. These are: weak ratings (0.1044-0.1824 S), moderate ratings (0.348-0.472 S), and poor ratings (0.0027-0.0813 S). These ratings indicate a high likelihood and potential for pollutants to migrate into the study area's groundwater resources. The filtration coefficient (transverse resistance) values are primarily moderate to high (544 – 81105 Ωm), which is consistent with the high probability of contaminant plumes passing through the overburden into the underlying aquifers. The local geology of an area is deemed favourable for groundwater development and sustainability if it comprises porous and permeable sand, gravel, or pebbles of suitable thickness and significant depth, forming the primary subsurface medium that contains the aquifer zone. The presence of lithological barriers, such as clay (aquitard), within the lithological sequence above an aquifer zone is also crucial for obstructing the migration and infiltration of pollutants. This investigation has yielded valuable geophysical data and illustrated the applicability and effectiveness of the electrical resistivity techniques in assessing subsurface protective capacity and aquifer vulnerability. This is anticipated to aid in the formulation and implementation of strategies to reduce groundwater pollution in both residential and industrial areas.

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

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