Trends in

Applied Sciences Research

ISSN 1819-3579

Academic
Journals Inc.

www.academicjournals.com

Trends in Applied Sciences Research 6 (2): 165-173, 2011
ISSN 1819-3579 / DOI: 10.3923/tasr.2011.165.173

Assessing Aquifer Vulnerability to Contaminants near Solid Waste Landfill Sites in a Coastal Environment, Port Harcourt, Nigeria

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ABSTRACT

2-D resistivity imaging and Vertical Electrical Sounding (VES) surveys were integrated in the study of the aquifer vulnerability to surface contaminants near two solid waste landfill sites in Port Harcourt municipality, Rivers State, Nigeria. Seven vertical electrical soundings and four 2-D resistivity surveys were utilized for the subsurface aquifer characterization. The study was aimed at characterizing a typical Niger Delta coastal aquifer as well as assessing its potential risk to contaminants seepage in terms of the Dar-Zarouk parameters and aquifer transmissivities. The results of interpretation of both data suggests that the study areas are underlain dominantly by sandy formations of varying grain sizes with little clay/shale intercalations at depths. The depth to the aquifers ranges from 23.89 to 73.38 m giving an average of 52.05 m in the study areas. The quantitative assessment of the geoelectric layers showed that the longitudinal conductance (S) of the overburden layers has values ranging from 0.009 Siemens to 0.06 Siemens, while the tranverse resistance (T) of the aquifers varies from 11 to 2.12×10^2 Ωm^2. The low values of the protective capacity of the impermeable overlying materials with high transmissivities of the adjoining aquifer material will make the aquifer highly vulnerable to seepage and migration of contaminants within and around the landfills subsurface layers. With the aid of the 2-D resistivity tomography, two distinct pollutants were mapped and identified within and around the landfills. These are compounds of anomalously high resistivities between 725 and 4419 Ωm suspected to be landfill gases (Ammonia, methane, sulphur (IV) oxide, or carbon (IV) oxide) at depths exceeding 31.4 m and leachate contaminant plumes of low resistivities between 15.6 and 179.0 Ωm at depths between 1.25 m to more than 31.3 m. These revelations suggest that the aquifer has been contaminated and highly vulnerable to surface pollutants in the area.

Key words: Solid wastes, aquifer vulnerability, leachate plume, Dar-Zarouk parameters

INTRODUCTION

Ground water resources have been under rapidly increasing stress in large parts of the world due to pollution. Pollution is primarily the result of irrigated agriculture, industrialization and urbanization, which generates diverse wastes, with the attendant impact on the ecosystem and ground water. Wastes may be loosely defined as any material that is considered to be of no further use to the owner and is, hence discarded (Allen, 2001). Waste is generated universally and is a direct consequence of all human activities. They are generally classified into solid, liquid and gaseous.

In Port Harcourt municipality, solid wastes are mostly deposited into open dump landfills. This is because landfill is the simplest, cheapest and most cost-effective method of disposing wastes (Barrett and Lawler, 1995). The landfills are poorly conceptualized in design with no adequate engineered systems to contain landfill emissions. They are indiscriminately sited within the municipality without regard to the nature of soil, hydrogeology and proximity to living quarters. The most dominant wastes in the study areas are mainly decomposing household, municipal and hazardous (toxic) industrial wastes (Ehirim *et al.*, 2009a).

The study area is characterized by the proximity of the aquifer to the surface, high annual precipitation, permeable soil which enhances seepage flow and flat topography. The implication of the nearness of the aquifer to the surface is that short traveling time in the unsaturated (Vadose) zone do not allow enough time for landfill emissions to be consumed before they get into the aquifer (Ehirim *et al.*, 2009b).

The importance of investigating the vulnerability of the aquifer to surface pollutants due to solid waste landfills is eminent to the availability of portable water resources for both present and future generations. This is especially important due to the nearness of the aquifer to the surface and the permeable soil media (Ehirim and Nwankwo, 2010). The concept of aquifer vulnerability derives from the assumption that the physical environment may provide some degree of protection of groundwater against human impacts, especially with regard to pollutants entering the subsurface (aquifer). Aquifer vulnerability thus combines the hydraulic inaccessibility of the saturated zone to the penetration of pollutants with the attenuation capacity of the strata overlying the saturation zone (Foster, 1998).

The electrical resistivity method is a unique geophysical tool used in ground water and landfill studies (Zohdy, 1964; Dahlin and Zhou, 2002; Rosqvist *et al.*, 2003). The resistivity method is used for electrical sounding and imaging. The electrical sounding provides information about vertical changes in subsurface electrical properties and thus, it is useful in the determination of hydrogeologic conditions such as the depth to water table, depth to bedrock and thickness of soil (Zohdy, 1964). The electrical resistivity imaging maps ground water contaminant leachate plumes, contaminant source, migration paths and depth (Griffiths and Barkers, 1993).

These measurements were used to estimate the Dar zarouk parameters from the resistivities and thicknesses of the layers and hence the hydraulic conductivities and transmissivities used in evaluating the vulnerability of the aquifer to surface contaminants. This study is driven by the desire to investigate the geologic structure of a typical Niger Delta aquifer with a view to assessing the pollutant risk of the aquifers to the seepage of contaminants near two solid waste landfills in the municipality. This became necessary as the inhabitants in the study areas depend mostly on ground water for their water supply needs.

MATERIALS AND METHODS

Location and accessibility of the study area: The study area is delineated by longitudes 6°55' to 6°58' E and latitudes 4°52' to 4°54' N and is accessible through networks of linked roads (Fig. 1). It is characterized by alternate wet and dry seasons (Iloeje, 1992), with a total annual rainfall of about 240 cm; relative humidity of over 90% and mean annual temperature of 27°C (Udom and Esu, 2004). The areas are dominated by moderate vegetation cover and slightly flat topography.

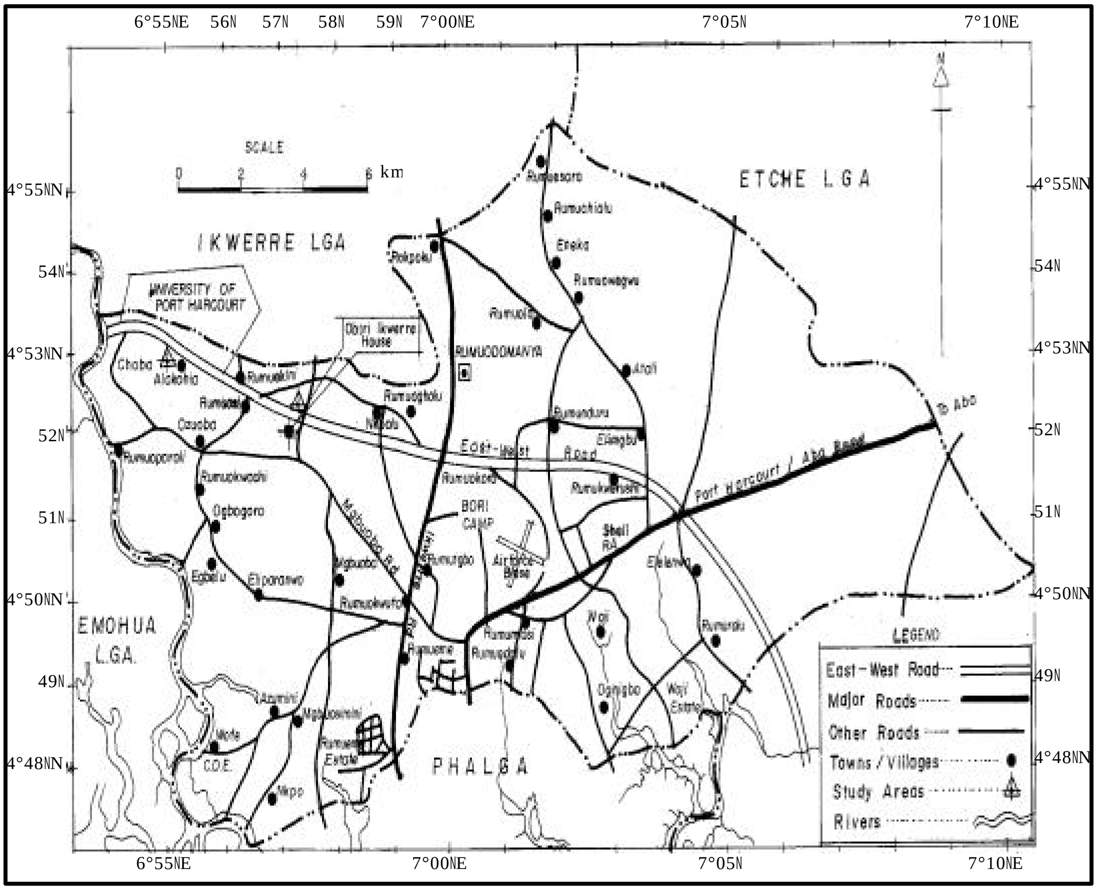

Fig. 1: Location map of the study area

The geology of the study area: Geologically, the area under study is a typical Niger Delta environment underlain by the Benin formation classified as coastal plain sand (Reyment, 1965). It consists of massive, highly porous and permeable freshwater bearing sandstones with minor clay intercalation (Fig. 2). The formation is generally water bearing and hence it is the main source of portable groundwater in the municipality (Etu-Efeotor, 1997). The aquifers are recharged mainly by surface precipitation and nearby drainages.

Sediments deposition and groundwater flow are generally in the NE-SW trend inline with the regional trend of the basin (Ehirim and Ebeniro, 2006).

Methodology: A total of 7 vertical electrical soundings and four 2-D imaging surveys were used for the study. Seven Vertical Electrical Soundings (VES) were carried out in the two landfill locations using ABEM Terameter (SAS) 1000C. A maximum electrode expansion (AB/2) of 400 m and MN/2 of 50 m were utilized in the survey, using the Schlumberger electrode array. The measured resistance values (R) were converted into apparent resistivity (ρ_a) by multiplying with a geometric factor (K), such that:

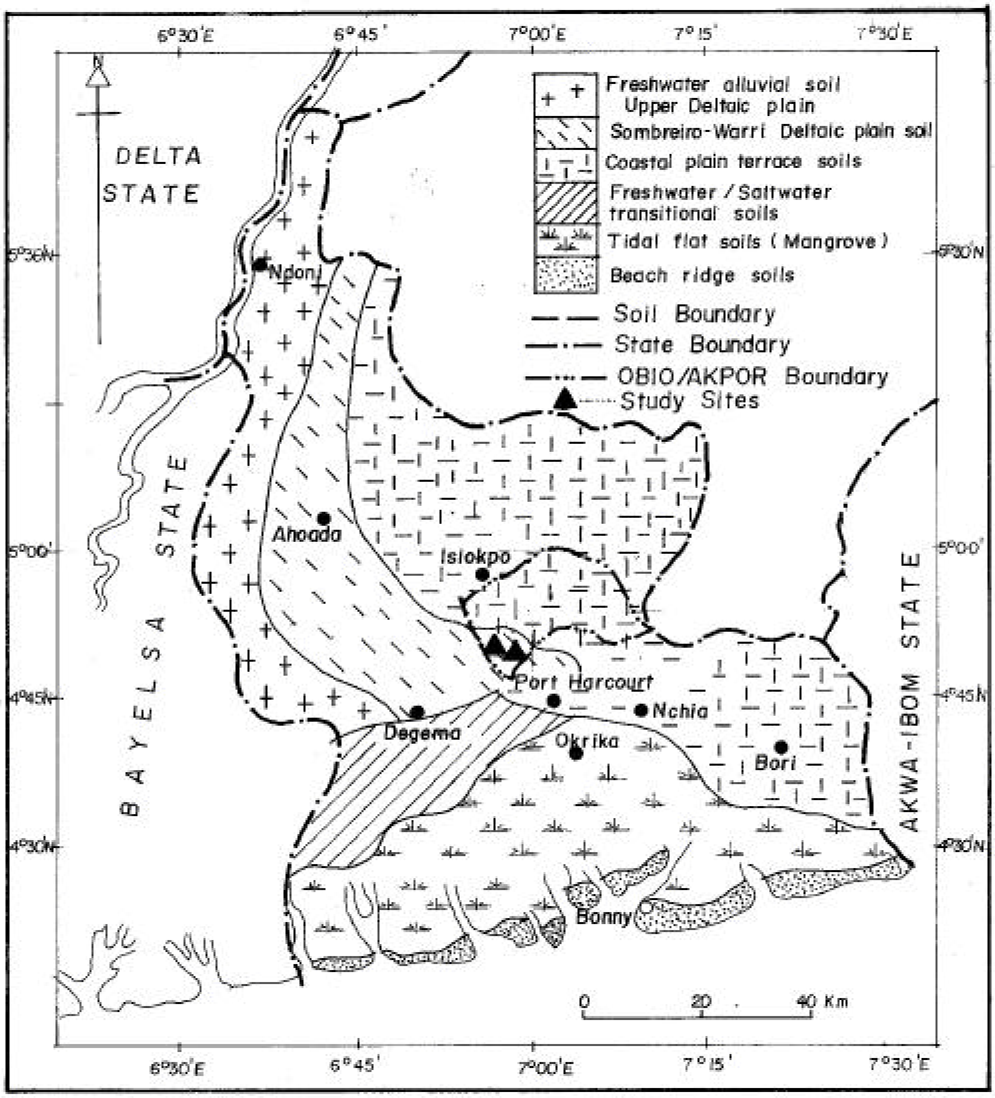

Fig. 2: Geological map of the study area

$$\rho_a = \frac{\pi\left[\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2\right]R}{MN} \quad (1)$$

$$= K.R \quad (2)$$

These values were then entered manually in a recording sheet for computer processing using Schlumberger automatic analysis software (Henker, 1985).

The 2-D resistivity imaging uses a multi-electrode system with equal electrode spacing a ranging from 10-60 m for successive measurement (Fig. 3). A 20 electrode Wenner-alpha configuration was adopted for the survey and successive electrode positions were occupied along

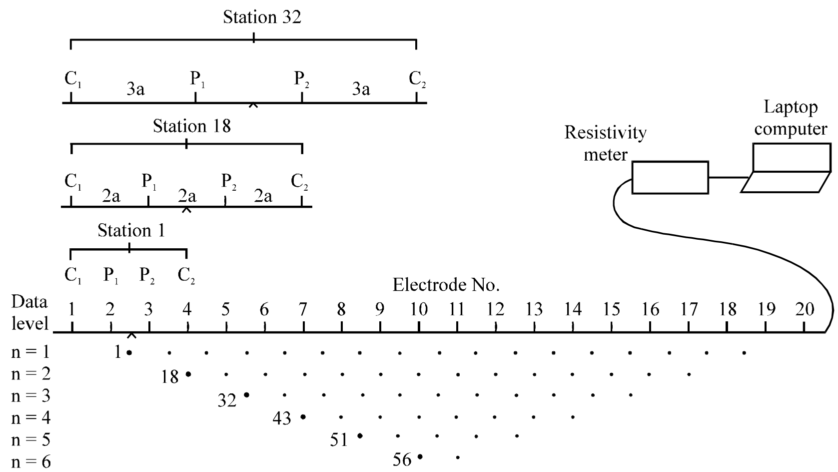

Fig. 3: The arrangement of electrodes for a 2-D electrical survey and the sequence of measurements used to build a pseudo section (Loke, 1999)

the survey path by leap froging (Loke, 1999). The Wenner-alpha configuration was adopted because of its good signal strength and continuous coverage. The apparent resistivity values were calculated from the field resistance values using the equation:

$$\rho_a = 2\pi aR \tag{3}$$

where, a is the electrode spacing and R is the field resistance value.

The values of the apparent resistivities, electrode spacing and the x-locations were entered in a text file for processing using RES2DINV (2006).

RESULTS AND DISCUSSION

The Vertical Electrical Soundings (VES) and 2-D resitivity imaging techniques were integrated in the study of the vulnerability of the coastal aquifers to surface pollutants around two landfill sites within Port Harcourt municipality. The results of the interpretation of the vertical electrical sounding data revealed different geoelectric layers in terms of their resistivities and depths in the study areas.

A total of 4 to 6 geoelectric layers were delineated with varying type curves. The curve types identified ranges from AK to KQ type curves reflecting the lithological variations with depth in the study areas. The nature of the type curves suggests that the measured resistivities vary with depth of investigation in the study sites.

The geological interpretation of the VES results reveal that the geoelectric layers are dominantly sandy formations of varying grain sizes and moisture contents, with little clay/shale intercalations at depth (Fig. 4). These sandy formations constitute the vadose zones at shallow depths and unconfined multi-aquiferous systems in the area. The depth to the aquifers ranges from 23.89 to 73.38 m, revealing the variable nature of the depth to the aquifer systems in the sites with an average depth of 53.05 m.

The quantitative assessment of the Dar-Zarouk parameters obtained from the results of the vertical electrical soundings revealed that the longitudinal conductance S (overburden protective capacity) in the study areas ranges from 0.009 Siemens to 0.06 Siemens. These range of values for

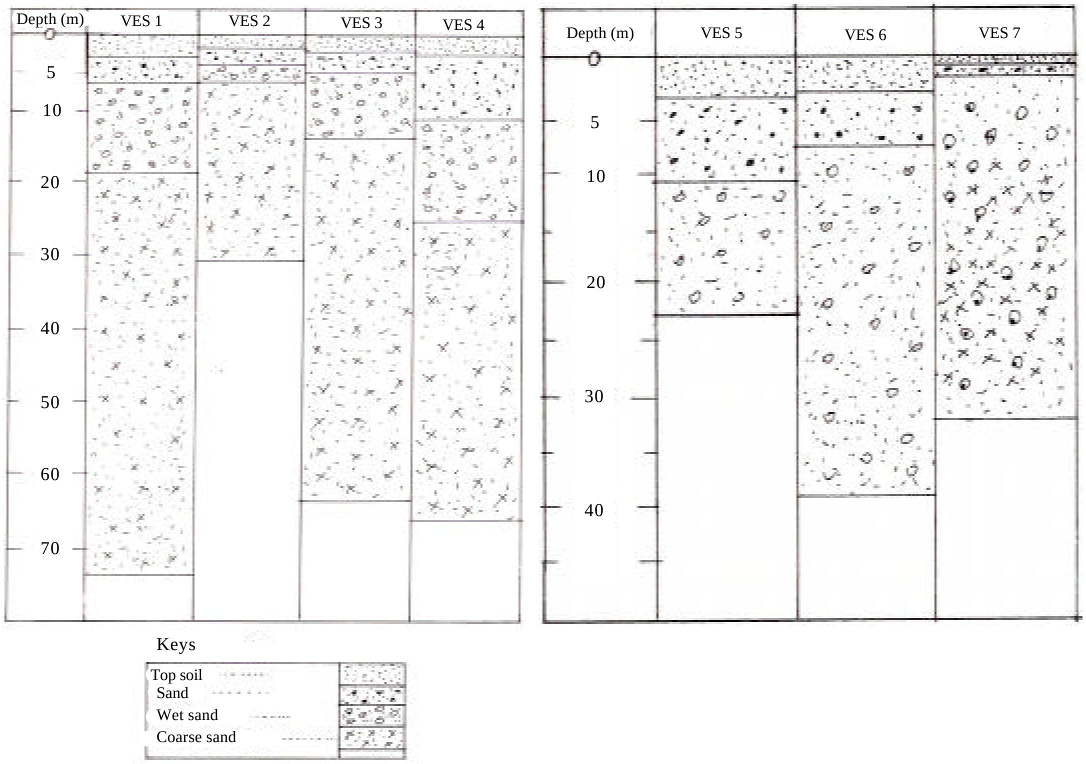

Fig. 4: Geoelectric sections of the VES's

Table 1: Computed values of the Dar-Zarouk parameters from the VES curves

VES No.	Resistivity (Ωm) ℓ_1	ℓ_2	ℓ_3	ℓ_4	ℓ_5	ℓ_6	Transverse resistance (R) ($\times 10^3\,\Omega m^2$) R_1	R_2	R_3	R_4	R_5	R_6	Longitudinal conductance (S) ($m\Omega^{-1}$) S_1	S_2	S_3	S_4	S_5	S_6
1	137.30	748.10	380.00	503.80	263.10	108.00	0.38	2.71	4.49	10.18	9.11	-	0.020	0.005	0.030	0.04	0.13	-
2	132.20	197.00	646.00	387.50	599.70	193.10	0.17	0.34	2.14	9.52	-	-	0.009	0.009	0.005	0.06	-	-
3	185.20	333.40	803.80	2211.00	1237.00	-	0.26	1.19	7.39	107.65	-	-	0.008	0.010	0.010	0.02	-	-
4	138.90	604.70	1561.00	1214.00	1020.00	-	0.26	5.65	21.22	49.17	-	-	0.010	0.020	0.009	0.03	-	-
5	164.50	345.00	538.40	358.60	-	-	0.51	2.65	4.84	-	-	-	0.020	0.020	0.020	-	-	-
6	59.17	90.78	121.40	548.90	-	-	0.53	0.41	3.85	-	-	-	0.040	0.050	0.260	-	-	-
7	14.20	204.00	2860.00	5850.00	518.00	397.00	0.011	0.14	7.44	86.58	6.84	-	0.060	0.003	0.0004	0.0025	0.03	-

the overburden protective capacities are less than the critical value of 1.0 Siemens (Table 1). These suggest that the overburden layers do not have significant amount of clay/shale impermeable beds. These are interpreted as zones or layers of probable risks to aquifer contamination. Underlying this bed are porous and permeable sandy formations of varying thicknesses, grain sizes and moisture content which constitute the aquifer.

The tranverse resistance (T) of the aquifers varies from 11 to 2.12×10^2 Ωm^2 (Table 1). These were interpreted as zones of high transmissivity. The high values of the tranverse resistances (Transmissivities) are due to the lithological nature of the aquifer materials which are porous and permeable to fluids in accordance with the results of the vertical electrical sounding. The low values of the protective capacity of the overburden clay/shale layer and the high transmissivities of the

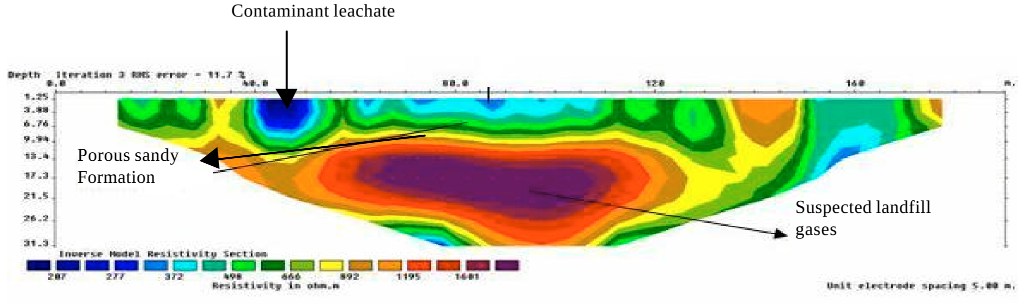

Fig. 5: Inverted resistivity sections of site 1 profile 1

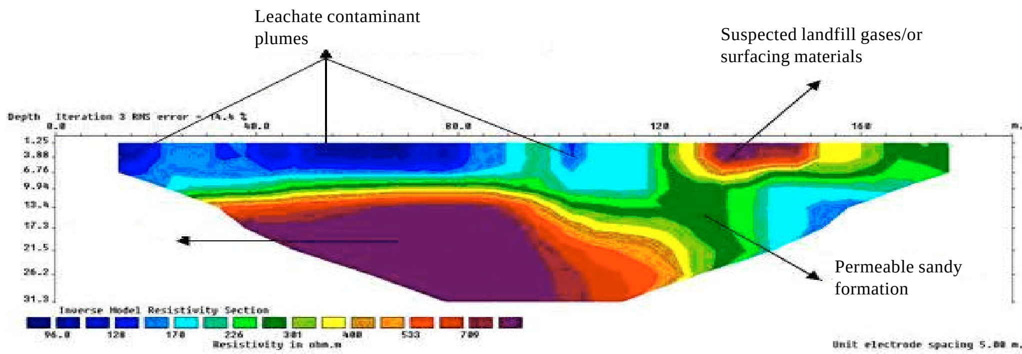

Fig. 6: Inverted resistivity sections of site 1 profile 2

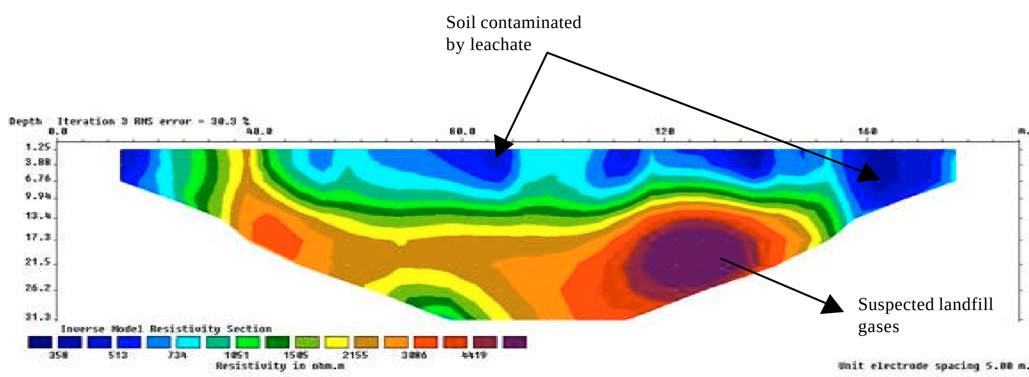

Fig. 7: Inverted resistivity sections of site 2 profile 1

vadose zones and the aquifers, will aid the seepage and migration of contaminants within and around the landfills subsurface layers.

Compounds of anomalously low, intermediate and high resistivities were mapped and identified within and around the study sites using the 2-D electrical resistivity tomography techniques (Fig. 5-8). The highly resistive anomalies were mapped and identified as (pink to purple) with resistivities ranging from 725 to 4419 Ωm and at depth exceeding 31.3 m. These anomalously high resistive features could be associated with the presence of landfill gases (Ammonia, methane, sulphur (IV) oxide, or carbon (IV) oxide) generated as a result of the anaerobic decomposition of the landfill municipal wastes.

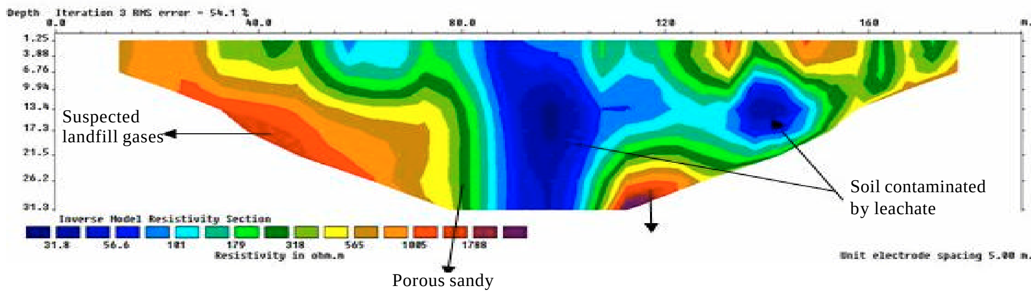

Fig. 8: Inverted resistivity sections of site 2 profile 2

These gases have been displaced to various degrees with respect to depth in the study sites due to their low densities and pressure buildup within the landfill and are migrating to the surface through the permeable and porous sandy formations. They are relatively soluble in the moisture permeating the pores of the formations, thereby causing serious contamination of the groundwater aquifer.

The low resistive zones identified as (deep blue) with resistivity ranging from 15.65 to 179 Ωm were interpreted as leachate contaminant plumes containing dangerous pathogens, dissolved organic and inorganic constituents. These features manifests at depths ranging from 1.25 m to more than 31.3 m in the study areas and are observed to have seeped from surface points to depths exceeding 31.3 m. This observed seepage is enhanced by the porous and permeable nature of the dominant sandy formations of the aquifer materials.

Finally, layers of increasing resistivities in the entire sections (green to yellow) with resistivities ranging from 225 to 2155 Ωm were also mapped and identified as porous and permeable sandy layers of varying grain sizes and moisture contents.

Based on the results of the 2-D imaging, no appreciable clay/shale impermeable layer was delineated and hence, the major lithological units are sandy formations of varying grain sizes in accordance with the results of the VES interpretations in the sites.

CONCLUSIONS

The results of both VES and the 2-D resistivity imaging revealed the various lithological units in the study sites based on their respective depths of investigation. The geologic interpretation of the VES showed that the study areas are dominantly underlain by sandy formations of varying grain sizes and moisture content with high transmissivities.

The quantitative assessment of the protective capacity of the geoelectric layers overlying the aquifers showed that the longitudinal unit conductance ranges from 0.009 siemens to 0.06 siemens. This implies poor aquifer protection and indicates zones of probable risks to soil and groundwater contamination. The formations do not show good aquifer protective capacity. Thus, they are vulnerable to any near-surface contamination.

With the aid of the tomograms, two distinct contaminant plumes had been mapped and identified with an intermediate resistivity layers within the study sites. They are:

- Highly conductive leachate contaminant plumes seeping from surface points to the aquifers
- Highly resistive gaseous contaminants that are probably due to landfill gases (Ammonia, methane etc.) obtained as a result of the anaerobic decomposition of the landfill organic wastes

The hydrogeologic features of the study areas indicated that contaminants derived from the waste disposal sites infiltrate through the porous and permeable soil media into the vulnerable aquifers. This suggests that the soil and the groundwater system may have been contaminated to depths exceeding 31.3 m in the sites.

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