Geoenvironmental Study Of Groundwater Contamination In A Dual Aquifer Environment Using Earth Resistivity Imaging

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Abstract: The variation of electrical resistivity as a function of soil properties was used as a vital tool to study groundwater contamination in the vicinity of some selected solid waste disposal sites in the municipal town of Zaria. The Abem Lund Imaging system with Terrameter SAS 4000 was used for the resistivity data measurements and the Res2dinv software was used for the processing and interpretations of the data. Due to the high conductivity of the contaminant plumes it was possible to delineate their pathways into the regolith and fractured aquifer environments. Resistivity data from inverted models obtained from profiles near monitoring wells, correlated well with electrical conductivity (EC) and total dissolved solid (TDS) values of water samples taken from theses wells. The inferred water resistivity and the soil resistivity obtained from the resistivity tomosections at depths of water table revealed that the samples, which were collected from hand dug wells whose depths are within the overburden (regolith aquifer), are more polluted than the samples which were collected at deeper levels corresponding to the borehole samples (fractured aquifer). The findings of this study suggest the potentiality of the resistivity imaging technique as a pre-characterization tool for mapping subsurface contamination in the vicinity of waste disposal sites.

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1. Introduction

The evaluation of groundwater and soil properties has become increasingly important for site characterization when more industrial wastes and domestics solid refuse come into contact with groundwater and soils causing subsurface contamination. (Yoon, et, al, 2002).The variation of electrical resistivity as a function of soil properties is a vital tool for assessing the contaminated media. Electrical resistivity method is the most commonly applied geophysical method to measure the apparent resistivity of subsurface materials. Under many subsurface conditions, electrical resistivity methods can quickly and cheaply locate the general position of the contamination plumes and identify areas most feasible for sampling and monitoring. Electrical resistivity is a function of a number of soil properties, including the nature of the solid constituents (particle size distribution, mineralogy), arrangement of voids (porosity, pore size distribution, connectivity), degree of water saturation (water content), electrical resistivity of the fluid (solute concentration) and temperature. (Samouëlian, et, al, 2005). The water solution resistivity is a function of the ionic concentration, and the resistivity of the solid grains is related to the electric charge density at the surface of the constituents. These parameters affect the electrical resistivity, but in different ways and to different extents. Electrical resistivity experiments have been performed to establish relationships between the electrical resistivity and each of these soil characteristics. Nevertheless, the electrical resistivity of bulk soil decreases as the concentration of leachate increases. Hence the higher the concentration of leachate in pore fluid, the lower electrical resistivity. The lower electrical resistivity of pore fluid can be explained. Many contaminants contain an ionic concentration considerably higher that the background level of native ground water. When such a contaminant is introduced into an aquifer, the electrical resistivity of the saturated zone is reduced. Earth resistivity imaging survey across such a suspected area can identify this reduced resistivity zone as an anomaly. But by combining knowledge of Hydrogeological and geophysical data with chemical data from monitoring wells the extent of dumpsite leachate can be delineated by geo-electrical imaging as a response to the varying electrical resistivity in the contaminated area. In this investigation five different municipal solid waste disposal sites were surveyed. These include Tsamiya dumpsite and Old cemetery dumpsite both in Samaru, Palladan dumpsite, Kapa garage dumpsite and Abubakar Iman primary school dumpsite both in Tunduwada.

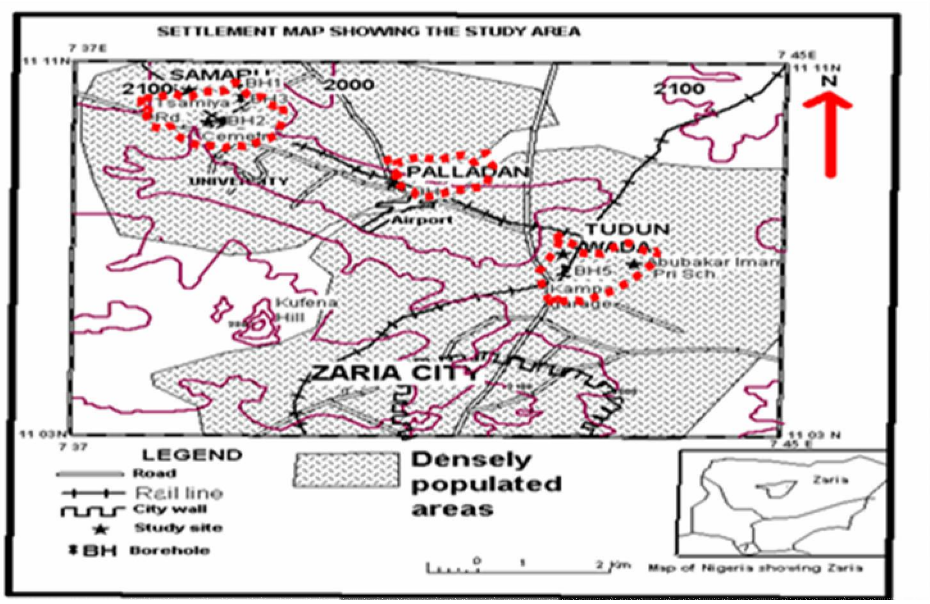


Fig. 1: The settlement map of Zaria showing the surveyed locations as modified from McCurry, (1970).

2. Material and Method.

Site Description

The main goals of this study were to identify and delineate the extent of contaminated leachate plumes below surface as well as testing the efficiency of the 2-D resistivity method as a pre characterization tool for tracing the properties of the disposed waste and its severity underneath.The Samaru, Palladan and Tudun-wada areas are located in the most densely populated parts of Zaria Township (fig 1). Zaria is located approximately between Latitudes 11^{o} 03'N and Latitude 11^{o} 11'N to Longitude 07^{o} 37'E and Longitude 07^{o} 42'E. The approximate average elevation is about 670 m above mean sea level. It occurs in a dissected portion of the Zaria–Kano plains. The Zaria-Kano plains are an extensive peneplain developed on the crystalline rocks of the Nigerian Basement Complex. Zaria occurs within a semi-arid tropical continental climate, characterized by a distinct wet and dry season. Rainfall commences at about May and ends early to mid October. The mean annual amount of rainfall is about 1067mm. The eastern and western part of the study area are dissected and drained by the Basawa and Kubanni rivers and their tributaries respectively. Extensive exfoliation and chemical weathering have produced residual granitic inselbergs .The largest of such inselbergs is the Kufena Hill, just on the southern portion of the study area and which provides the main relief in the area. There are also low lying hills to the east of Kufena, around Zaria city and Tudun Wada. Fig 2 shows one of the waste disposal site located in Samaru.

Fig. 2: Tsamiya Dumpsite in Samaru. This well was initially used for domestic purpose by the indigenes but served as a monitoring well for the purpose of this research.

Hydrogeological studies undertaken in the North-central Nigeria basement complex, including Zaria revealed that the occurrence of ground water in the crystalline basement rocks occur within soft overburden, saprolite or regolith aquifer and fractures within the basement rocks. The regolith aquifer holds a great quantity of groundwater and most hand dug wells are located in this shallow aquifer for domestic water supply (Alagbe, 2002). At some locations, these aquifers are interconnected and form single unconfined Hydrogeological unit (Osazuwa and Abdullahi, 2008).

Geo-electrical Relationships

When an electrical current is introduced into the saturated soil it tends to move in a tortuous path through intergranular spaces following much the same path as the groundwater. In the case of groundwater flow the driving force is the hydraulic potential; in electrical flow it is the electrical potential. If the soil material itself is nonconductive, such as quartz sand, and relatively free of clay, the magnitude of the current depends primarily on effective porosity and pore-water conductivity (or resistivity). Conductive minerals such as magnetite in the matrix, as well as granular surface conductance can also affect electrical flow, but these are normally of secondary importance.

A commonly used means of expressing the relationship between pore-water ρ_w resistivity and bulk resistivity ρ_o is by formation factor F (Archie, 1942)

$$F = \frac{\rho_o}{\rho_w} \text{--------------------------------} (1)$$

The formation factor is related to porosity ϕ in the following empirical equation (Winsauer et al, 1952)

$$F = a\phi^{-m} \text{-------------------------------} (2)$$

Where ϕ = porosity a = constant ranging from 0.47 to 2.2 m = constant ranging from 1.3 to 2.6. Combining equation (1) and (2)

$$\rho = a\rho_w \phi^{-m} \text{--------------------------------} (3)$$

In surface electrical resistivity methods, an electrical current is introduced into the ground at the surface using two electrodes, and the resultant electrical potential measured between two central electrodes as shown in the Figure 3. There are a number of electrode arrangements which have been developed for use in geoelectrical work, but only the Schlumberger and Wenner arrays are widely used. In the Schlumberger array the central electrodes are kept relatively close together as compared to the separation of the outside current electrodes, while in the Wenner the distance between all electrodes is equal. For this investigation the Wenner array was used hence further discussion in this paper will refer to that method.

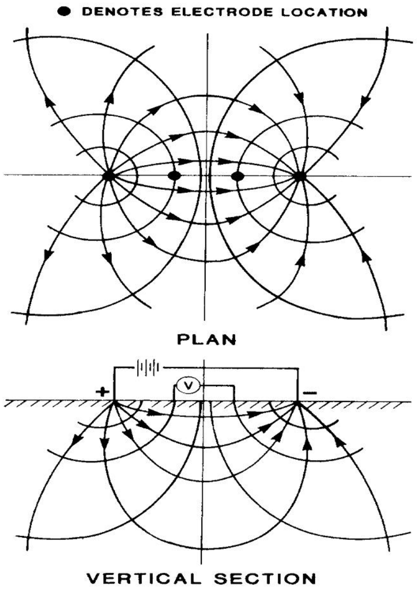


Fig 3: Electrical current flow in the Earth – Wenner electrode configuration.

The configuration shown in Fig 3 is the Wenner array from which the apparent resistivity of the bulk earth can be determined by the following equation

$$\rho_a = 2\pi a \frac{\Delta V}{I} \text{ ------------------------------}(4)$$

Where a is the selected electrode spacing, ΔV is the potential difference measured between the two central electrodes and I is the current imposed between the two outside electrodes and measured simultaneously with the potential difference ΔV .Two-dimensional electrical imaging/tomography surveys are usually carried out using a large number of electrodes, 25 or more, connected to a multi-core cable. In this survey, the Wenner 32SX protocol was adopted and in this, forty-two electrodes were used and adequate contacts were made with the ground. The electrode selector while measuring selects both the current and the potential electrodes based on the datum point to be measured at each time during data collection. Three stacks were used in order to ensure a reliable average data measurement. There are three basic modes of operation for any resistivity method: sounding, profiling and sounding – profiling (CVES). To obtain a good 2-D picture of the subsurface, the coverage of the measurements must be 2-D as well. As an example of the sounding profiling (CVES) resistivity method, Fig. 4 shows a possible sequence of measurements for the Wenner electrode array for a system with 20 electrodes. In this example, the spacing between adjacent electrodes is "a". The first step is to make all the possible measurements with the Wenner array with electrode spacing of "1a". For the first measurement, electrodes number 1, 2, 3 and 4 are used. Notice that electrode 1 is used as the first current electrode C1, electrode 2 as the first potential electrode P1, electrode 3 as the second potential electrode P2 and electrode 4 as the second current electrode C2. For the second measurement, electrodes number 2, 3, 4 and 5 are used for C1, P1, P2 and C2 respectively. This is repeated down the line of electrodes until electrodes 17, 18, 19 and 20 are used for the last measurement with "1a" spacing. For a system with 20 electrodes, notes that there are 17 (20-3) possible measurements with "1a" spacing for the Wenner array. After completing the sequence of measurements with "1a" spacing, the next sequence of measurements with "2a" electrode spacing is made. First electrodes 1, 3, 5 and 7 are used for the first measurements. The electrodes are chosen so that the spacing between adjacent electrodes is "2a". For the second measurement, electrodes 2, 4, 6, and 8 are used. This process is repeated down the line until electrodes 14, 16, 18 and 20 are used for the last measurement with spacing '2a' for a system with 20 electrodes. Note that there are 14(20-2x3) possible measurements with "2a" spacing. The same process was repeated for measurements with '3a', '4a', '5a' and '6a' spacing. To get the best results, the measurements in a field survey should be carried out in a systematic manner so that, as far as possible, all the possible measurements are made. This will affect the quality of the interpretation model obtained from the inversion of the apparent resistivity measurements (Dahlin and Loke, 1998). The 2-D electrical imaging/tomography is one geophysical development in recent years which can map even areas with moderately complex geology (Griffith and Barker, 1993).

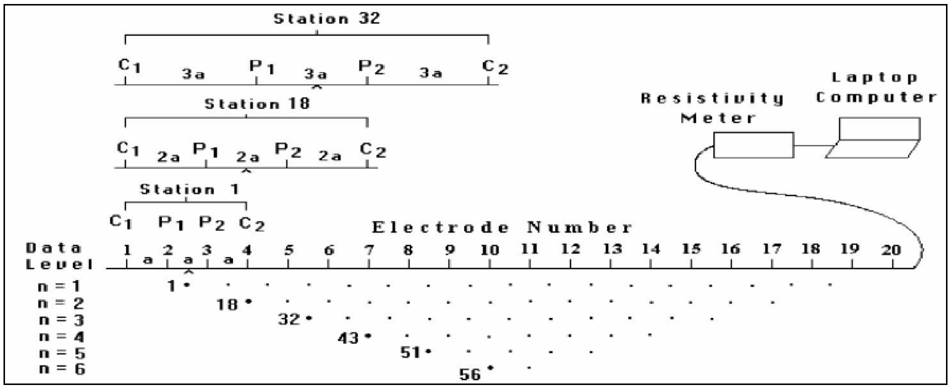


Figure 4: The arrangement of electrodes for a 2-D ERT survey and the sequence of measurements used to build up a pseudosection. (Loke, 2004).

One technique used to extend horizontally the area covered by the survey, particularly for a system with a limited number of electrodes, is the roll-along method. After completing the sequence of measurements, the cable is moved past one end of the line by several unit electrode spacings. All the measurements that involve the electrodes on part of the cable that do not overlap the original end of the survey line are repeated (Fig. 5).

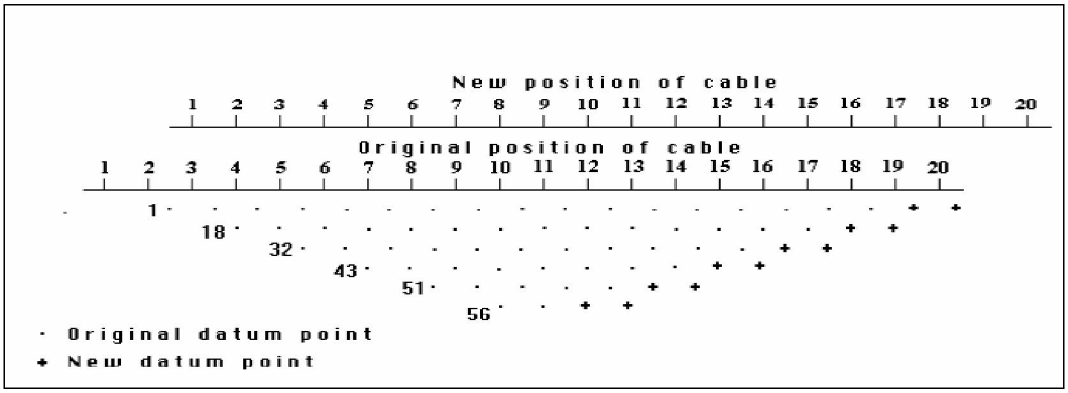


Fig. 5: The use of the roll-along method to extend the area covered by a 2-D ERT survey. (Loke, 2004).

3. Discussion of Results

The results obtained in this investigation are presented as case studies from the five selected dumpsites.

Case Study I: Old Cemetery Dumpsite Profile line H03.

This profile was taken along the western perimeter margin of the dump over the rail line. The electrode spacing was 4.0 m which gave a total length of 160 m, thus allowing depth of investigation down to 20 m Fig 6. This depth covered the depth beyond water table in the area as revealed by static water level of local wells in the area.

Resistivity Model H03. The model (Fig 6) clearly shows a contaminated topsoil of resistivity range from 22.4 – 35.0 Ohm-m, from the surface at the 136 m mark sloping down gradually to a depth of 16.0 m at the 48.0 m mark. The entire profile line has an overburden thickness of over 20.0 m at some points, narrowing down to about 17.0 m towards the northern end of the profile line. This suggests the possibility of the leachate plume migrating into the fractured aquifer at deeper levels of the basement. Water sample analysis result from a hand dug well (HW1) very close to the 32.0 m mark of this profile, showed high electrical conductivity and high total dissolved solid. The water is also found to be polluted with the heavy metals Pb, Cd, Cr and Ni with contaminations levels exceeding the regulated guidelines provided by the World Health Organization (WHO) .

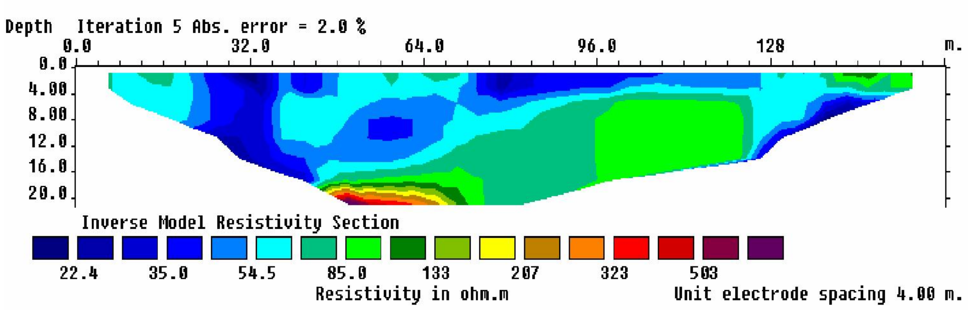


Fig 6 Inverted model of Profile line H03

Case Study II: Tsamiya Dumpsite Profile S01

Resistivity measurements were taken at this profile which defines the western margin of the dumpsite. A hand dug well at the time the resistivity data were taken was right within the dump Fig 2. The electrode spacing was 5.0 m which gave a total length of 200 m, thus allowing depth of investigation down up to 25.0 m (Fig 7); this depth covered the depth beyond water table in the area as revealed by depths of hand dug wells.

Resistivity model S01

Examining the resistivity model (Fig 7), from the 135.0 m mark to 150.0 m mark, we find a trend of decreasing near surface resistivity right from the surface down to a depth of 20.0 m. The substantial decrease in resistivity(from 82.0 – 40.9 ohm-m) obtained from the 2-D data at these depths is believed to be due to groundwater contamination as a result of accumulation of leachate, a similar trend can be seen between the 70.0 m mark and 80.5 m mark also from the surface down to about 21.0 m. However between the 80.5 m and 115.0 m, a near surface low resistivity saturated zone appears not to be able to migrate beyond a depth of 5.0 m probably because of a non permeable material of resistivity ranging from 116-164 Ohm – m defining the subsurface topography of the dumpsite. Hence the migration pathways of the contaminant are delineated in the directions of the accumulations of the contaminants. These pathways are likely to be with materials that are highly porous and permeable. The water analysis of the hand dug well which showed elevations in concentration of organic/inorganic parameters exceeding the permissible health limits supports the fact that the delineated low resistivity portions represents accumulated leachate plumes.

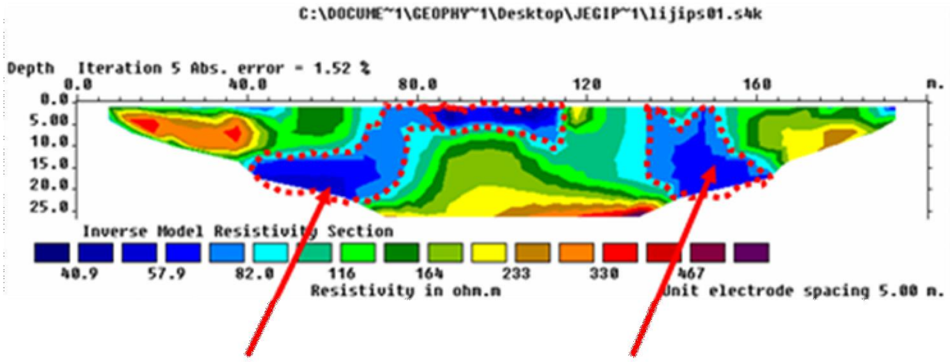


Fig 7: Inverted model of Profile line S01.

Case Study III: Palladan Dumpsite-Profile P03.

This profile was taken across the dump at the western flank of the dump. Eighty electrodes were planted in this profile with a spacing of 5.0 m thereby transversing a horizontal distance of 400.0 m trending N-S direction. This was made possible by the adoption of the roll along technique in this profile.

Resistivity Model P03

The model (Fig 8) shows that the top 5 -10 m of regolith has resistivity of less than 34.1 Ohm-m with the top 5 m having a resistivity of less than 16.6 Ohm-m. It indicates that within 10 m depth groundwater is strongly contaminated. The penetration of this strong contamination appears to be controlled by a layer of the subsurface with varying thickness across the entire profile. This layer is interpreted as clay layer especially as the resistivity (70.0 Ohm – m and above) is within the range of the resistivity of clay. The depth of penetration increases southwards as the clay layer thins out under the control of the subsurface topography, the strong contamination can be seen extending deeper into the weathered basement up to a depth of over 25.0 m at the 320.0 m mark. This conclusion is supported by the result of the water chemistry analysis of water sample collected from a 27.0 m deep borehole (PBH1) located near the profile line about 5.0 m on the western side of the 320.0 m mark which showed slight elevations in concentrations of some of the heavy metals (Pb, Cd and Ni) above WHO guidelines for portable water. The inversion also reflects the bedrock at 25.0 m depth at profile position 75.0 m and 300.0 -320.0 m while the bedrock with varying moisture content and degree of weathering dominates the profile beginning from depth of 10.0 m down to 30.0 m. The degree of weathering between points B and B$^{/}$ suggests the possibility of the interval serving as a migration pathway for contaminants into the fractured aquifer zone as was also found in profile P02. All the hand dug wells in this location had depths within the regolith aquifer and all had high TDS and showed elevations in concentrations of some heavy metals (Pb, Cd, Cr, Ni) above the WHO guidelines for drinking water. Unfortunately these wells are the major sources of water for domestic needs of the inhabitants in the environs.

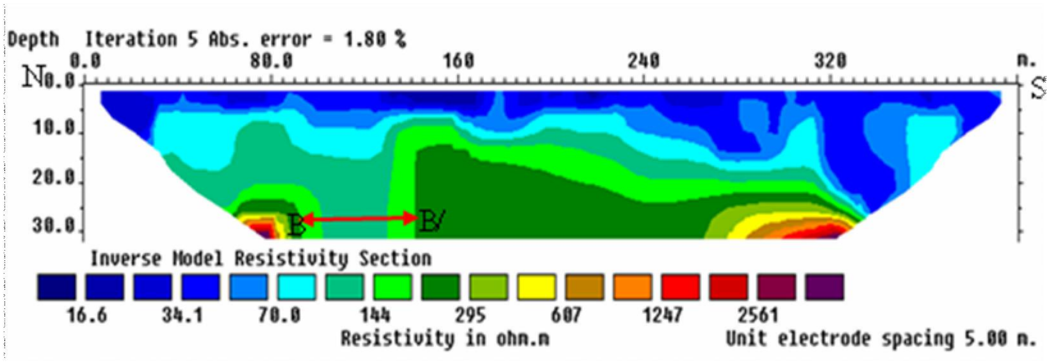


Fig 8: Inverted model of Profile line P03.

Case Study IV: Kampa Garage Dumpsite- Profile T01.

Resistivity Model T01.

This profile was taken at the northern perimeter margin of the dumpsite trending E-W direction. The electrode spacing was 2.5 m which gave a total spread length of 100 m allowing an investigation depth of 15.0 m. This depth covered beyond the depth of water table in the area. Examining the model (Fig 9), from x = 0.0 m to x = 27.5 m from x =32.5 m to 92.5 m, we find a trend of decreasing near surface resistivity at depth of 0.0 m down to 6.0 m and at depth of 0.0 m down to 15.0 m, respectively The substantial decrease in resistivity(19.7 – 7.36 ohm-m) obtained from the 2-D data at these depths is believed to be due to groundwater contamination as a result of accumulation of leachate, a conclusion supported by the shallow water table in the location as revealed by hand dug well TW1 which measured 2.0 m as the depth to water table along this profile. This conclusion is also supported by the water analysis of the hand dug well which showed elevations in concentration of organic/inorganic parameters exceeding the permissible health limits. The granite outcrop observed in the location is also evident in the inverted model which reflects the bedrock at depths ranging from 0.0 m to 15.0 m at the 27.5 - 32.5 m mark. The bedrock with varying moisture content and degree of weathering was also encountered at about

6.5 m depth down to about 12.5 m between the 15.0 m mark and 27.5 m mark. The subsurface topography is controlled by the bedrock dipping in the E-W direction.

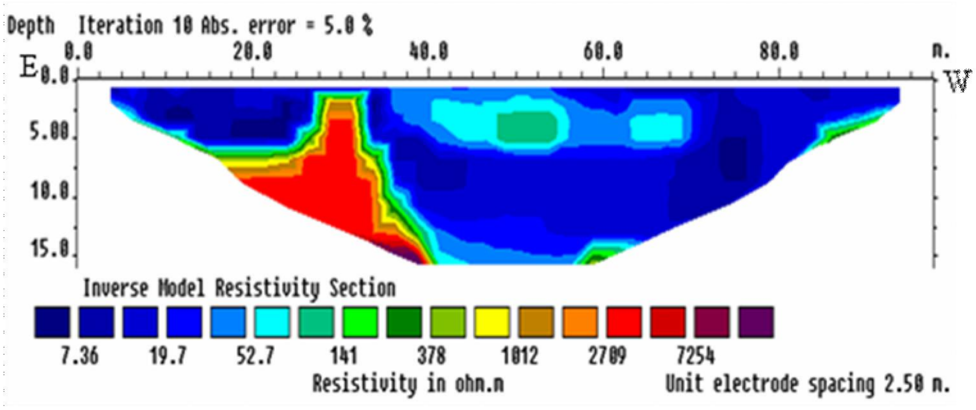


Fig. 9: Inverted model of Profile line T01

Case Study V: Abubakar Imam Primary School Dumpsite Profile IPT04

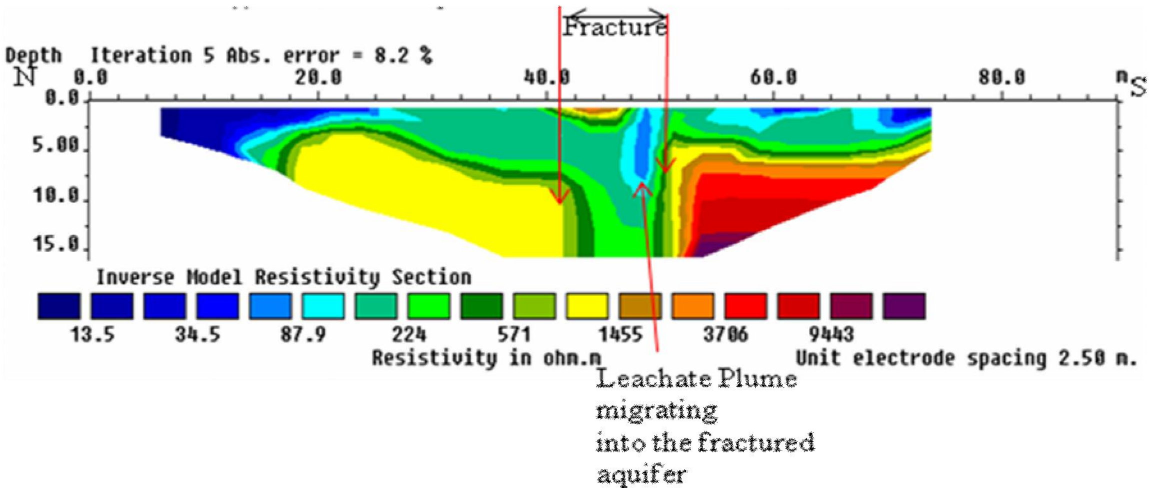
The model (Fig 10) shows low resistivity values ranging from 13.4 - 34.4 ohm-m from the surface layer up to a maximum depth of 6 m recorded between the first electrode (x = 0.00 m) up to the 25 m mark. This low resistivity is in the directions of hydraulic gradient where about eight electrodes were located on the dump and therefore is attributed to leachate bubbles within the refuse dump. Like in profile T04 the inversion also reflects the bedrock at 5.0m depth while the bedrock with varying moisture content and degree of weathering dominates the profile beginning from depth of 5m down to 15m. The high resistivity observed at a depth of 5m in this profile is further evidence that the bedrock is a shallow fresh basement of granite, (Plate 1). Another important feature of interest in this profile is the vertical contact between the weathered basement and the fresh basement as can be seen in the profile between 42.0m and 52.5m. This suggests the presence of fracture of possible width of 10.5m filled with material of higher porosity and permeability which could serve as a major pathway of contaminant plume into the groundwater. The high rms error is probably due to the sharp contrast in resistivity between the highly contaminated thin topsoil layers overlaying the shallow high resistivity granite bedrock. For the bedrock elevation, the 2D resistivity data for each electrical resistivity imaging line were generated into 3-dimensional representation of the subsurface topography using SURFER 8 package. Fig 11 shows one of the results obtained in the Old cemetery dumpsite.

In the study of groundwater contamination, Ebraheem et al., 1990 found that the resistivity of leachate plume is a function of the soil resistivity. The geophysical and hydrochemical data were therefore proved as follows. The specific conductivity measurements of well water samples were converted into water resistivity ($\rho_w = {}^{1}\!/_{\sigma_w}$), while soil resistivity $\rho_{s,}$ were estimated from inverted tomography models nearest to the well at the depth corresponding to the water table depth (Ebraheem et al., 1996), to ensure that the

observed values are close representative of the saturated zone. The resulting data are given in table 1.Finally, in order to obtain a relationship between water quality and soil resistivity, a plot of the water resistivity as a function of soil resistivity was done. The fitted line between soil and water resistivity (Fig 12) indicates the following empirical relationship:

$$\rho_w = 0.28125\rho_s + 0.98 \text{-------------------- (5)}$$

where, ρ_w is the water resistivity in Ω-m and ρ_s is the soil resistivity in Ω-m.



Leachate Plume migrating into the fractured aquifer

Fig 10: Inverted model of Profile line IPT04

Plate 1: Coarse-grained granite exposed within Abubakar Imam Primary LEA primary school dumpsite, Tudun Wada, Zaria. (Photo by Jegede, S. I.)

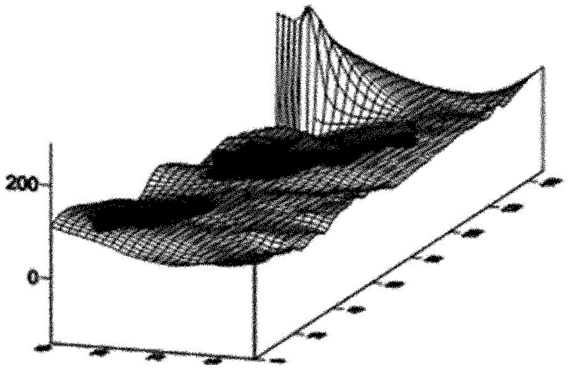


Fig 11: 3D mesh diagram showing the apparent Resistivity values of ERT profile H03 Depression and undulations in dark shading are good prospects of groundwater accumulations.

Table 1: Geophysical and Hydrochemical data used to obtain the relationship between soil and water resistivity.

Nearest profile to Well	Name of Well	Depth of Water Level (m)	EC (µS/cm)	Soil resistivity ρ_s (Ω m)	Water resistivity ρ_w (Ω m)
H03	HW1	4.30	1340	23.70	7.46
P03	PW1	4.60	1660	16.50	6.02
P03	PW2	4.30	740	34.00	13.51
P04	PW3	4.70	1120	28.70	8.93
P05	PW4	4.60	1538	18.60	6.50
T01	TW2	2.00	1585	19.70	6.31
T02	TW1	4.50	2862	16.00	3.49
S02	SW1	5.00	1650	16.20	6.06
HO6	HBH1	25.00	238	130.00	42.02
H06	HBH2	27.00	284	150.00	35.12
P04	PBW1	27.00	280	153.00	35.71

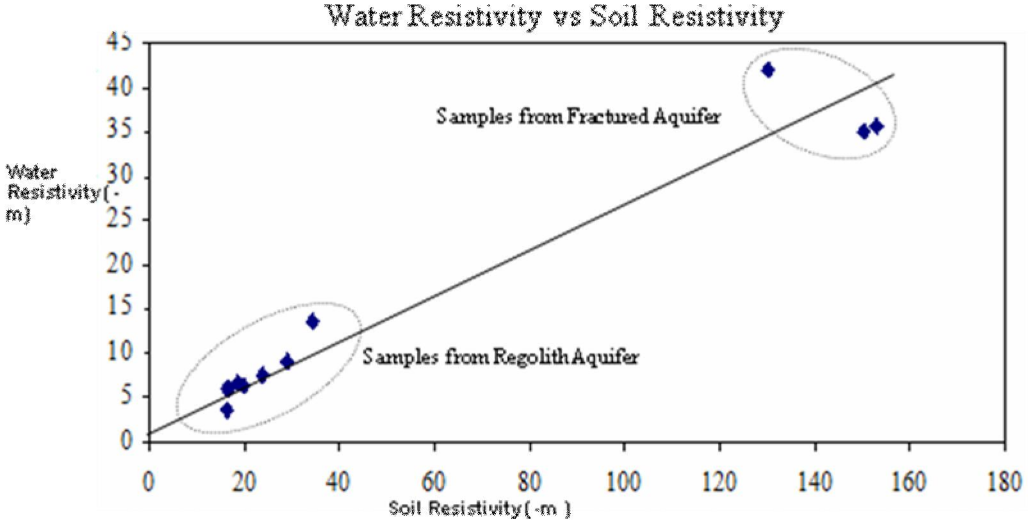


Figure 12: The relation between soil resistivity and water resistivity

This empirical relationship between soil resistivity and water resistivity reveals that the soil resistivity is strongly affected by groundwater salinity, and provides a reaffirmation of the basis for applying resistivity methods to study groundwater contamination. Figure 12 shows that the samples, which were collected from hand dug wells whose depths are within the overburden (regolith aquifer environment), are more polluted with resistivity values of soil and water samples ≤ 36.0 Ω-m and ≤ 14.0 Ω-m respectively than the samples which were collected at deeper levels corresponding to the borehole samples (fractured aquifer environment).

4. Conclusion

The 2-D resistivity imaging technique has been successfully used in this study to map the contamination plume and to characterize the dumpsites in terms of subsurface resistivity distribution of the waste material and soil underneath the vicinity of each dumpsite. The interpreted resistivity section which correlates well with the water chemistry result, suggests the potentiality of 2D resistivity imaging technique as a pre-characterization tool for mapping subsurface contamination in the vicinity of waste disposal sites. However the complexity of subsurface conditions beneath contaminated lands requires a multidisciplinary approach combining the systematic and careful application of hydrogeological, chemical and environmental geophysical techniques. The bedrock topography showed several basements i.e. “depressions” and “ridges”, where the depression basement could be favourable zones for groundwater development. There are such depression zones in and around the dumpsites, which act as good groundwater potential zones, but they are extremely polluted especially in the regolith aquifer environment.

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