Application of Resistivity Methods to Groundwater Protection Studies in Niger Delta

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***Abstract*- A resistivity investigation was carried out in order to provide information on the subsurface layers and characterization of the protective capacity of overburden units to groundwater in Egbeleku, a community where a proposed landfill will be sited by Shell Petroleum Development Company. Fifteen vertical electrical soundings (VES) using the Schlumberger electrode configuration and one azimuthal resistivity sounding (ARS) were carried out. Results of the resistivity survey indicated mainly four geoelectric layers; top soil, clayey sand/sandy clay, clay and sand. The fourth layer constitute the groundwater aquifer which was determined to be confined by the third ubiquitous layer constituted by clays with thickness varying from 11.0 – 42.2 m and sandy clay/clayey sand of about 30.2 – 44.0 m thick. The longitudinal conductance map showed that the area has moderate to good protective capacity as a result of the thick clay, sandy clay and clayey sand protecting the groundwater in the aquifer. The location of the landfill site is in the region of groundwater discharge rather than a recharge region as indicated by azimuthal resistivity sounding and groundwater head contour map which showed that groundwater flow direction is SW – NE towards the proposed landfill area. Hence, the groundwater in this area is sufficiently protected.**

Keywods- Contaminants; Protective Layers; Landfill; Leachates; Residence Time; Geoelectric Horizon

I. INTRODUCTION

In the Niger Delta, solid wastes are mostly deposited into open dumps and landfills. This is because open dumps and landfills are the commonest, simplest, cheapest and most effective method of disposing wastes. These landfills/dumpsites are mostly not engineered to contain leachate and are indiscriminately sited without regard to the nature of soil and hydrogeology. An adverse consequence of these indiscriminate dumping of wastes in open dumps and non-engineered landfills is the production of leachate from decomposing wastes. This can cause significant impairment of groundwater use for domestic water supply as well as surface waters that receive leachate [1].

Groundwater contamination from landfills often results from leaking leachate water that has percolated through waste and accumulated various ions in solution [2]. Modern landfills have protective layers of clay and plastic which act as barriers underneath the waste. These barriers are however absent in most landfills in developing countries like Nigeria or when present are not adequate and hence, allow leachate seepage into the surrounding aquifers. At Uvwiamuge [3] reported that the integrity of the engineered liner layer at the Ughelli West Engineered dumpsite had been compromised and intense downward percolation of leachates have been recorded. Contamination from landfills typically forms a “plume” that moves outward and downward into surrounding and underlying aquifers [2]. The leachates become part of the groundwater flow system immediately they reach the water table. The extent of pollution is greater in high rainfall area than less humid and arid areas [4].

However, as groundwater percolates into/flows through an aquifer it is naturally filtered as groundwater passes through the pore spaces. During the filtration process, the rock matrix acts as sieves which slows flow rates as water forces its way through the small pore spaces resulting in long residence time. Residence time of percolating water in aquifers with large pore spaces is shorter than that for smaller pore spaces and as a result water moves faster leading to poor natural filtration process. In such case contaminants may be difficult or impossible to attenuate by natural filtration. Clayey or silty particles in or overlying an aquifer are protective layers that can provide natural protection to the aquifer from contaminants.

The soils ability to lessen the amount or reduce the severity of groundwater contamination is called soil attenuation [5]. Deep, medium and fine-textured soils are the best, whereas coarse-textured materials are the worst in terms of contaminant removal [5]. Contaminant attenuation in aquifers depends on water flow rates through the aquifer which in turn depend on the residence time of percolating water that contains contaminants through the overlying materials above the aquifer. Aquifers are given protection by these overlying layers, also called protective layers. An effective groundwater protection is given by protective layers with sufficient thickness [6] and low hydraulic conductivity leading to longer residence time of percolating water [7].

II. LOCATION, GEOLOGY AND HYDROGEOLOGY

The study area (Fig. 1) is located in the western part of the Niger Delta basin and lies between longitudes $5^0\ 47^1$E and $5^0\ 48^1$E and latitudes $5^0\ 41^1$N and $5^0\ 42^1$N. The Niger Delta was formed in the Tertiary period from the interplay between subsidence and deposition arising from a succession of transgressions and regressions of the sea [8]. These gave rise to the deposition of three lithostratigraphic units in the Niger Delta. These units are Akata Formation, Agbada Formation and Benin Formation in order of decreasing age [9].

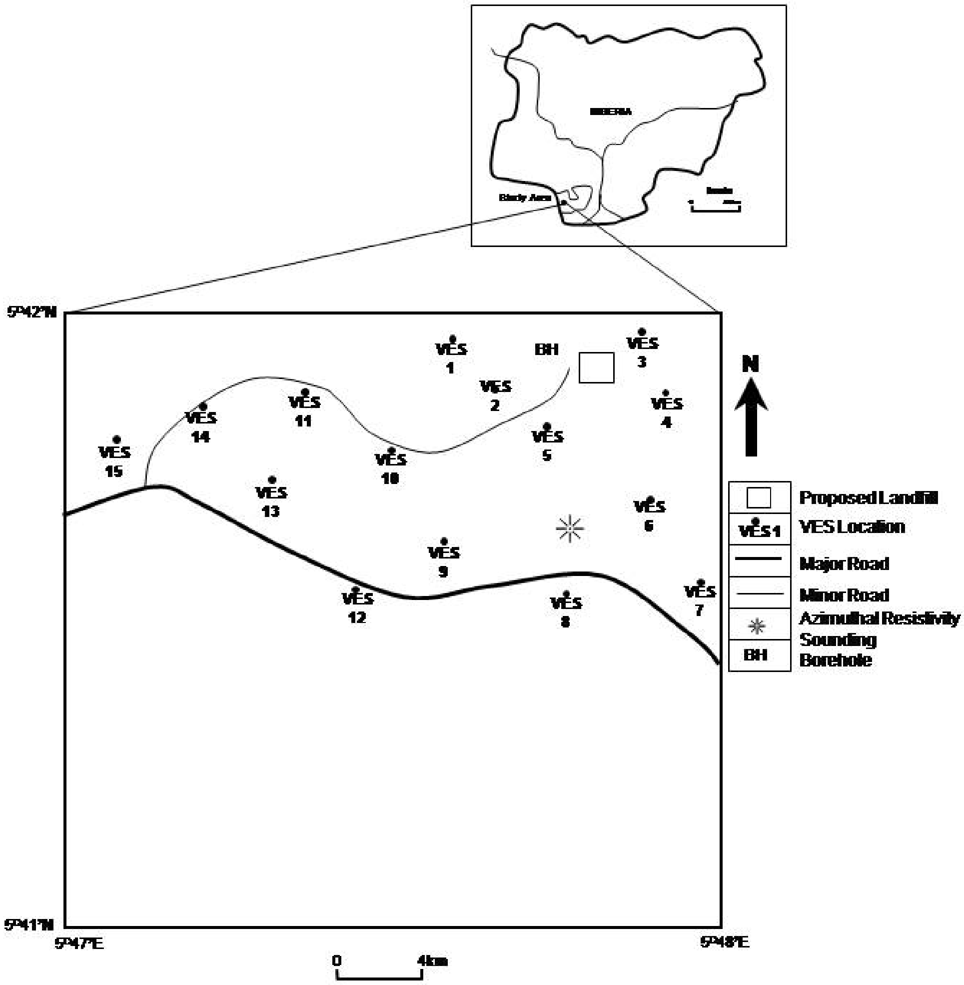

Fig. 1 Map of study area

The basal Akata Formation is made up of mainly marine shales and sand beds. Overlying the Agbada Formation which is a parallic sequence consisting of sands and shales. The Benin Formation consists of predominantly massive highly porous sands and gravels with locally thin shale/clay interbed forms a multi-aquifer system [10-12]. The Benin Formation is overlain by the Quaternary Sombreiro-Warri Deltaic Plain deposits made up of fine to coarse grained sands, sandy clays, silts and clay bands thought to have been laid down during the Quaternary interglacial marine transgression [13, 14]. The hydrogeological setting indicates that the study area is underlain by sands, clayey sand, sandy clays, silts and clays. Groundwater occurs under confined condition. The aquifer is recharged mainly by rainfall infiltrating areas where the aquifer becomes unconfined. The annual total rainfall varies between 500 cm at the coast and about 254 cm landwards [10, 15].

III. METHODOLOGY

The geophysical survey in the study area involved vertical electrical sounding (VES) and azimuthal resistivity sounding (ARS) techniques. The ABEM Terrameter (model SAS 4000) was used to acquire fifteen geoelectric sounding data at different stations using the Schlumberger electrode configuration. The electrode spacing (AB) was varied from 1 – 600m. The measured apparent resistivity data were presented as sounding curves which were obtained by plotting the apparent resistivity (ρ_a) in ohm-m against half electrode spacing (AB/2) in m. The curves were then interpreted by curve matching and computer iteration techniques (Fig. 2) which reduced errors to acceptable levels [16].

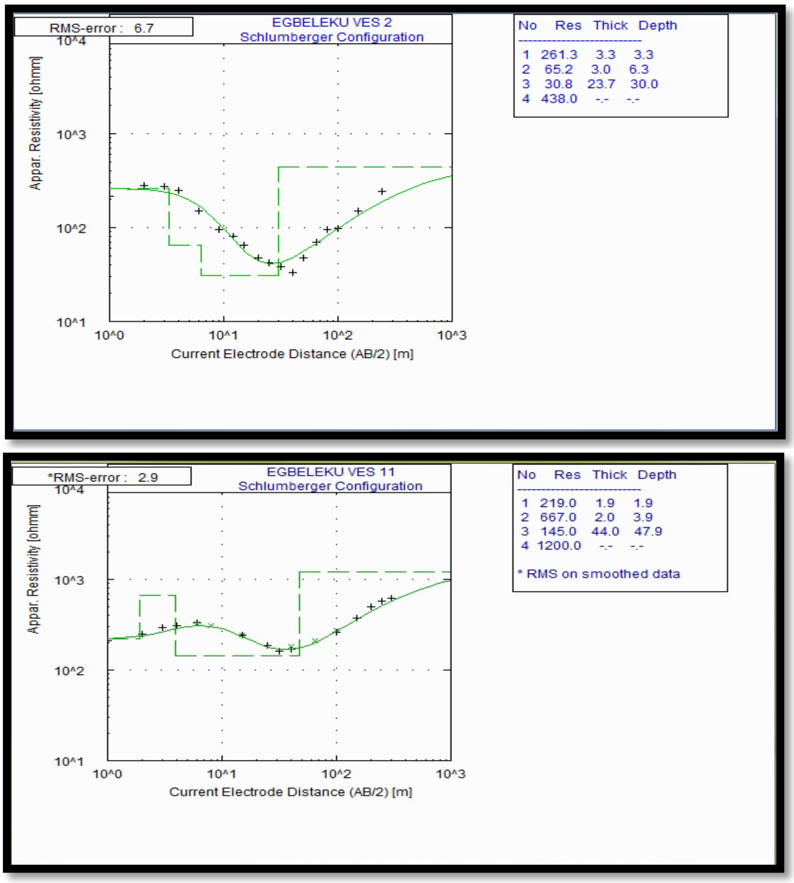

Fig. 2 Some computer generated model data curves at Egbeleku

The geoelectric parameters (the layer resistivity ρ_i and the layer thickness h_i) obtained were used to derive the longitudinal unit conductance (Si) which is a second order geoelectric parameter or the Dar Zarrouk parameter [17] as shown in Table 1.

TABLE 1 GEOELECTRIC PARAMETER, LONGITUDINAL CONDUCTANCE AND PROTECTIVE CAPACITY AT EGBELEKU

VES Stn	**Resistivity (ohm-m)** $\rho_1/\rho_2/\rho_3/ \ldots /\rho_n$	**Thickness (m)** $h_1/h_2/h_3/\ldots/h_n$	$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}$	**Protective Capacity**
1.	1496.1/182.8/25.7/1495.9	4.1/3.2/19.0	0.76	Good
2.	261.3/65.2/30.8/438	3.3/6.3/23.7	1.08	Good
3.	1986.4/321.7/47.7/512.5	4.4/4.4/42.2	0.90	Good
4.	211.0/77.0/203.0/381.0	2.2/1.3/36.0	0.20	Moderate
5.	1858.9/413.3/156.0/589.0	4.3/4.3/41.6	0.28	Moderate
6.	407.9/115.8/303.0/1004.4	1.2/7.2/19.7	0.16	Weak
7.	991.0/309.0/125.0/1880.0	2.5/3.6/38.2	0.32	Moderate
8.	1125.0/350.0/55.0/1580.0	2.7/1.5/40.8	0.75	Good
9.	625.0/121.0/36.0/320.0	1.8/3.6/41.3	1.18	Good
10.	250.0/110.0/57.0/315.0	1.9/2.0/33.2	0.61	Moderate
11.	219.0/667.0/145.0/1200.0	1.9/2.0/44.0	0.31	Moderate
12.	1620.0/477.0/129.0/964.0	2.2/1.1/35.2	0.30	Moderate
13.	467.0/134.0/1100.0	1.9/30.2	0.23	Moderate
14.	261.3/65.2/30.8/488.0	3.3/6.3/30.0	1.08	Good
15.	165.0/117.0/16.0/1015.0	1.4/3.2/11.0	0.73	Good

The total longitudinal unit conductance is given by:

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (1)$$

n is the number of layers overlying the aquifer and varies from 1 to n.

One Azimuthal resistivity sounding (ARS) was carried out in the study area with the aid of an ABEM SAS 4000 Terrameter. Apparent resistivity values were measured using Schlumberger electrode configuration expanded about a center point in azimuths of 0º, 45º, 90º, 135º.

The apparent resistivity values obtained were plotted as functions of direction to produce a polar diagram. The figure is elliptical and diagnostic of anisotropy and inhomogenous medium. A pattern of anisotropy was obtained from the polar diagrams [18]. The anisotropy was calculated using the equation: $\lambda = (\rho_t \rho_L^{-1})^{1/2}$ [19].

IV. RESULTS AND DISCUSSION

A. Vertical Electrical Sounding

The interpretation of the sounding curves (Fig. 2) shows that the following four curve types exist at Egbeleku viz: QH (73.3 %), HA (13.3 %), KH (6.7 %) and H (6.7 %) and are characterized by four distinct geoelectric layers, namely top soil, sandy clay/clayey sand, clay and sand as shown in Fig. 3.

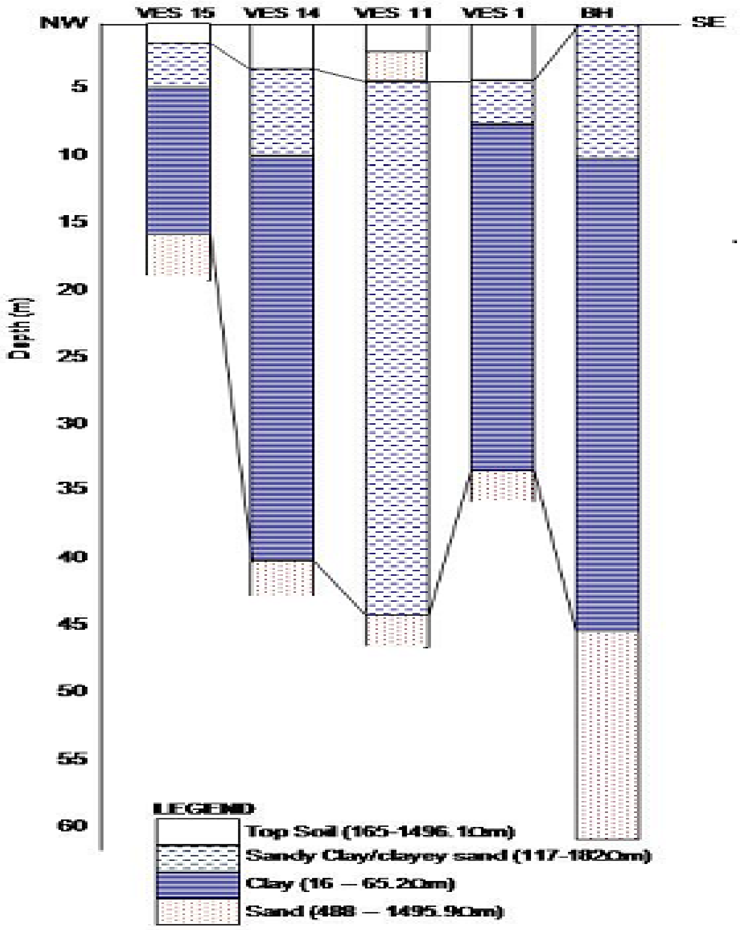

Fig. 3 Geoelectric section at Egbeleku correlated with a borehole data

The resistivity of the first layer is variable and it varies between 211.0 – 1858.9 Ωm while its thickness ranges from 1.2 – 4.3 m. This layer is underlain by a second layer made up of clay/clayey sand and having resistivity values ranging between 62.0 – 182 Ωm while its thickness varies from 1.3 – 7.2 m. However, at VESes 5, 7, 8, 10 and 14, the second layer is sandy with resistivity values ranging from 309.0 – 667.0 Ωm with a thickness of 1.1 – 4.3m. The third layer consists of clay and has resistivity values ranging from 16.0 – 82.7 Ωm, while its thickness varies from 11.0 – 41.6 m. At locations VESes 7 and 14 the lithology of this layer is sandy clay of about 35.2 – 38.2 m thick and clayey sand (VES 11) of about 44.0 m thick. The resistivity of the sandy clay and clayey sand lenses ranges from 125.0 – 145.0 Ωm. The third layer is underlain by sand which constitutes the aquifer unit in the area, the thickness of this layer could not be determined as the electrode current terminated within this layer. However, the depth to this aquifer varies from about 15.6 – 51.0 m.

To determine the resistivity variations of the subsurface at various depths, isoresistivity maps were generated from the computer model data. The isoresistivity map at depths of 5 m, 20 m, 30 m and 40 m at Egbeleku is shown in Fig. 4. The colors indicate the various lithology and their resistivity range. The brick red color indicates areas having clay lithology and their resistivity values ranging from 11.0 – 77.0 Ωm. The yellow color indicates areas having clayey sand/sandy clay lithology with resistivity values ranging from 110.0 – 182.0 Ωm while the red color represents areas with sandy lithology with resistivity values ranging from 203.0 – 1858.9 Ωm.

The isoresistivity map of Egbeleku (Fig. 4) shows that at 5 m, 73.3% of the area is underlain by clay (representing 26.7% of the area) and sandy clay/clayey sand (representing 46.6% of the area) while the remaining area (26.7%) is underlain by sand. As depth increases the lithology of the subsurface becomes more clayey as the sandy fraction reduces. The area underlain by clay, sandy clay and clayey sand increased to 86.6% and 80% at 20 m and 30 m respectively. However, as depth increased to 40 m sand seem to dominate as 66.6% of the area is underlain by sand while the remaining 33.4% is underlain by clayey lithology. It can be seen from the isoresistivity map that protective layers of clayey underlies the area around the proposed site for the landfill up to 40 m. Excavation for the landfill can be done up to 25 m and still have over 15 m thick clayey materials acting as natural liners to prevent percolating leachate into the underlying groundwater aquifer.

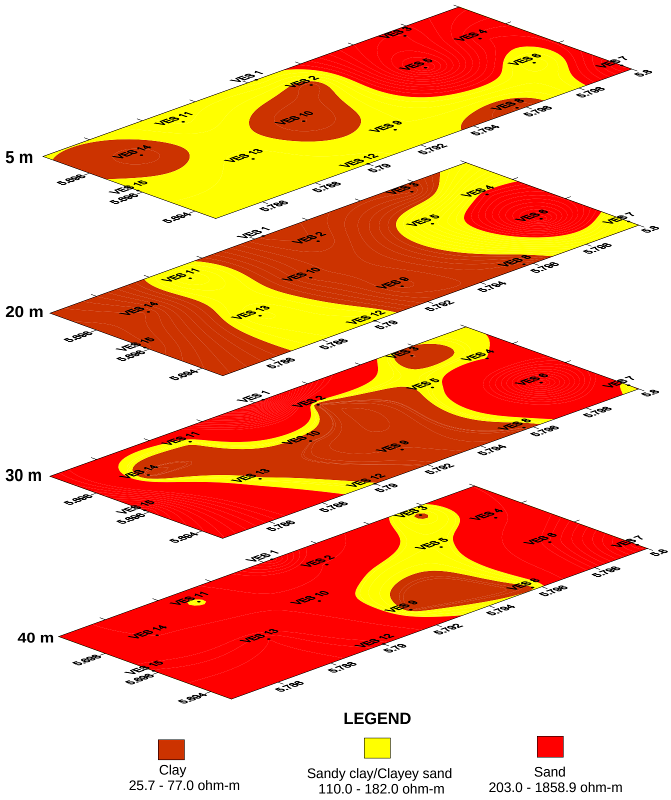

Fig. 4 Isoresistivity map of Egbeleku at 5m, 20m, 30m and 40m depths

The derived longitudinal conductance values in Table 1 were used to produce a protective capacity maps using SUFFER 8 software [20]. The overburden protective capacity was evaluated based on the protective capacity rating approach of [21, 22] as shown in Table 2.

TABLE 2 PROTECTIVE CAPACITY RATING [22]

Longitudinal conductance (mho)	Protective capacity rating
< 0.10	Poor
0.10 – 0.19	Weak
0.20 – 0.69	Moderate
0.70 – 4.90	Good
5.00 – 10.00	Very good
>10.00	Excellent

B. Protective Capacity of the Area

The overburden protective capacity of Egbeleku as indicated by the protective capacity map is shown in Fig. 5. The yellow color indicates area with weak protective capacity having longitudinal conductance of 0.10 – 0.19 mho. The light green color depicts area with moderate protective capacity having longitudinal conductance of 0.20 – 0.69 mho while the area with forest green color has good protective capacity having longitudinal conductance of 0.70 – 4.90 mho.

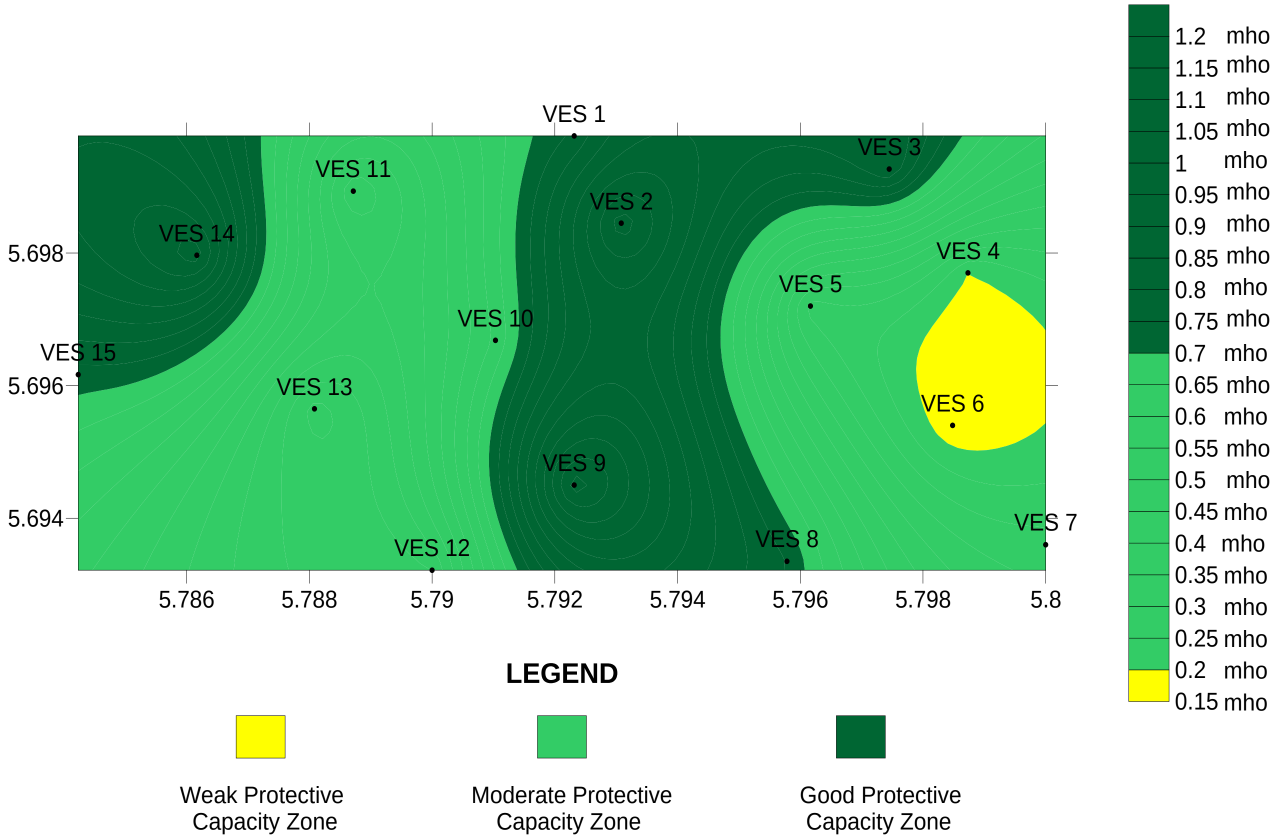

Fig. 5 Longitudinal conductance map

The area around VES 6 has weak protective capacity; this is as a result of the presence of one underlying layer of sandy clay at 5 m and probably multiple layers of sands from depths of 7.2 m downwards, the aquifer in this area may be prone to contamination resulting from short residence time in the sandy layers. The following areas (VESes 4, 5, 7, 10, 11, 12 and 13) have moderate protective capacity while location VESes 1, 2, 3, 8, 9, 14 and 15) fall within areas with good protective capacity. The aquifer in these areas is protected from percolating fluids. The groundwater in the study area is given protection by the covering layers of clay, sandy clay which have sufficient thickness. Groundwater is given protection by geologic barriers having sufficient thickness also called protective layers [6] and low hydraulic conductivity. Silts and clays are suitable protective layers and when they are found above an aquifer they constitute a protective cover [23].

The overburden clays, sandy clays and clayey sand with average thickness of 22.4 m above the aquifer in the study area help protect the aquifer from surface and near surface contamination because their low hydraulic conductivity leads to long residence time of percolating water. During this long percolating period, contaminant degradation can occur by mechanical, physicochemical and microbiological process [7].

V. GROUNDWATER FLOW DIRECTION

The basic analogy between electrical flow and groundwater flow is illustrated in the forms of Ohm's law and Darcy's law [24, 25]. It is possible to determine the direction of groundwater flow from electrical resistivities measured as a function of azimuths [25]. When apparent resistivities measured in azimuths are plotted as radii, they generate anisotropy figures which are an ellipse. The major axis of these figures (polar diagram) coincides with the strike of the fractures/pores, while the true resistivity parallel to the fracture is equivalent to the minor axis of the ellipse [26, 27]. The inferred structural trend from the polar diagram is dominantly in SW-NE direction which is the direction of groundwater flow (Fig. 6). The grain size (porosity) is a major factor creating anisotropy with the values the coefficient of anisotropy varying between 1.35 – 1.67 (Table 3). The values of coefficient of anisotropy were found to increase in magnitude with depth of investigation indicating porosity increasing with depth. Groundwater flow contour map (Fig. 7) obtained from heads in hand-dug wells and a borehole was used to determine the flow direction established from azimuthal resistivity sounding. The result confirms that groundwater flow is in SW – NE direction.

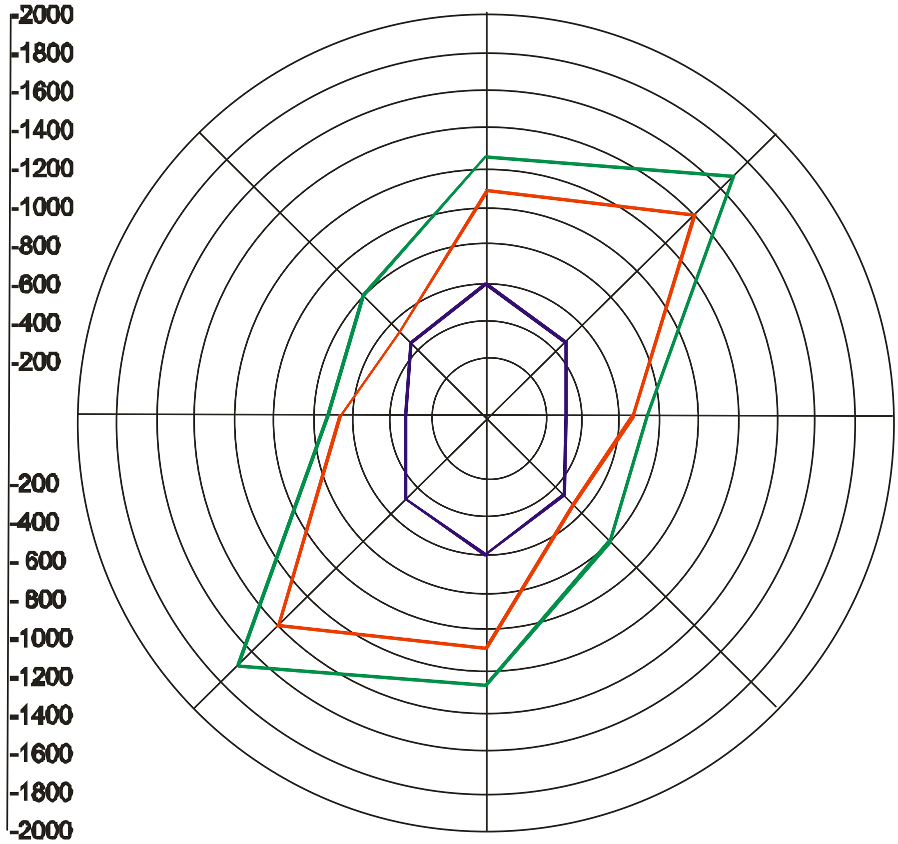

Fig. 6 Azimuthal resistivity polar diagram

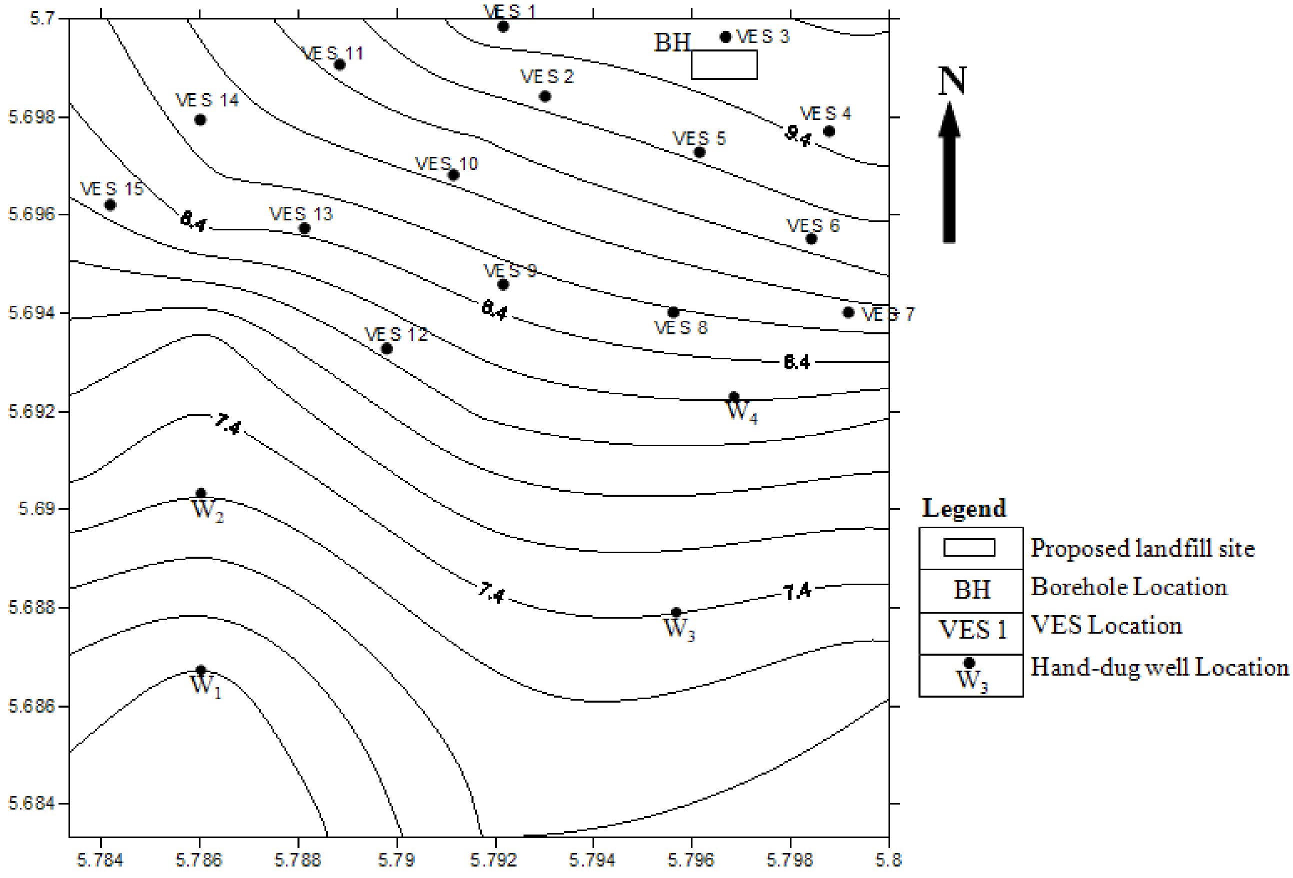

Fig. 7 Groundwater flow contour map of Egbeleku

TABLE 3 COEFFICIENT OF ANISOTROPY

Location	AB/2	ρ_t	ρ_L	λ	Trends
Egbeleku	50	5.75	3.15	1.35	N-S
	75	11.50	4.10	1.67	NE-SW
	100	14.00	5.70	1.57	NE-SW

The proposed sanitary landfill in this area when it becomes operational will have minimal impact on the groundwater because of the clay and sandy clay which acts as liners are sufficiently thick to prevent infiltration of leachates into the groundwater. Also the location of the landfill site is in the region of groundwater discharge rather than a recharge region as indicated by azimuthal resistivity sounding and groundwater head contour map which shows that groundwater flow direction is SW – NE dominantly towards the proposed landfill area. Hence, the groundwater in this area is sufficiently protected.

VI. CONCLUSION

Electrical resistivity sounding in combination with azimuthal resistivity sounding is a useful tool for investigation of the subsurface of an area as it can provide information on the spatial variation in lithology, subsurface integrity with respect to the evaluation of the protective capacity of the area and the direction of groundwater flow and hence, direction of the contaminant plume. Several observations were made from the interpreted resistivity data.

The vertical electrical sounding results showed the presence of four geoelectric horizons, namely top soil, clayey sand/sandy clay, clay and sand. The results of vertical electrical sounding correlated well with borehole data from the area. The fourth horizon (sand) constitutes the aquiferous unit which is confined by clay, sandy clay and clayey sand layers with thickness ranging from 11.0 – 44.0 m.

The overburden protective capacity rating was evaluated based on the total longitudinal conductance values. The protective capacity map showed that over 90 % of the area have moderate to good protective capacity (with 46.7% of the area having good protective capacity). The clay, sandy clay and clayey sand above the aquifer act as natural protective layers by increasing the residence time of percolating water and acting as natural filters. The proposed landfill site is located in the region of groundwater discharge rather than a recharge region, hence, the aquifer is not vulnerable to contamination.

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