ASSESSMENT OF LEACHATE CONTAMINATION OF GROUNDWATER AT SOME WASTE DISPOSAL SITES IN THE SOUTHERN GUINEA SAVANNAH ECOLOGICAL ZONE OF NIGERIA USING GEOELECTRIC PROCESSES

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ABSTRACT

This study aims at determining the leachate contamination of the groundwater resource at selected domestic wastes disposal sites in Minna, Nigeria for a population about 2.1 million, to locate aquifers and hydraulically active structures by tracing the movement of contaminant plumes and seepages in ground at the selected locations. Resistivity data was collected using a terrameter (SAS4000) while the Vertical Electrical Sounding (VES) mode was deployed using the Schlumberger array to enable investigation of the depth penetration of contaminant plume. The induced polarization (IP) was used to determine the level of contaminant plume. The VES readings measured at 50m intervals along each profile line and 100m inter-profile distance, with a maximum current electrode separation of 200m and potential electrode separation of 30m. There are equal numbers of three and four layers observed on the profile, which has ten VES points. The first layer has a resistivity range between 48.4 Ωm & 428 Ωm and thickness between 0.65m & 3.83m. However, isolated resistivity area such as VES; N_5 (287Ωm), N_6 (295Ωm) and N_8 (428Ωm) also suggested sandy/soil rich in organic matter (humus material/soil). The second and third layer is the fractured basement which has very low resistivity values for most VES (N_1–48.5Ωm, N_2–38.7Ωm, N_3–41.6Ωm, N_5–61.5Ωm, N_7–49.6Ωm, N_8–60.7Ωm, N_9–108Ωm and N_{10}–97.6Ωm) that indicated leachate presence and contamination, which results from increased ionic concentration. In conclusion, it was discovered that the study area had high conductivity values for some of the locations using the resitivity determination method. This indicated the presence of water within the study area. It was also concluded that the IP which indicated high concentration of metals caused the lowering of the resisitivity values at some of the locations, thus indicating the presence of metals within the study area.

Keywords: Chargeability, domestic waste, groundwater, profile, VES

INTRODUCTION

It is common knowledge that the activities of most urban settlement generate a lot of industrial and domestic solid wastes, which have an environmental concern and can be hazardous to surface or groundwater resources (Ma *et al.*, 2009). Groundwater had been a significant source of water supply in the most developing metropolis, just as most arid regions hence, the mode of disposal of municipal waste that could have a direct consequence on the quality of water for

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the consumption of the populace is of more significant concern (Singh *et al*. 2008).

In the developing world, the usual method for the disposal of domestic waste is usually through open dumpsites, which are accompanied with waste burning (Singh *et al.* 2011). Minimal effort is directed towards sanitary landfilling practice, *e.g*. the use of daily cover. Site selection is generally based on geographical rather than geological and hydrogeological considerations, *i.e*. the closer the site to the source of the waste, the better regarding logistics. It is not uncommon, therefore to find waste disposal sites within municipal boundaries and surrounded by residential areas. Such open dumpsites pose a serious health risk not just regarding degradation of groundwater quality but also to related problems associated with proximity to litter, feral animals, scavenging birds, vermin and airborne contamination arising from the mobilisation of fine particulate matter (Klinck and Stuart, 1999).

In Minna metropolis and its environs, municipal and domestic wastes are disposed indiscriminately at open dumps and uncontrolled landfill without adequate protective measures. The landfills are not underlain by impermeable soils/ materials (liners) that are naturally suited to protect the underground water or covered with soil cap to minimize water infiltration, mitigate odours, and limit vector breeding; there are also no drainage systems for leachate collection from the solid waste and surface runoff, and no gas collector and ventilation or flaring systems. The impact of waste dump has a great danger to groundwater and health risk to the inhabitants.

According to Andrews *et al.* (2011), landfills are the final depositories for a wide range of solid waste from both residential and commercial sources, and therefore have the potential to produce leachate containing many organic compounds found in consumer products such as pharmaceuticals, plasticizers, disinfectants, cleaning agents, fire retardants, flavourings, and preservatives, known as emerging contaminants (ECs). In recent years, there had been growing concern and some passionate discussions about what constitutes a landfill, the transformational changes of the different types and its management and the effect of varying emerging contaminants.

This study aims at determining the leachate contamination of the groundwater resource at some selected wastes disposal sites in Minna, Nigeria and also to locate aquifer and hydraulically active structures by tracing the movement of contaminant plumes and seepages in the ground at the selected locations.

METHODOLOGY

Field Procedures

The land area surveyed had a dimension of 1km by 650m with the coordinate 9.6368^0 and 9.6343^0 N; 6.5938^0 and 6.5989^0 E located in the northern part of Minna, Nigeria. It was sectioned into profile lines at fixed separation and staked off at the points at which readings were referenced. The coordinates of each spot measured its latitude, longitude and elevation.

Paths on which data referenced were cleared along the profile line for ease of collection of data and information. Figure 1 presents the map of Niger State and that of the study location while Figure 2 shows the study location of the waste disposal site.

Resistivity data was collected using a terrameter (ABEM SAS4000) while the Vertical Electrical Sounding (VES) mode was deployed using the Schlumberger array method to investigate the depth penetration of contaminant plume. The VES readings measured at 50m intervals along each profile line and 100m inter-profile distance, with a maximum current electrode separation of 200m and potential electrode separation of 30m at the MINNA NORTH waste disposal site. The VES points were used to pick the induced polarisation (IP) readings. A total of 154 VES and 154 IP station data were

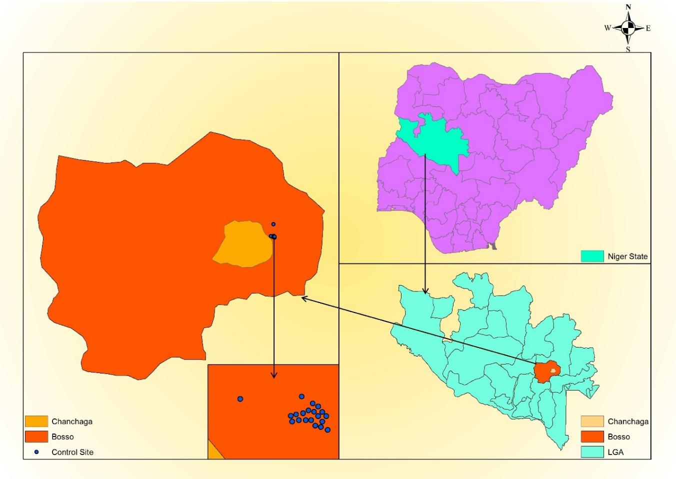

FIGURE 1
Extracted map of the study area (Minna) showing the VES and IP points

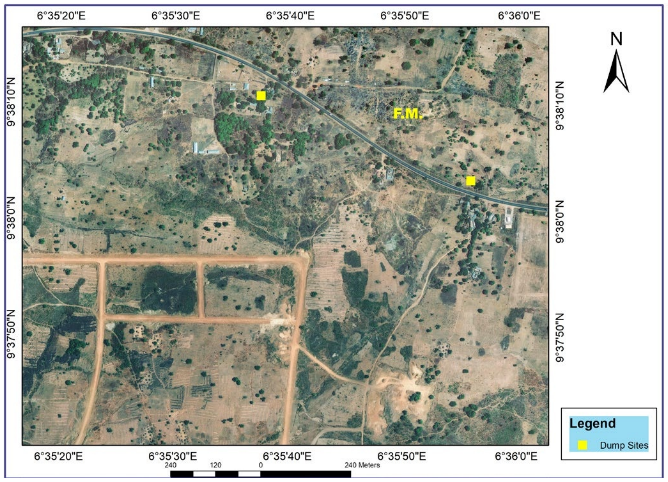

FIGURE 2
Waste disposal site for the Minna north location, Minna

recorded on the Minna North waste disposal site. Seven (7) profiles consisting of 70 VES and IPs were selected for the study. 21 VES and 21 IP stations were selected as control outside the study location which was 100m away from the exposed site.

The resistivity data collected in ohm was used in formula by putting geometric factor ‘K’ to get the apparent resistivity values in ohm-m. An iterative 1-D software program IPI2win was used for data analysis to generate the pseudo-sections, resistivity cross sections, digitised resistivity and chargeability layer curves or log graphs and resistivity-depth tables. Iso-resistivity maps at some depths (surface, 5m, 10m, 12m, 15m and 20m) were generated for the waste disposal site and control site at MINNA NORTH to compare the extent of lateral leachate seepage using Surfer 11 software.

RESULTS AND DISCUSSION

Data Analysis of Vertical Electrical Sounding (VES) and Induced Polarization (IP) Profiles

The initial “raw” resistance field values in ohms were afterwards converted to resistivity values using the appropriate geometric factor. The processed apparent resistivity and chargeability data were inputted into the 1-D IPI2win software to generate the pseudo-sections, the resistivity cross sections, digitised resistivity and chargeability layer curves or log graphs and resistivity-depth table. Also, Surfer 11 software was used to generate iso-resistivity contour maps at varying depths, regolith thickness map and the depth to basement map.

Geo-electrical sounding data and induced polarisation data can be calculated and analysed digitally by using IPI2Win Software. Nevertheless, the 1-D IPI2win software could only accommodate ten station points on each profile; hence, data on one VES point was not captured for each of the fourteen profiles. However, this has no consequence on the overall result as the fourteen VES points are at the extreme northern flank where the shallow basement is familiar with highly resistive materials.

Pseudo and Resistivity Cross Sections for VES and IP points along Profile A. There are ten VES points on profile A (Figure 3), and three distinct layers are prominent on the profile. However, there are differences in VES A_3, A_4 and A_8 which has four layers respectively. The first layer has a resistivity range between 61.3Ωm and 585Ωm, and the corresponding thickness is between 0.50m and 1.82m. The second layer resistivity range between 14.4Ωm and 719Ωm and the similar thickness is between 0.48m and 9.66m. The thickest point is at VES A_9, and the thinnest is at A_4. The last layer has resistivity range between 799Ωm and 58051Ωm.

First layer resistivity indicated lateritic topsoil. However, isolated resistivity area such as VES; A_3 (411Ωm), A_4 (303Ωm), A_6 (350Ωm), A_7 (585Ωm) and A_9 (365Ωm) also suggested sandy soil which is rich in organic matter (humus soil) as not all portions of the site are covered with waste. The second layer is the weathered/fractured basement which has very low resistivity values for most VES (A_1–44Ωm, A_2–17.6Ωm, A_4–14.4Ωm, A_5–22.4Ωm, A_6–68.1Ωm, A_{10}–28.9Ωm) compared to the resistivity values of the VES points on the control profile P. This indicated very high leachate presence in first and second layers on the waste site. This is as a result of the leachate diminishing the electrical resistivity of the formation containing them (Martinho and Almeida, 2006). The third layer is the new basement for the three-layered VES points. The four-layered VES points (VES A_3, A_4 and A_8) have four geologic formations; lateritic topsoil, weathered basement, fractured basement and new basement. The geologic formations are consistent with the study conducted Mohammed *et al.* (2007) over the study area.

IP anomaly on profile A indicated increased chargeability values are moving downwards from the first layer to the second. As the chargeability value increased from 0.68m/sec to 2.09m/sec (VES A_1), the resistivity value lowered from 61.3Ωm to 44.5Ωm. This characteristic is the same for most three layered and some four-layered formations (VES A_2, A_4, A_5 A_6, A_8 and A_{10}). However, due to the presence of mineralisation in the metamorphic zone between the fresh and weathered basement rock and loose sand, there is significant IP effect at VES A_3 - 24.6m/sec and VES A_5 - 16.4m/sec as stated by Bernstone and Dahlin (1996). These IP effects confirmed leachate presence in the layers. There appears to be a fracture at A_{10}, hence, vertical and lateral leachate plume transport.

Conversely, profile P on the control site has four-layer formation that does not indicate the increased trend in the chargeability values with a corresponding low resistivity value (Figure 4). The first layer resistivity ranges between 121Ωm and 704Ωm and chargeability values between 0.01m/sec and 4.86m/sec. The IP effect differs on the control site, as it is not discriminating between equally conducting targets (Dahlin *et al.,* 2002), hence, confirms the presence of leachate contaminants on the waste site.

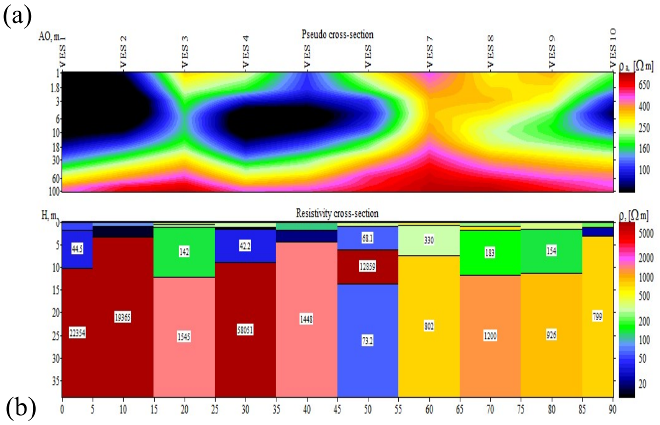

FIGURE 3

(a) Pseudo cross-section (b) Resistivity cross-section along profile A (IPI2win Software)

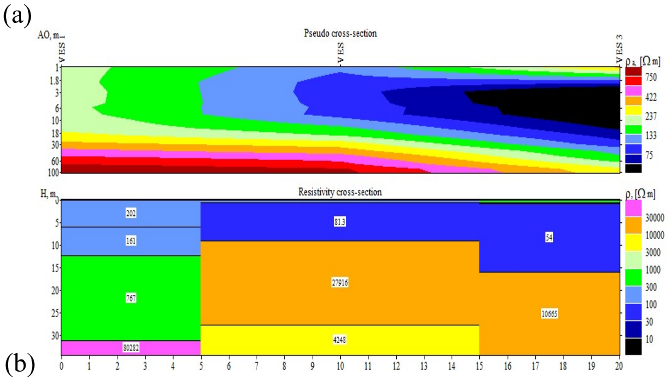

FIGURE 4
(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile P (IPI2win Software)

Interpretation of VES and IP points along Profile B. Profile B has ten VES points (Figure 5). There are three and four distinct layers on the profile. The first layer has resistivity range between 21.4Ωm and 657Ωm and thickness between 0.58m to 3.67m. The minimum depth of 0.58m is at VES B$_6$ and maximum depth at VES B$_4$ (3.67m). The second layer resistivity ranges between 11.9Ωm and 171Ωm, and the corresponding thickness is between 0.77m and 17.2m. The thickest point is at VES B$_4$, and the thinnest is at B$_1$. The last layer has resistivity range between 836Ωm and 137102Ωm.

First layer resistivity indicated lateritic topsoil. The second layer is the weathered/ fractured basement which has a little resistivity value for most VES points of B$_1$, B$_2$, B$_3$, B$_6$, B$_7$, B$_8$, B$_9$, and B$_{10}$. The resistivity values of 11.9Ωm, 47.5Ωm, 19.3Ωm, 31.6Ωm, 57.5Ωm, 109Ωm, 28.5Ωm, 41.3Ωm respectively were observed for those points. When compared to the resistivity values of the VES points on the control profile Q$_1$, Q$_2$, and Q$_3$ with values of 63Ωm, 506Ωm, and 61.8Ωm respectively, they were observed to be relatively high. These infer leachate presence in first and second layers of the waste site up to a depth of 7.58m. The third layer is the new basement, and this geo-electric section agrees with the work of Alagbe (2002). The geo-electric section of the control site on profile Q indicated three and four layered formations (Figure 6); the topsoil, weathered/fractured basement and new basement similar to the waste site. However, the consistency of small resistivity values of the second layer on the waste site is lost except on VES Q$_2$. Also, the first layer low resistivity values of VES Q$_1$ and VES Q$_3$ is unlikely due to leachate contamination (Osazuwa and Abdullahi, 2008a).

Increased chargeability values evident moving downwards from the first layer to the second or third indicated IP effect on profile B. As the chargeability value increased from 1.47m/sec to 2.06m/sec (VES B$_2$), the resistivity value lowered from 273Ωm to 47.5Ωm. This characteristic is same for most VES points (VES B$_3$, B$_4$, B$_5$, B$_6$, B$_7$, B$_9$ and B$_{10}$) at varying depth and moisture content similar to the work of Osazuwa and Abdullahi (2008b). These IP effects confirmed leachate presence in the layers. This is as a result of having more leachate plume in the second or third layer due to its downward migration from the top and or lateral movement across VES points as it percolates through pore spaces (Jegede *et al.* 2011).

The second layer thickness of VES B$_4$ (17.2m), its low resistivity value (171Ωm) and increased chargeability, suggests a well weathered/fractured formation with high aquifer potential. An increased chargeability value (1.76m/sec and 7.08m/sec) at the second and third layers of VES B$_5$ is an indication of the salinity of the groundwater (Barker, 1990). However, lateral seepage of the contaminant plume may contaminate the aquifer. On the other hand, groundwater resource available at control site profile Q, especially VES Q$_1$ and VES Q$_3$ can be explored without fear of contamination (Afolayan *et al.* 2004). Significant chargeability effect in the third layer (26.8m/sec) at VES Q$_3$ is due to mineralisation in the contact metamorphism zone between the weathered and the fresh basement rock (Dahlin *et al.* 2002).

Interpretation of VES and IP points along Profile C. There are ten VES points along profile C (Figure 7). Three distinct layers were observed on VES C$_1$, C$_2$, C$_5$ and C$_{10}$. However, four layers were observed on VES C$_3$, C$_4$, C$_6$, C$_7$, C$_8$ and C$_9$. The first layer resistivity range is between 20.0Ωm and 494Ωm and thickness between 0.51m and 3.13m. The maxi-

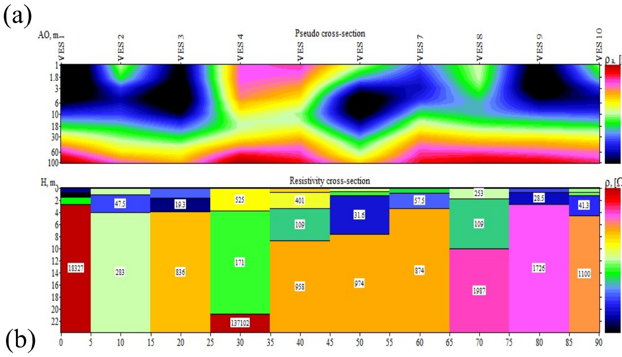

FIGURE 5
(a) Pseudo cross-section (b) Resistivity cross-section along profile B (IPI2win Software)

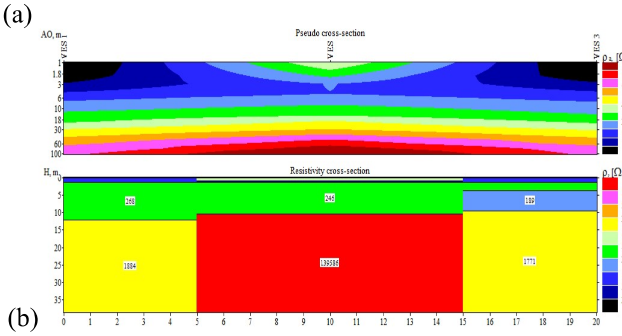

FIGURE 6
(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile Q (IPI2win Software)

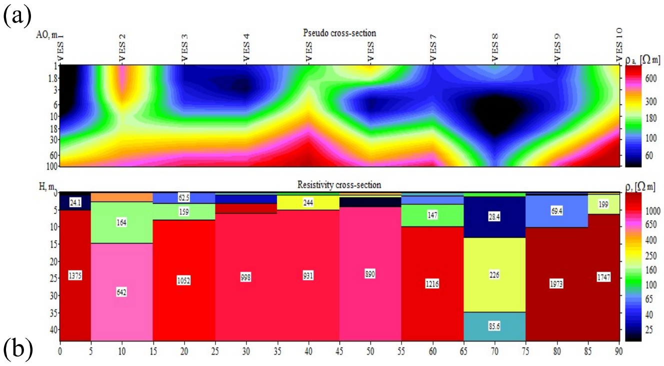

FIGURE 7

(a) Pseudo cross-section (b) Resistivity cross-section along profile C (IPI2win Software)

mum thickness on the first layer is at VES C_3 (3.13m) and the minimum at VES C_9. The second layer resistivity ranges between 24.1Ωm and 244Ωm, and the corresponding thickness is between 0.30m and 12.1m. The thickest point is at VES C_2, and the thinnest is at C_9. The last layer has resistivity range between 642Ωm and 1973Ωm.

The resistivity of the first layer indicated lateritic topsoil; however, five VES points (C_1, C_3, C_4, C_7 and C_9) presented low resistivity that is an indication of high ionic concentration. The second layer of the three-layered geo-electric formation and the third layer of the four-layered geo-electric composition constitute the weathered/fractured basement that has very low resistivity values for most VES points (C_1–24.1Ωm, C_4–36.1Ωm, C_6–23.3Ωm, C_7–65.3Ωm, C_8–28.4Ωm and C_9–69.4Ωm) as compared to that of the control profile R (Figure 8) which are mostly higher. It is an indication of leachate invasion with high conductivity at that depth (Rafiu and Abu, 2014). The third/fourth layer can be referred to as the fresh basement.

The increase in chargeability values and a correlating decrease in resistivity values on profile C are consistent with other works like Osazuwa and Abdullahi (2008b). At comparably low resistivity on VES C_1 chargeability value increased from 1.13m/sec to 3.67m/sec. The near indifference in the IP effect on VES C_2 may be due to an anomaly. The VES point C_8 with four layers and indicating fracture may have the highest concentration of leachate contaminants on this profile (Figure 7) which was collaborated by the increased chargeability and colour transition from light to the deep blue colour of the layer. Alternate rise and fall of resistivity value between geo-electric layers as seen in VES C_8 and C_9 indicated fracture (Salako and Udensi, 2005). These IP effects confirmed leachate presence in the sheets. Though VES C_7, C_8 and C_9 seem water-bearing and have aquifer potential, the leachate plume permeating through pore spaces and the fracture will render it contaminated. There exist vertical and lateral flow of leachate between VES C_3 and VES C_9.

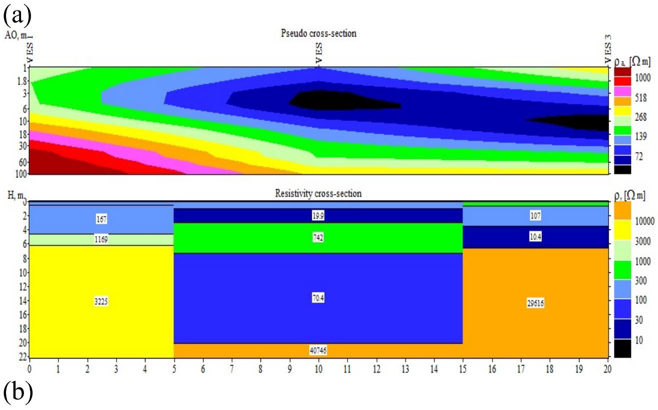

FIGURE 8

(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile R (IPI2win Software)

Conversely, first layer resistivity at the control profile R ranges between 111Ωm and 518Ωm suggesting lateritic topsoil. Significant chargeability effect in the third layer (22.2msec) at VES R_2 and (20.5msec) VES R_3 is due to mineralisation in the contact metamorphism zone between the weathered and the fresh basement rock (Dahlin *et al.,* 2002). Additionally, aquifer characteristics of the weathered/fractured basement of VES R_2 agree with groundwater availability in basement complex (Mohammed *et al.,* 2007). This significant IP effect and the higher resistivity variations revealed the marked difference in the characteristics of the two sites.

Interpretation of VES and IP points along Profile D. There are three and four layers observed on profile D that has ten VES points (Figure 9). The first layer, which is topsoil mostly, has a resistivity range between 28.8Ωm and 606Ωm with the minimum at VES D_1 and maximum at VES D_7. The maximum thickness on this layer is 1.33m (VES D_8), and the minimum is 0.50m (VES D_9). The resistivity further lowered in the second layer ranging between 4.21Ωm and 68.3Ωm for most VES points, with a thickness ranging between 0.72m and 21.2m. This represents the weathered/fractured basement (Mohammed *et al.,* 2007). The third layer serves as the new basement and has a resistivity value range between 1626Ωm and 188463Ωm.

The lower resistivity trend noticed in the second layer for most VES points (D_1 –14.9Ωm, D_2–35.0Ωm, D_3–13Ωm, D_4–19.6Ωm, D_6–39.6Ωm, D_7–68.3Ωm, D_8–47.5Ωm and D_9–4.21Ωm) is indicative of the presence of leachate due to the waste deposited (Martinho and Ameida, 2006). Comparing this result with resistivity values of S_2–109Ωm and S_3–227Ωm on the control profile S, indicated that it is free of contamination. Increased chargeability value from 0.09m/sec to 3.53m/sec (VES D_1) correlates well with that of the low resistivity value of 28.8Ωm to 14.9Ωm. This increasing chargeability with lowering resistivity is evident in most of the sounding stations. Further qualitative analysis of Figure 11a suggests that the leachate plume presence is as deep as 19 m at VES D_1 and varying depth and moisture content across the profile (VES D_2, D_4, D_5, D_6, D_7, D_8 and D_9). This is because of having more leachate plume in the second or third layer due to its vertical and horizontal seepage through the sediment. Variation in VES D_2 may be due to mineralisation

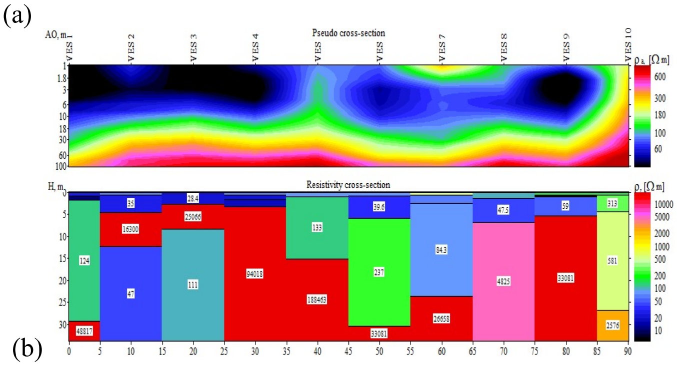

FIGURE 9

(a) Pseudo cross-section (b) Resistivity cross-section along profile D (IPI2win Software)

in the contact metamorphism zone between the weathered and the fresh basement rock (Dahlin *et al.,* 2002). Though VES D_1, D_2, D_5, D_6 and D_7 seem water-bearing and have aquifer potential considering the overburden thickness, the leachate permeating through pore spaces and the fracture will render it contaminated. Significant chargeability effect in the third layer at VES D_3 (4.66m/sec) and VES D_6 (3.58m/sec) maybe is due to leachate migration and ionic saturation (Meju, 2006).

Considering and comparing the IP effects on both waste and control site, it is evident that there exists some difference. IP effect on the control profile S indicated an inconsistency in trend (Figure 10). Whereas high near-surface chargeability values on VES S_1 (5.30m/sec and 4.26m/sec) and at VES S_2 (7.71m/sec) may be due to the presence of disseminated organic matter; the significant IP at VES S_1 that peaked at 51.9m/sec is due to mineralization in the contact metamorphism zone between the weathered and the fresh basement rock (Dahlin *et al.,* 2002). The overburden thicknesses and low resistivity values (97.9Ωm and 90.5Ωm) of the weathered basement at VES S_2 and VES S_3 indicated points with high aquifer potential (Salako and Udensi, 2005) that is free from contamination.

Interpretation of VES and IP points along Profile E. Profile E (Figure 11) has ten VES stations. Four distinct layers are prominent on the profile. However, there are differences in VES E_3 and E_5 with three layers. The first layer has a resistivity range between 57.1Ωm and 594Ωm and thickness between 0.50m and 2.16m. The maximum thickness on the profile at VES E_3 is 2.16m with a resistivity value of 61.9Ωm, while the minimum is at VES E_2 (0.50m) with a resistivity value of 506Ωm. The second layer resistivity ranges between 9.63Ωm and 580Ωm and thickness between 0.20m and 78.2m. The maximum thickness on the profile at VES E_5 is 78.2m with a resistivity value of 492Ωm, while the minimum is at VES E_8 (0.20m) with a resistivity value of 23.6Ωm. The third layer resistivity ranges between 26.6Ωm and 474Ωm and thickness between 1.17m and 54.2m for the four-layered sediments. The last layer resistivity ranges between 1037Ωm and 84978Ωm.

The first layer is lateritic and isolated sandy soil at VES E_4, E_7 and E_8. The second layer is the weathered basement, and the third is the fractured basement. The second and third layers both form the saturation zone (Osazuwa and Abdullahi, 2008b). The fourth layer on this profile is the fresh basement. The very low resistivity values for most VES (E_1–31.3Ωm, E_2–22.4Ωm, E_4–84.9Ωm, E_6– 31.4Ωm, E_7–26.6Ωm, E_8–23.6 Ωm, E_9–9.63Ωm) is an indication of the presence of leachate from organic waste. However, comparing this to the near surface resistivity values of the VES points on the control profile T (T_1–209Ωm, T_2–467Ωm and T_3–475Ωm) were observed to be free from contamination (Figure 12). Further observation of Figure 13b indicates that the leachate plume seeps down to about 12.5 m at VES E_1. The VES points E_1, E_2, E_5,

E_6 and E_7 may be the highest concentration of leachate plume and contamination on this profile with varying degree of thickness and moisture content. These characteristics vertical and lateral leachate contaminant plume seepage is similar through the profile except at VES E_4, which has an uplifted basement (Figure 11a). There exists a near-surface lateritic

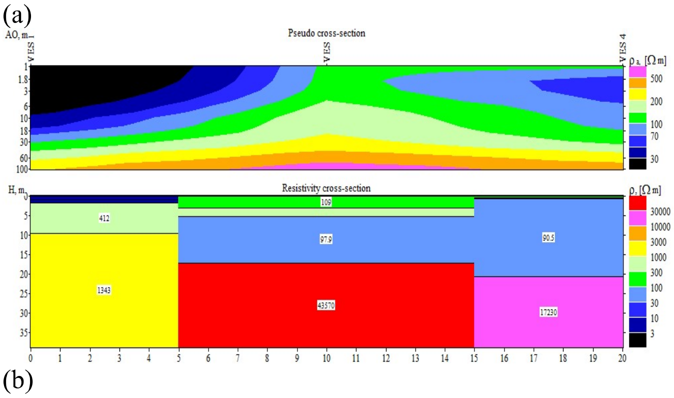

FIGURE 10

(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile S (IPI2win Software)

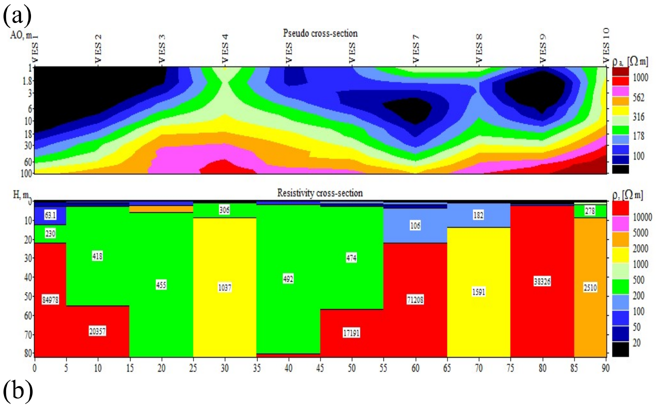

FIGURE 11

(a) Pseudo cross-section (b) Resistivity cross-section along profile E (IPI2win Software)

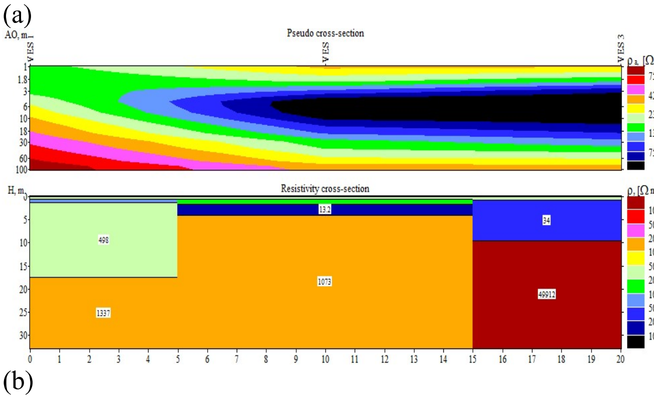

FIGURE 12

(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile T (IPI2win Software)

material at the second layer of VES E_3 that is weathered and fractured, hence, the high chargeability of 22.9m/sec at the third layer. Though VES E_1, E_6, E_7 and E_8 seem water-bearing and have aquifer potential, the leachate permeating through pore spaces and the fracture will render it contaminated (Alagbe, 2002).

IP effect on profile E indicated increased chargeability values are moving downwards from the first layer to the second. It was further enhanced at the third layer that is sandy and weathered/fractured basement for most VES points due to pore space (Abdu1lahi *et al.,* 2010). As the resistivity value increased from 63.1Ωm to 230Ωm, the chargeability value lowered from 3.17m/sec to 0.48m/sec (VES E_1). This characteristic is the same for most of the VES points (VES E_2, E_4, E_5, E_6, E_7, E_8 and E_9). These IP effects confirmed leachate presence in the weathered layers. Increased chargeability despite high resistivity at VES E_4, E_5 and E_6 may be due to high permeability of the weathered layer (Osazuwa and Abdullahi, 2008b). Higher chargeability values observed in VES E_3 can be interpreted as the IP effect resulting from mineralisation in the contact metamorphism zone between the weathered and fresh basement rock (Eduvie, 2003).

Significant IP effect (4.34m/sec to 9.39m/sec) is apparent in the control profile within the saturation zone of the weathered/fractured basement. This is due to good aquifer potential and salinity of the water (Barker, 1990) which confirms the lack of presence of leachate plume contaminant on the control site.

Interpretation of VES and IP points along Profile F. There are ten VES stations (Figure 13) on profile F. Four distinct layers are prominent on the profile, however, VES F_2, F_3 and F_7 are three layered. The first layer has resistivity range between 11.6Ωm and 324Ωm and a thickness range of 0.50m and 1.66m. The maximum thickness is at VES F_3 (1.66m), and the minimum is at VES F_5 (0.50m). The second layer has a resistivity range between 11.1Ωm and 363Ωm with thickness range between 0.70m and 15.4m. The thickest point is at VES F_7, and the thinnest is at F_5. The last layer has resistivity range between 1118Ωm and 25958Ωm.

The first layer represents lateritic topsoil. The second and the third layers together formed the weathered/fractured basement, which has very low resistivity values ranging between 11.1Ωm and 82.3Ωm for most VES points on the profile indicating the invasion and presence of leachate contaminants and seepage by filtration (Aristedemou *et al.* 2000). However, the resistivity for similar formation on profile U of the control site posted a range between 20.4Ωm and 415Ωm in comparison (Figure 14). The first layer resistivity values on profile U are also high (VES U_1–356Ωm, VES U_2–69.5Ωm, VES U_3–176Ωm). The depth of leachate contamination may have peaked at 16.3m on profile F. Though, VES F_1, F_3, F_4, F_5, F_6, F_7, F_8 and F_9 seem water-bearing and have aquifer potential considering the overburden thickness, the leachate permeating through pore spaces and the fracture will render it contaminated (Salako, 2005). The third layer is the fresh basement for the three-layered VES points (F_2, F_3 and F_7). The four-layered VES points have four geologic formations; lateritic topsoil, weathered/fractured, fresh basement. The geologic formations are consistent with Mohammed *et al.* (2007).

Increased chargeability value from 1.28m/sec to 7.06m/sec on VES F_3 correlates well with decreased resistivity values from 92.3Ωm to 56.3Ωm (Osazuwa and Abdullahi, 2008b). This characteristic is the same for other points on the profile (VES F_1, F_2, F_4, F_7, F_8 and F_9). Colour transition from light to deep blue is an indication of the high leachate concentration, which seeps down the sediment by filtration (Figure 15a). Chargeability variations in saturation and weathered zones VES F_5 and VES F_6 may be due to high permeability of the zone; hence the ionic concentration of the next layer. However, due to the presence of mineralisation in the metamorphic region between the fresh and weathered basement rock and loose sand, there is significant IP effect (VES F_5-8.58m/sec and VES F_{10}-11.7m/sec) as stated by Bernstone and Dahlin (1996). These IP effects confirmed leachate presence in the layers.

Furthermore, significant IP effect (1.88m/sec to 10.7m/sec) is apparent in the control profile U within the

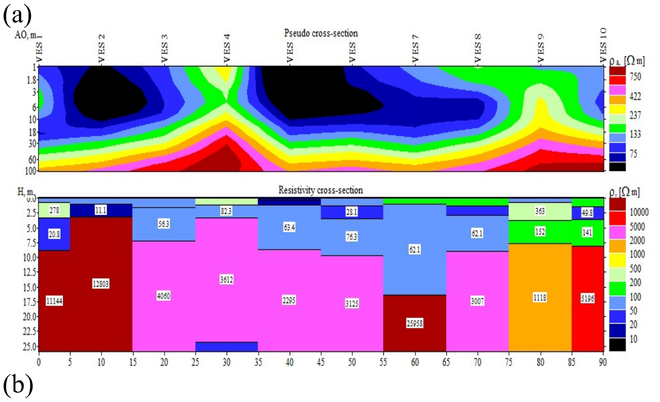

FIGURE 13

(a) Pseudo cross-section (b) Resistivity cross-section along profile F (IPI2win Software)

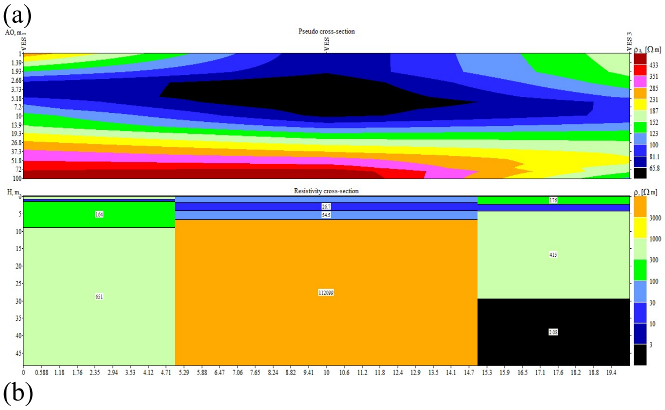

FIGURE 14

(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile U (IPI2win Software)

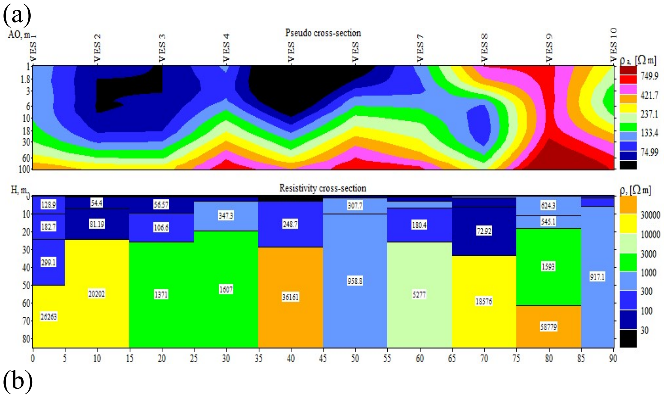

FIGURE 15

(a) Pseudo cross-section (b) Resistivity cross-section along profile G (IPI2win Software)

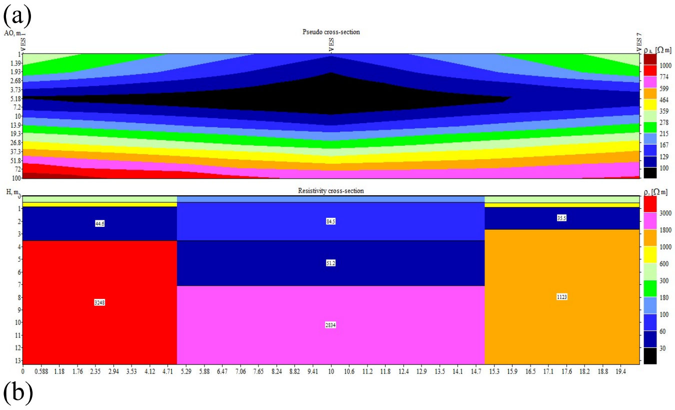

FIGURE 16

(a) Pseudo section (b) Resistivity section along MINNA NORTH control profile V (IPI2win Software)

saturation zone of the weathered/fractured basement. This is due to good aquifer potential and salinity of the water (Barker, 1990) which confirms the lack of presence of leachate plume contaminant on the control site. Conditions for groundwater availability in basement complex according to Afolayan *et al.* (2004) are evident.

Interpretation of VES and IP points along Profile G. Prominently observed in Figure 15 are three and four distinct layers on the ten VES stations on profile G. However, VES G_7 has five layers. The first layer has a resistivity range between 20.3Ωm and 643Ωm and thickness between 0.50m and 11.1m. The maximum thickness is at VES G_9 and the minimum at VES G_3. Second layer resistivity ranges between 54.4Ωm and 545Ωm. It is thinnest at VES G_7 (2.34m) and peaked at VES G_1 (25.7m). The third layer resistivity ranges between 49.9Ωm and 694Ωm and thickness between 11.5m and 31m. The last layer had a resistivity range between 676Ωm and 58779Ωm.

The four-layered formation had a topsoil first layer, clayey sand and weathered second layer, fractured basement and fresh basement, whereas the three-layered structure has lateritic topsoil, weathered/fractured basement and fresh basement. Low resistivity values in the weathered/fractured basement for most VES points (G_2–54.4Ωm, G_3–56.6Ωm, G_4–69.6Ωm, G_7–75.9Ωm and G_8–72.9Ωm) compared to what obtained on profile V of the control site (V_1–791Ωm, V_2–84.5Ωm, V_3–734Ωm) which is higher, indicated leachate presence and contamination of profile G on the waste site (Rafiu and Abu, 2014). However, there appears a shallow weathered basement at VES G_9 (Figure 15a) that is three-layered, with a sandy first layer resistivity of 623Ωm and 11.1m thickness. Though VES G_2, G_3, G_4, G_5, G_7 and G_8 seem water-bearing and have high aquifer potential, the leachate plume permeating through pore spaces and the fracture may render it contaminated. There exist vertical and lateral flow of leachate between VES point G_2 and G_8 (Figure 15b).

IP effect on profile G indicated increased chargeability values are moving downwards from the first layer to the second and the third for VES G_4 and G_8 at low resistivity. As the chargeability value increased from 0.63m/sec to 1.39m/sec on VES G_4, the resistivity value lowered from 118Ωm to 69.6Ωm. The high chargeability values on VES G_1 without corresponding low resistivity may be due to structural variation (primarily clay control) as reported by Osazuwa and Abdullahi (2008b). As chargeability value increased (1.44m/sec to 7.46m/sec) the second layer resistivity also increased (183Ωm to 299Ωm). However, chargeability variations for VES G_2, G_3, G_5, G_6 and G_7 may be due to the permeability of the weathered and saturation zone, hence high leachate migration (Meju, 2006) at the third layer. VES G_2 and G_5 situate the highest concentration of leachate plume and contamination on this profile. The thickness of leachate migration within these VES points is between 1.0m and 25.7m. VES G_8 derived its leachate content in the second layer due to the lateral and downward flow from G_5 (Figure 15a). First layer resistivity was 634Ωm which is sandy.

The high first and second layer resistivity values of profile V on the control site suggest a site free of any contamination. The resistivity values are; VES V_1–306Ωm, VES V_2–159Ωm, VES V_3–315Ωm for the first layer (Figure 16). Chargeability variations of the weathered zone are not consistent in trend and similar to those of the waste site. Shallow depths on profile V suggest that it has poor aquifer potentials despite the low third layer resistivity values (Figure 16).

CONCLUSION

Data analysis and the interpretation of this survey have indicated the suitability and efficiency of the electrical methods (VES and IP) in probing subsurface structures and delineating leachate plume contaminant in basement terrain like Minna. According to Barker (1990), chargeability will increase as the salinity of the groundwater rises to 500 mg/L. Hence, the correlation between the increased chargeability due to increase in salinity of groundwater and increased ionic concentration, and that of lowered resistivity as a result of leachate contamination confirms the presence of leachate plume in the studied areas.

Jegede *et al.*, (2011) in a similar study, holds that the rate of migration of leachate contaminant plume depends on the compaction of the soil texture, the presence of loose soil, fractures, depressions, undulations and dipping topography of the subsurface. Hence, leachate contamination of the underground was observed on most of the site at varying depth within 12m especially at the second and third layers. Those prominent with significant IP effect, permeability and unconfined overburden thickness (i.e. 15m and beyond) at the Minna north site were located at VES D_7 (21.2m), F_7 (15.4m), G_2 (17.4m) and G_8 (27.1m). Fractures observed suggests a geological feature that could facilitate leachate plume transport and aquifer reservoir. The rate of leachate contaminants migration on the Minna north waste disposal site put at 0.6m per year could only mean that in another ten years, an average depth of 12m leachate contaminated zone now, would have graduated to 18m. This is within the aquifer zone for groundwater in the basement complex (Mohammed *et al.*, 2007) and locations like VES; B_4 (17.2m), C_8 (11.9m), E_7 (18.1m), G_3 (16.1m), H_7 (16.4m), I_2 (12.9m), J_3 (17.5m) and N_9 (13.8m), would have been contaminated and likely aquifer compromised.

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