Geophysical Characterization of the Abandoned Gaborone Landfill, Botswana: Implications for Abandoned Landfills in Arid Environments

E.M. SHEMANG[#1], K. MICKUS*[2], M.P. SAME[#3]

[#]Department of Geology, University of Botswana, Private Bag, UB 00704 Gaborone, Botswana,

[1]shemae@mopipi.ub.bw

*Department of Geography, Geology and Planning, Missouri State University Springfield, MO 65897 Missouri USA

[2]kevinmickus@missouristate.ed

Abstract--- **A geophysical investigation using electromagnetics (EM), electrical resistivity and ground penetrating radar was carried out on the abandoned Gaborone landfill that was decommissioned in 1992 after being active for ten years. The aim of the study was to map the physical boundaries of the decommissioned landfill, map the distribution of waste and identify zones of leachate within and below the landfill. The results of EM conductivity measurements show a wide distribution of conductive materials, which represents a zone of active leaching which is mostly concentrated in the centre of the landfill. In-phase EM measurements also identified zones occupied by metallic waste that are less distributed over the landfill. Results of the resistivity survey indicated a three layer resistivity structure within and surrounding the landfill. The top layer is a more resistive cover material (68 - 127 ohm-m) and varies in thickness from over the landfill. The second layer is a low resistivity zone (3-40 ohm-m) and indicates a zone of high leachate activities. At the bottom is a more resistive layer (greater than 500 ohm-m) which is likely bedrock that underlies the abandoned landfill. The ground penetrating radar images also indicated a three layer structure over the landfill which is similar to the resistivity results. All the methods implied that the leachate has not penetrated the bedrock but the large amount of leachate suggests that it may leak into the unlined landfill in the future despite being in an arid environment. Of the three methods, the resistivity survey provided the most complete information on the subsurface conditions of and beneath the landfill.**

Keywords--- **electromagnetics; electrical resistivity; ground penetrating rada;, landfill; Botswana**

I. INTRODUCTION

The improper disposal of waste in urban areas is one of the major contributors to groundwater contamination in developing countries [1]. Gaborone, the capital of Botswana (Fig. 1) is a rapidly developing city that has seen its population grow from 17,718 in 1971 [2] to 208,411 in 2005 [3]. In order to safely accommodate this growing population and to aid in properly disposing its municipal waste, Botswana has developed a long-term waste management strategy with the objective of achieving a state of sustainable waste management. The aims of this waste management policy are to protect human health, the environment and natural resources. In order to achieve the waste management objectives, the Gaborone City Council (GCC) has closed the previous landfill (operated from 1982-1992) and opened a new landfill, which is located in the vicinity of the old landfill (Figs. 1 and 2). The new landfill is designed, constructed and operated to ensure minimal environmental impact in the surrounding areas unlike the old landfill which was basically a dumpsite.

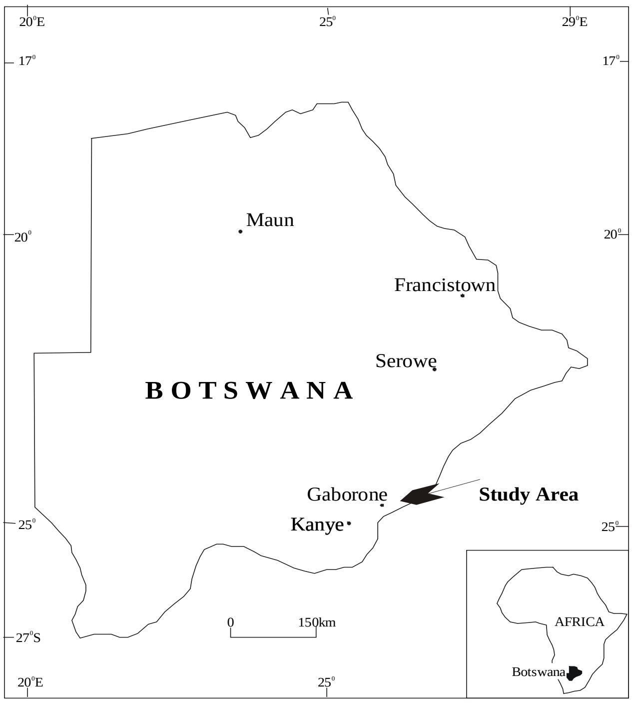

Fig. 1 Map of Botswana showing the location of the study area

Groundwater in the vicinity of dumpsites or landfills may be contaminated by leachate from the deposited waste [4], [5]. In arid environments, the leachate may take a longer time to penetrate the surrounding soil or bedrock due to the lack of rainfall but may still contaminate the groundwater [6]. Urban waste materials which are mainly domestic garbage are commonly deposited in landfills without appropriate protective measures (e.g., clay and/or plastic liners). Thus, any rainfall entering the landfill or in situ fluids may percolate through a landfill and incorporate decomposing organic material, dissolved salts and other contaminants [7]. These contaminated liquids may leave the disposal site, enter the underlying groundwater system and make the groundwater unpotable. If this water is used, the health of users is put at risk [7].

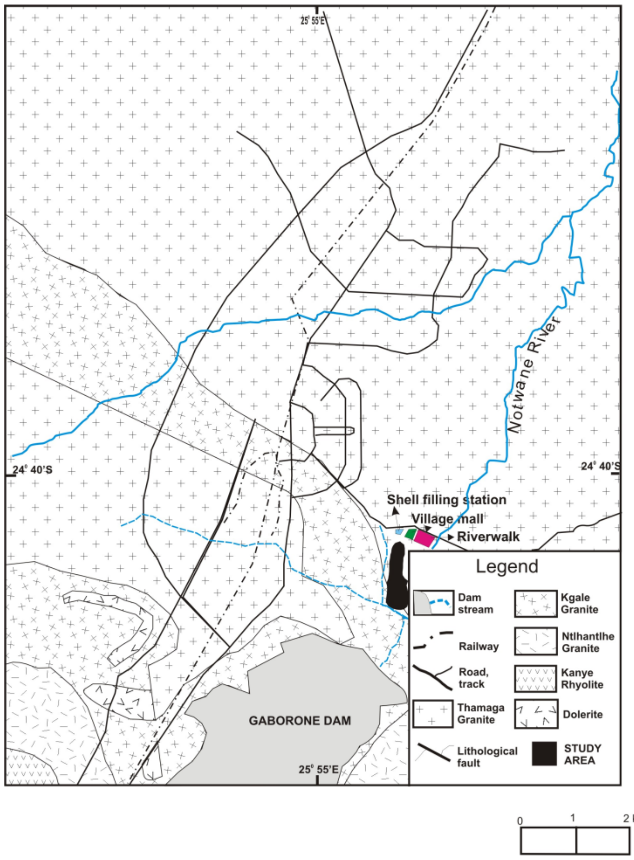

Fig. 2 Bedrock geology of Gaborone, Botswana showing the location of the study area

Previous investigations on groundwater contamination due to open and abandoned landfills indicate there are several parameters that will influence the type of contamination found at each landfill [8], [9]. In arid environments, it has been commonly assumed that due to the lack of precipitation, there may be minimal leachate produced that could entered any surrounding groundwater systems [9]. In order to produce substantial leachate, the landfill must contain large amounts of sludge and liquid waste [9], [10], [11]. Then the leachate may be able to take up organic and inorganic material by physical, hydrolytic and fermentative processes [12]. In doing so, the organic material and inorganic ions (e.g., heavy metals) may be incorporated into the leachate. Previous chemical studies of leachate from landfills in Jordan [9], [10], [11] show that the leachate entering the groundwater system was nonpotable at most locations mainly due high concentrations of chlorides and sulfates with some sites having high levels of lead, cadmium, iron and zinc. At landfills in Kuwait, [9] showed that the leachate contains a low level of organic content due to waste decomposition. Other studies (e.g. [13], [14]) found that the groundwater closer to the landfill contained less heavy metal contamination than sites farther from the landfill possibly due to redox reactions within the igneous rocks. The above studies indicate that the contaminated groundwater depends on content within the landfill and the material the leachate flows through. Additionally, [16] found that groundwater contamination depends on the direction the leachate flows from the landfill as various monitoring wells surrounding a landfill in Oklahoma showed that the leachate plume was found in preferential pathways.

To properly evaluate the extent and potential for groundwater contamination, the total volume and the nature of the waste within a landfill is commonly performed in addition to any leachate emanating from the landfill [17]. The most common approach to monitor the leachate emanating from a landfill is to drill a series of monitoring wells around the landfill that penetrate into either the vadose and saturated zones or both. However, these wells are expensive to drill and maintain especially in a developing country. Also, any wells that are drilled and monitored are commonly located randomly because of budgetary constraints. These wells provide only point source information and leachate plumes tend to migrate along preferential pathways and even closely spaced monitoring wells may miss some of the contaminants [16]. Therefore, geophysical methods have been commonly used ([16] to interpolate the subsurface conditions between the monitoring wells. There are a number of geophysical techniques that can be used to delineate the properties of the landfill including seismic reflection [18], magnetics [19], gravity [20], electrical [5], electromagnetics (EM) [21] and ground penetrating radar (GPR) [22]. While all these techniques are useful in helping defining the boundaries and internal composition of dumps and landfills, the electrical and electromagnetic techniques have been found to be useful due to the electrically conductive nature of most of the waste material and the ion-rich fluids within the sites (e.g. [23], [24], [25], [26]). The most important geophysical aspect in using geophysical methods in studying landfills is that the waste site contains elevated electrical conductivities that can be used to map the physical boundaries of the site, determining the thickness of the waste and to locate regions of higher leachate within and surrounding the site.

In this study, three non-invasive electrical geophysical techniques: 1) loop-loop EM, 2) electrical resistivity imaging (ERI) and 3) GPR were used to investigate the internal structure, volume and depth of the abandoned landfill in Gaborone, Botswana. The above methods have been used by several investigators (e.g. [7], [21], [25], [26], [27]) to investigate the internal structure of landfills and the leachate migrating from the landfills. These studies have shown that each electrical/electromagnetic method, while sensitive to the subsurface electrical conductivity structure, will image different aspects of the landfill structure in order to give a more complete image of the subsurface. The value of electrical geophysical methods in waste investigations is particularly enhanced where a multi-proxy approach is used [25], although time constraints and lack of records of waste burial (as is common at large volume waste sites) can be challenging. A multi-proxy approach based on EM providing an areal coverage of the site and on GPR combined with ERI, were applied along two transects, in order to map and delineate outline of the old landfill and potentially also in detecting and mapped zones of leachate concentration.

The EM induction techniques have been used to successfully map out where conductive material is concentrated in environmental applications [23], [25]. [26]. The EM induction techniques have the advantage of being able to cover a large area fast, there are no current/electromagnetic wave injection problems and they have excellent resolution in determining lateral conductivity anomalies [28]. However, the EM methods have limited vertical depth resolution and in some EM methods only one frequency is used limiting the conductivity resolution.

The ERI method has also been applied not only to map the extent of the closed waste sites, but can also reveal potential pollution plumes (e.g. [18], [25], [29]-[34]) as well as determine the direction of migration of the plumes and therefore provide a basis for remediation if the environment is under threat. ERI is particularly relevant for our study because the common environmental applications of ERI include mapping of landfill spatial extent and volume and detection of potentially hazardous leakages from landfill liners. Test surveys at known waste sites (e.g., [35]) show that the bulk electrical resistivity of household and other mixed waste is often low compared to that of both the soil capping the waste and geological strata located beneath wastes, indicating that many other 'buried' materials could also be located and characterized by electrical resistivity measurements [26]. Many waste sites contain considerable quantities of metal, making the use of magnetic surveying methods useful [19] however in the case of GCC, the high value of scrap metal, and the non-metalliferous nature of household, medical and industrial toxic waste make non-metal bearing waste the most common waste type in GCC. The ERI method has the advantage of having relatively high vertical and horizontal resolution with numerous interpretation algorithms for 2 and 3-dimensional modeling and inversion of the data. However to determine depth information the current electrodes must be relatively far apart and this may not be possible in all urban situations.

The GPR method has been extensively applied to map landfill boundaries, measure material porosity and water content, and detect liquid organics within the landfill (e.g. [22], [36]-[41]) . Even though, the GPR method has the highest resolution of all the EM techniques, the GPR signal is easily absorbed in high dielectric materials (e.g., clay-rich soils) and this severely limits the vertical resolution of the method. Thus, GPR method is best used to image the upper sections of a landfill (the depth depending of the frequency of the antenna, 30 m for 25 MHz and 2 m for 200 MHz [42]. However, higher frequencies produce higher spatial resolved images. Given this tradeoff, it is best to use at least two different frequency antennae and also compare the results with those obtained by other electromagnetic methods.

The above discussion shows the usefulness of geophysical methods, especially electrical methods, in defining the depth, internal structure and the location of leachate plumes from landfills. In arid environments, there have been a number of geophysical investigations to delineate the structure and nature of the landfill and the surrounding area (e.g. [16], [22], [25], [26], [43]-[45]). While these studies showed that the ERI, GPR and EM methods are useful in determining the same features of landfills and the leachate in arid environments as for more wet environments, only the study by [25] has employed the same methods as this study but while they studied the landfill structure in detail they did not study the leachate plume emanating from the landfill. In addition, the other investigations listed above either studied the landfill structure or the emanating leachate plume but not both as this study.

II. STUDY AREA

The geology of Gaborone and the surrounding region is located in the northern part of the Archean Kaapvaal craton [46]. More specifically, the old GCC landfill is located on the Gaborone granite complex which includes medium- to coarse-grained porphyritic rapakivi granite (Fig. 2). This region is structurally stable however a system of joints and fractures (Fig. 3) exist in the area which could serve as migration channels for leachates from the landfill to enter the local groundwater system.

The abandoned landfill covers an area of 300 by 650 meters (Fig. 4). It contains domestic waste that is 5m high relative to the ground surface with the long axis of the landfill or its length oriented in the north – south direction. The ground around the landfill slopes towards the Notwane River (Fig. 2). On the western side of the landfill is a small stream which runs in the southeast direction.

Drainage in and around the landfill goes into the small stream which discharges its waters into the Notwane River.

Fig. 3 Photo showing the jointing and rapakivi texture of the Gabrone granites which are located within the study area

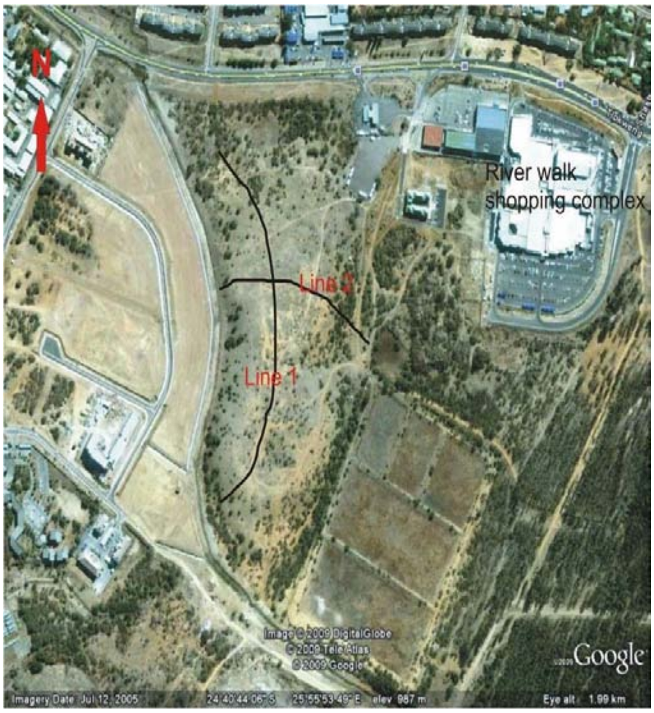

Fig. 4 Google Earth image of the Gabrone landfill and surrounding area showing the location of the two GPR and electrical resistivity profiles.

III. Data Acquisition

A. Electromagnetics

EM measurements were collected using the Geonics EM31-MK2 ground conductivity meter. This instrument induces current into the ground by emitting a 9.8KHz electromagnetic field. The use of one frequency usually means that only one depth determination can be determined however the EM31 data can be collected in the vertical and horizontal dipole configurations. This allows for two depth determinations and for average soil conductivities, the detection limits of 3 m and 6 meters have been determined using the quadrature component of the induced magnetic field of the horizontal and vertical diploes respectively [47]. Additional depth information can be determined by measuring the in-phase component of the induced magnetic field where depth information can be increased by 1 to 1.5 meters [47]. However, the quadrature component is more readily interpretable as the ground conductivity is linearly related to it [47]. To image the conductivity structure of the GCC, 110 profiles running from N-S were collected with each profile spaced 2 meters apart (Fig. 5). Along each profile, vertical and horizontal dipole measurements were collected using both the quadrature and in-phase components every 2 meters.

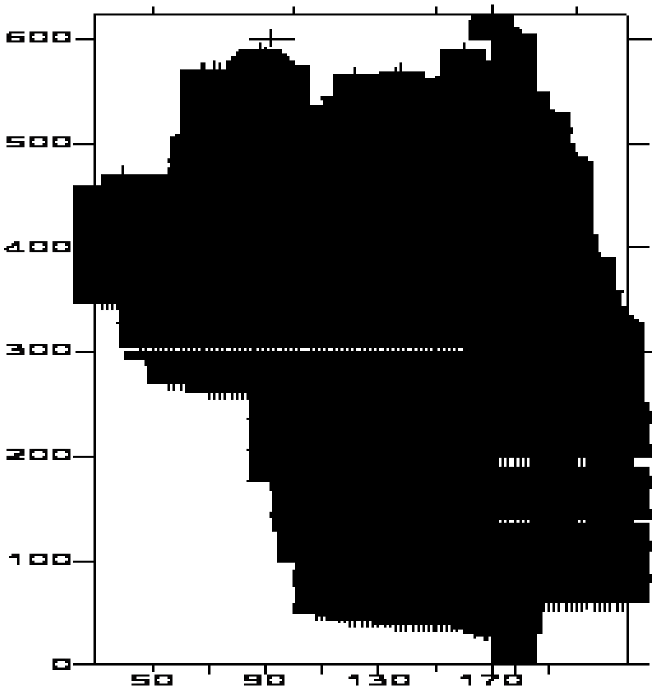

Fig. 5 Location of the EM31 profiles

B. Electrical Resistivity Survey

Direct current electrical resistivity measurements were collected along two profiles (one running from S-N and the other from E-W) (Fig. 5) across the GCC using the ABEM Lund Imaging system. These ERI profiles were collected in order to determine the two-dimensional electrical resistivity structure of the GCC. The data were measured as continuous vertical electrical soundings (CVES) roll-along [48], [49] using the Schlumberger array as this method combines the depth information from vertical soundings and lateral information from the profiling method. An electrode spacing of 2 m was used for the N-S profile, while a 3 m spacing was used for the E-W profile. The electrodes are connected to a switching box where the measurement protocol is computer controlled [50]. A continuous profile is collected using the roll-along technique [48] where the last cable in the measurement sequence is moved to the front of the profile and connected to the first cable after all data have been collected for a given cable length. In addition, the topographic changes along each profile were determined using a total station distance meter and a theodolite. The elevation was determined at each electrode point and these data were used in the modeling of the electrical resistivity data.

C. Ground Penetrating Radar

GPR measurements were acquired using the bistatic mode with a Mala Ramac. The bistatic mode uses separate transmitting and receiving antennae that allows for post data collection processing. The data can be collected in two ways: 1) reflection mode, where the receiver and transmitter are kept a fixed distance apart, and 2) common midpoint (CMP) mode, where the transmitting and receiving antennae are moved variable distance symmetrically about a fixed point along a profile [51]. The GPR data were collected with the antennae 5 cm above the ground using a 50 MHz antenna along the same two profiles as the ERI data (Fig. 4). The data were collected using the CMP mode with the transmitter trailing behind a receiver at a spacing fixed of 2 m to enable post collection velocity processing. The transmitter-receiver array was moved along a survey profile and the radar traces were collected to produce a GPR time reflection section.

After the GPR data were acquired, the x and y coordinates as well as a relative elevation above a datum was collected along both profiles using a theodoilte and electronic distance meter.

IV. DATA PROCESSING AND INTERPRETATION

A. Electromagnetics

The electromagnetic data were transferred to a computer from the data recorder. A Microsoft Excel Spreadsheet was used to create separate columns for each station including its x and y location, and the measured in-phase and quadrature values for the horizontal and dipole modes respectively. Conductivity and in-phase maps were then produced using Golden Software Surfer 8. Figures 6 and 7 show the conductivity anomaly maps (horizontal and vertical dipole modes, respectively) while Figs. 8 and 9 show the in-phase anomaly maps (horizontal and vertical dipole modes, respectively) of the study area.

B. Electrical Resistivity

The resistivity data were interpreted using a 2-D smoothed constrained inversion, employing a quasi-Newton technique to reduce calculations [52]. A 2-D model, consisting of a number of rectangular blocks, with the arrangement of the blocks loosely tied to the distribution of the data in the pseudosection. A forward modeling subroutine is used to calculate the apparent resistivity values and a non-linear least-squares optimization technique is used for the inversion routine [52], [53].

C. Ground Penetrating Radar

The GPR data was processed using the RadEXplorer^{Tm} software with allows for the typical GPR processing schemes to be applied to the data [54]. We applied DC removal, time adjustment, background removal, 2D spatial filtering, amplitude correction, predictive deconvolution, Stolt F-K migration on both profiles to produce final sections (Figs. 12 and 13) to be interpreted. Additionally, we applied a topographic correction to both profiles.

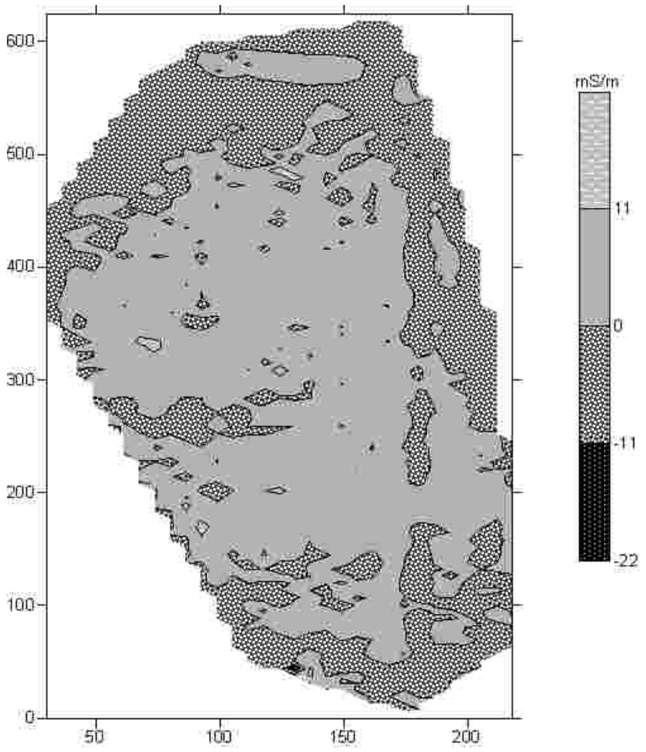

Fig. 6 The electrical conductivity (mS/m) of the Gaborone landfill determined by the horizontal dipole mode of the EM31. The x and y axes are in meters

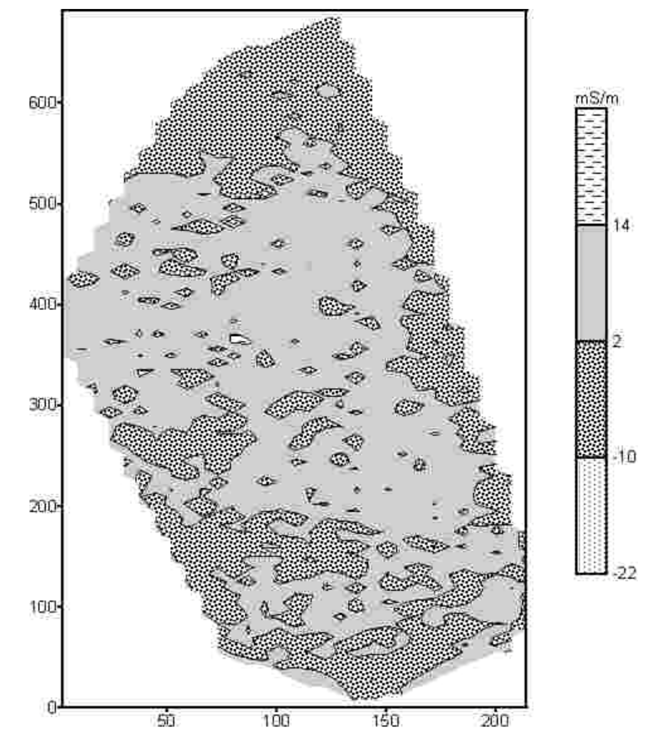

Fig. 7 The electrical conductivity (mS/m) of the Gabrone landfill determined by the vertical dipole mode of the EM31. The x and y axes are in meters

V. RESULTS AND DISCUSSION

A. Electromagnetics

The joint measurement of the quadrature and in-phase components greatly enhances the overall electrical structure of a region. The quadrature component or more commonly known as conductivity is linearly related to the ground conductivity unless the conductivity is high (> 300 mS/m). This makes the quadrature component most interpretable in terms of geology [47]. The in-phase component (measured in units of parts per thousand of primary EM field) is useful in locating high conductivity material (usually metals). Negative in-phase values usually indicate that the instrument is oriented perpendicular to a highly conductive object and extremely high positive values of conductivity indicate that the object is aligned parallel to the orientation of instrument [47].

Figures 6 and 7 show the conductivity maps determined from the horizontal dipole mode which images depths of approximately 3 meters and the vertical dipole mode which images depths to approximately ~ 6 m), respectively. Figure 6 shows that over 98% of the study area is underlain by shallow materials with conductivities in the range of -11 to 11 mSm^{-1}. The region with negative conductivities may contain large amounts of metallic material as negative conductivity values usually represent saturation of the instrument caused by high conductivity material at or near the surface [47]. The positive conductivity values cover most of the study area and represent the upper sections of the landfill. The relatively low conductivities suggest that the material has little larger pieces of metallic waste and/or little to no leachates. Other studies of landfills indicate that some near surface materials may have conductivities in areas of known leachates between 100 and 200 mSm^{-1} [25], [55]. The vertical dipole mode (Fig. 7) basically indicates the same patterns as the horizontal dipole mode. This suggests that the upper sections of the landfill are mostly made of nonconductive soil fill or similar material.

Figures 8 and 9 shows the in-phase components of the horizontal and vertical dipole modes respectively over the landfill. Areas with higher in-phase values (>50 ppt) show the regions where smaller metallic objects (e.g. iron rods) exist in the area. The presence of iron rods within the landfill is common in most landfills and a number of metallic rods were seen on the surface in the landfill. The area with higher in-phase values in general coincides with the higher conductivity values. When the results are combined, the upper 6 meters of the landfill consists of low conductivity soil fill interspersed with metallic rods.

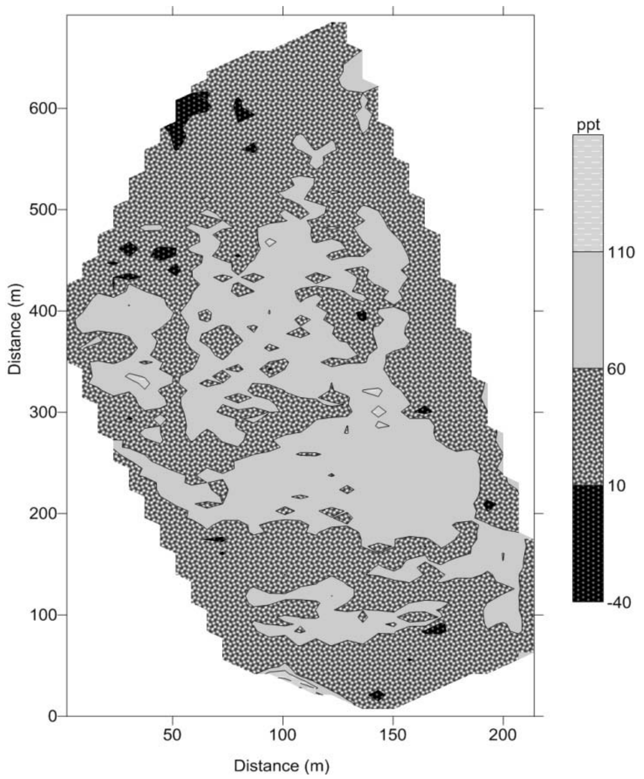

Fig. 8 The in-phase component (ppt) of the electromagnetic field of the Gaborone landfill determined by the vertical dipole mode of the EM31. The x and y axes are in meters

B. Electrical Resistivity

The results of the inversion of the two ERI profiles are shown in Figs. 10 and 11 as cross-sections that show the resistivity distribution of the landfill. Figure 10 shows three pronounced layers of different electrical resistivities along the N-S profile (Fig. 5). The top layer which varies between 2 and 7 meters thick has relatively high electrical resistivities between 68 and 127 ohm-m. These values represent the resistivity of the cover material which consists of mostly unconsolidated soil and correspond to the positive conductivity values found by the EM31 measurements (Figs. 6 and 7). The cover of the landfill does not have a consistent depth over the profile as areas with thinner cover coincide with the regions of higher conductivities seen from the EM31 data (Figs. 6 and 7). These areas also coincide with higher in-phase values (Figs. 8 and 9) and may represent more metallic rich areas.

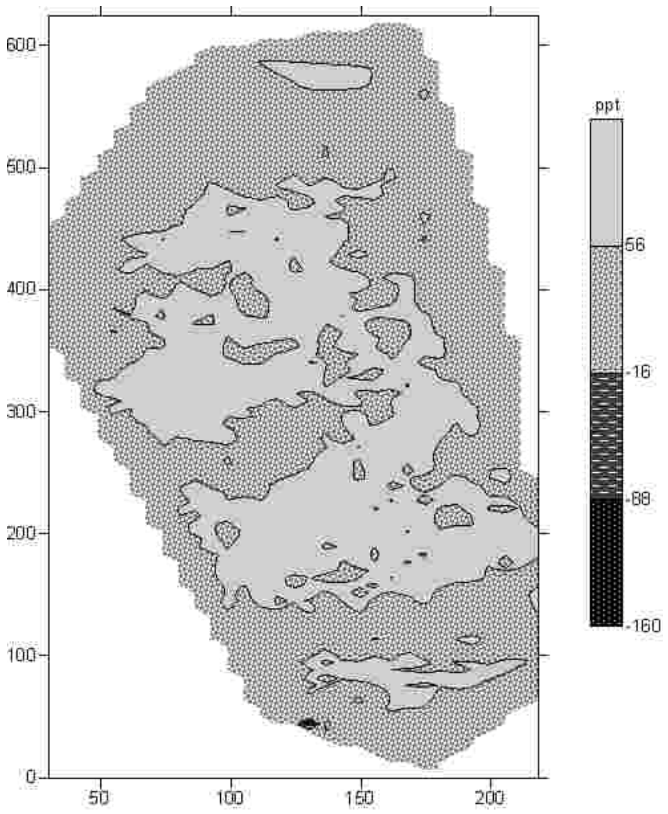

Fig. 9 The in-phase component (ppt) of the electromagnetic field of the Gaborone landfill determined by the horizontal dipole mode of the EM31. The x and y axes are in meters

A middle layer is represented by low electrical resistivity values (3-40 ohm-m) and it is basically continuous across the profile except for the region around 80 m where the values are higher. These low electrical resistivity areas that range in thickness between 8-12 meters are interpreted as trash cells areas where waste materials are located and leachates activities are high. Based on previous studies of landfill (e.g. [7], [25]), electrical resistivities of these values may be caused by organic wastes with some leachate material. The lower electrical resistivity values may represent higher amounts of leachate. The regions with the highest concentrations of leachate range from 120 to 200 meters along Fig. 10 and some these low electrical resistivity values even reach the surface (e.g., 144 m). The bottom layer of higher electrical resistivity values represents the bedrock rock beneath the landfill. The relatively high electrical resistivity values indicate that the leachate has not penetrated the bedrock despite the lack of landfill liner. Since it has been twenty-eight years since the landfill was commissioned, the arid environment has contributed to containing the leachate within the landfill. Additionally, the landfill is thicker on the northern side where the ERI method did not image the bedrock (e.g., 250 m). The thickness of the waste ranges between ranges between 12 and 20 m.

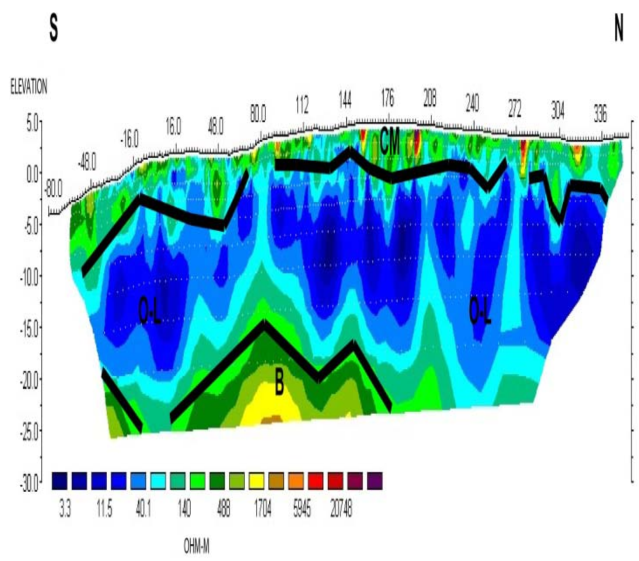

Fig. 10 Two-dimensional model of the electrical resistivity data along a north-south trending profile (Fig. 4). The bolded lines represent boundaries between different electrical resistivity packages with CM being the cover material, O-L being the organic waste with leachate and B being bedrock

The east-west electrical resistivity model (Fig. 11) shows the same three layers as the N-S model. The most prominent feature on this model is that the middle layer is split into two sections with the western section less resistive than the eastern section. This is probably due to the amount of leachate in the organic waste with the western section having higher leachate amounts.

C. Ground Penetrating Radar

The processed GPR time-sections for the north-south and east-west profiles are shown in Figs. 12 and 13, respectively. The time-sections illustrate two diagnostic properties that are of particular interest here: 1) reflections at interfaces between two

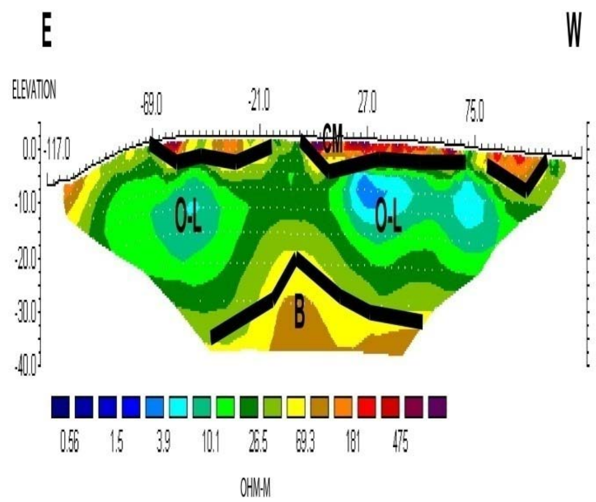

Fig. 11 Two-dimensional model of the electrical resistivity data along a east-west trending profile (Fig. 4). The bolded lines represent boundaries between different electrical resistivity packages with CM being the cover material, O-L being the organic waste with leachate and B being bedrock

geological media of differing dielectric permittivities; and 2) radar wave attenuation (or signal loss) as a function of ionic fluids that increase the electrical conductivity of the fill material. Buried waste (as found in and around landfills and dumpsites) can contain a large range of materials, with different (sometimes mixed) electrical conductivities including organic liquids (leachate) and metal wastes, in which radar wave penetration will be highly attenuated. Other types of waste include plastics, unreinforced concrete, brickworks, and dead animals, many of which have low electrical conductivities as compared with their surrounding material. Thus, GPR time sections can be used to delineate where more organic wastes with leachates are located. The GPR time sections showed that the cover layer that consists essentially of rock fragments and soil materials is about 5-6 meters thick. This is seen by the higher amplitude reflectors at trace 400 (Fig. 13) just above 7.5 meters. These reflectors are interpreted as the bottom of the cover material seen on the ERI models (Figs. 10 and 11). The lack of this reflector between traces 450 and 500 corresponds to region of little or no cover on east-west electrical resistivity model. Underlying this cover

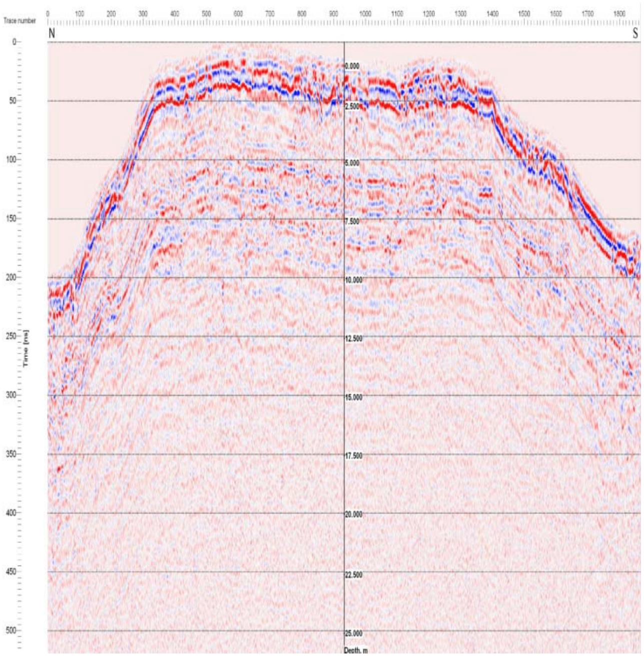

Fig. 12 Processed GPR reflection time section along a profile trending north-south across the landfill (Fig. 4)

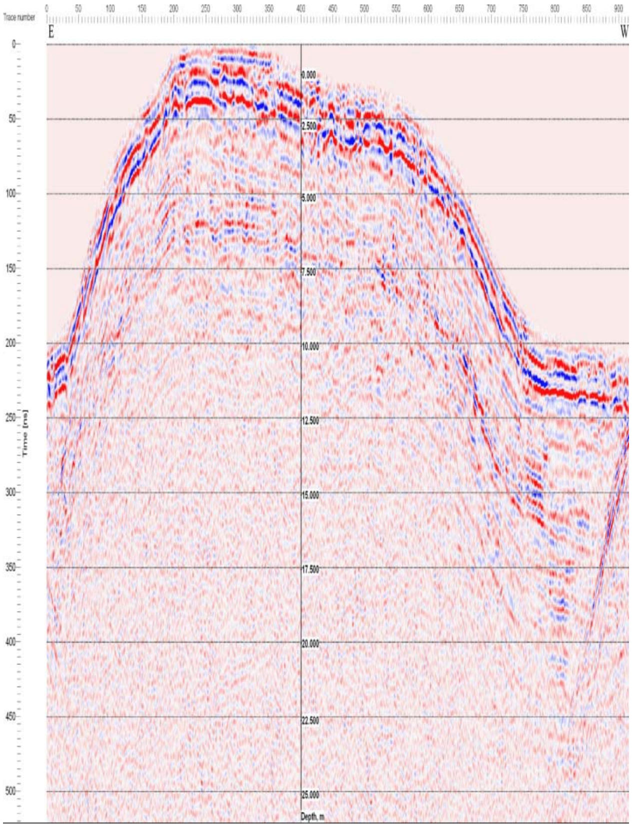

Fig. 13 Processed GPR reflection time section along a profile trending east-west across the landfill (Fig. 4)

material is the higher conductivity material and can be seen by the lack of high amplitude and continuous reflectors.

VI. CONCLUSIONS

Abandoned or closed landfills pose a potential risk to groundwater contamination in all environments. This is especially true in developing countries where monitoring wells are not common and in arid environments where groundwater recharge is low and thus will not dilute any leachate that enters the groundwater system. A geophysical investigation using three different methods of an abandoned landfill in Gabrone, Botswana, found regions of active waste decomposition and leaching. These regions were found to be concentrated at the centre of the landfill and less at its margins. The joint use of horizontal and vertical loop EM induction, electrical resistivity profiling and GPR was crucial in deciphering the nature of the buried material within the landfill as electrically conductive regions were determined to be metallic waste. The metallic waste was found to be more prominent at the centre of the landfill, as evidenced by prominent in-phase EM anomalies.

Three layers of electrical resistivity were mapped using electrical resistivity and GPR, and these layers are the most prominent zones at the landfill. The topmost layer is a cover material, made of rubbly materials and soils; the middle layer is a low resistivity zone of varying thickness. This zone is thought to contain a large amount of leachate and the lower layer is the highly electrically resistive bedrock. There were no low electrical resistive zones found within the bedrock which implies that leachate has not penetrated below the landfill to date. Given the large amount of leachate found by this study suggests that in arid environments, the time it takes leachate to penetrate beneath unlined landfills takes many decades if at all. This implies that in arid environments, leachate may only migrate to shallow levels of the groundwater systems in time scales of 10-20 years, however more studies over time are needed to confirm this implication. The lack of leachate migration to deeper levels of the groundwater system suggests that potable groundwater may be found by drilling to the depths greater than those found by this study.

While the use of EM, electrical resistivity and GPR methods in studying a landfill has been used by previous authors, our study is the first to combine these methods in an arid environment. This study found that no method delineated all aspects of the nature and structure of the landfill and the surrounding areas. By using the above methods, we have been found them to effectively map areas of active decomposition that are characterized by anomalous electrical conductivities and attendant low electrical resistivities. The GPR technique and resistivity methods can also be used the map out the subsurface boundaries of different materials in a landfill of similar nature. The use of EM, electrical resistivity and GPR has been shown to be an effective method to analyze landfills with only the magnetic method being more effective in locating metallic objects.

REFERENCES

[1] A. El-Naqa, "Environmental impact assessment using rapid impact assessment matrix (RIAM)", *Envir. Geology*, vol. 47, pp. 632-639, 2005.

[2] Land and Housing, Greater Gaborone structure plan (1994-2014), Ministry of Local Government. Gaborone City Council, Botswana, 1993.

[3] Central Statistics Office of Botswana, "Population of towns, villagesand associated localities", Dept. of Printing and Publications Services, Botswana, 2007.

[4] E. Hensel, and K. Dalton, "Interpretation of hybrid data for characterization of shallow landfills", in, *Proc. SAGEEP'95*, pp. 129-138, 1995.

[5] C. Bernstone,and T. Dahlin, "2D resistivity survey of old landfills", in *Proc. 2nd European EEGS Meeting*, pp. 188-191, 1996.

[6] M. Aljaradin, and K. Persson, " Design of sanitary landfills in Jordan for solid waste management.", *J. Applied Sci. Res.*, vol. 6, pp. 1880-1884, 2010.

[7] P. Soupios, N Papadopoulos, I Papadopoulos, M. Kouli, F. Vallianatos, A. Sarris, and T. Manios, "Application of integrated methods in mapping waste disposal areas", *Envir. Geology*, vol. 53, pp. 661-675, 2007.

[8] A. Kouzeli-Katsire, Bosdogianni, and D. Christoulas, "Prediction of leachate quality from sanitary landfills", *ASCE J. Envir.Engin.*, vol. 125, pp. 950-958, 1999.

[9] A. Al-Yaqout, A., and M. Hamoda, " Evaluation of landfill leachate in arid climate-a case study", *Envir. International*, vol. 29, pp. 593-600, 2003.

[10] Y. Abu-Rukah, and O. Al-Kofahi, The assessment of the effect of landfill leachate on ground-water quality-a case study. El-Akader landfill site-north Jordan," *J. Arid Envir.*, vol. 49, pp. 615-630, 2001.

[11] M. Hamoda, and A. Al-Yaqout, "Chemical characteristics of municipal solid waste landfills in arid climates", in *Proc. 8th Intern. Waste Management Landfill Symp.*, pp. 33-45, 2001.

[12] M. Barlaz, D. Schaefer, and R. Ham, "Bacterial population development and chemical characteristics of refuse decomposition in a simulated sanitary landfill", *Appl. Envir. Microbial.*, vol. 55, pp. 55-65, 1989.

[13] S. Mor, K. Ravindra, R. Dahiya, R., and A. Chandra, A., "Leachate characterization and assessment of groundwater pollution near municipal solid waste landfill site", *Envir. Monitoring Assess.*, vol. 118, pp. 435-456, 2006.

[14] S. Kale, A. Kadam, S. Kumar, and N. Pawar, "Evaluating pollution potential of leachate from landfill site from the Pune metropolitan city and its impace on shallow basaltic aquifers", *Envir. Monitoring Assess.*, vol. 162, pp. 327-346, 2010.

[15] J. Zume, A. Tarhule, and S. Christenson, "Subsurface imaging of an abandoned solid waste landfill site in Norman, Oklahoma", *Ground Water Monit. Remed.*, vol. 22, pp. 62-89, 2006.

[16] C. Bernstone, T. Dahlin, T. Ohlsson, and W. Hogland, "DC-resistivity mapping of internal landfill structures: two pre-exavacation surveys", *Envir. Geology*, vol. 39, p. 360-371, 2000.

[17] R. De Iaco, A. Green, H. Maurer, and H., Horstmeyer, "A combined seismic vol. reflection and refraction study of a landfill and its host sediments", *J. Applied Geophysics*, vol. 52, pp. 139-156, 2003.

[18] M. Marchetti, L. Cafarella, D. Di Mauro, and A. Zirizzott i, "Ground magnetometric surveys and integrated geophysical methods for solid buried waste detection: A case study", *Annals Geophysics*, vol. 45, pp. 563–573, 2002.

[19] F. Mantlik, M. Matias, J. Lourenco, C. Grangeia, H. Tareco "The use of gravity methods in the internal characterization of landfills-a case study", *J. Geophysical Engin.*, vol. 6, pp. 357-367, 2009.

[20] P. Soupios, I. Papadopoulos, M. Kouli, I. Georgaki, F. Vallianatos, and E. Kokkinou, "Investigation of waste disposal areas using electric methods: a case study from Chania, Crete, Greece", *Envir. Geology*, vol. 51, pp. 1249–61, 2007.

[21] L. Orlando, and E. Marchesi, "Georadar as a tool to identify and characterize solid waste dump deposits", *J. Applied Geophysics*, vol. 48, pp. 63–174, 2001.

[22] D. Nobes, "Troubled waters: environmental applications of electrical and electromagnetic methods", *Surv. Geophysics*, vol. 17, pp. 393–454, 1996.

[23] E. Atekwana, W. Sauck, and D. Werkema, D., "Investigations of geoelectrical signatures at a hydrocarbon contaminated site", *J. Applied Geophysics*, vol. 44, pp. 167-180, 2000.

[24] E. Cardarelli, and G. Di Filippo, "Integrated geophysical surveys on waste dumps: Evaluation of physical parameters to characterize an urban waste dump, four cases in Italy". *Waste Management and Res.*, vol. 22, pp. 390–402, 2003.

[25] M. Bavusi, E. Rizzo, and V. Lapenna, "Electromagnetic methods to characterize the Savoia di Lucania waste dump in southern Italy," *Envir. Geology*, vol. 51, pp. 301–308, 2006.

[26] G. Karlik, and A. Kaya, "Investigation of groundwater contamination using electric and electromagnetic methods at an open waste-disposal site: a case study from Isparta, Turkey", *Envir. Geology*, vol. 40, pp. 34-42, 2001.

[27] L. Perellin, "Applications of electrical and electromagnetic methods for environmental and geotechnical investigations", *Surv. Geophysics*, vol. 7, pp. 101-132, 2002.

[28] J. Reynolds, and D. Taylor, "Use of geophysical surveys during the planning, construction and remediation of landfills", in *Engineering Geology of Waste Disposal and Storage*, Geol. Soc. London Engin. Geology Spec. Publ. vol. 11, pp. 93–98, 1995.

[29] M. Meju, "Geoelectrical investigation of old/abandoned, covered landfill sites in urban areas: Model development with a genetic diagnosis approach", *J. Applied Geophysics*, vol. 44, pp. 115-150, 2002.

[30] M. Meju, "Geoelectrical characterization of covered landfill sites: A process-oriented model and investigative approach", *NATO Science Series*, vol. 71, pp. 319-339, 2006.

[31] R. De Iaco, A. Green, and H. Horstmeyer, "An integrated geophysical study of a landfill and its host sediment", *European J. Envir. Engin. Geophysics*, vol. 4, pp. 223–263, 2000.

[32] R. Guerin, P. Begassat, Y. Benderitter, J. David, A. Tabbagh, and M. Thiry, "Geophysical study of the industrial waste land in Mortagne-du-Nord (France) using electrical resistivity", *Near Surface Geophysics*, vol. 3, pp. 137–143, 2004.

[33] J. Porsani, W. Filho, V. Elis, F. Shimeles, J. Dourado, and H. Moura, The use of GPR and VES in delineating a contamination plume in a landfill site: a case study in SE Brazil", *J. Applied Geophysics*, vol. 55, pp. 199–209, 2004.

[34] J. Reynolds, *An Introduction to Applied and Environmental Geophysics*, New York, United States, Wiley, 1996.

[35] L. Peters, J. Daniels, J. Young, "Ground-penetrating radar as a subsurface environmental sensing tool", in *Proc. IEEE '82*, pp. 1802–1822, 1994.

[36] N. Trenholme, and L. Bentley, "The use of ground penetrating radar to accurately determine water table depths", in *Proc.. SAGEEP''98*, pp. 829-838, 1998.

[37] T. Butt, and O. Oduyemi, "A holistic approach to concentration assessment of hazards in the risk assessment of landfill leachate", *Envir. International*, vol. 28, pp. 597–608, 2003.

[38] R. Knight, "Ground penetrating radar for environmental applications", *Annual Rev. Earth Planetary Sci.*, vol. 29, pp. 229–255, 2001.

[39] I. Padaraze, and M. Forde, "Limits of effectiveness of digital impulse radar in contaminated land site investigation", in *Proc. 3rd Intern. Conf. Polluted and Marginal Land*, pp. 397-401, 1994.

[40] H. Wu, and Y. Huang, " Detection of illegal dump deposit with GPR: Case study Practice. Periodical of Hazardous, Toxic, and Radioactive Waste Management", . vol. 10, pp. 144–149, 2006.

[41] P. Annan, " Ground penetrating radar workshop notes", Sensors and Software Inc., Mississauga, Ontario, 1992.

[42] E. Al-Tarazi,,A. El-Naqa,,M. El-Waheidi, and J. Rajab, "Electrical geophysical and hydrogeological investigations of groundwater aquifers in Ruseifa municipal landfill, Jordan,", *Envir. Geology*, vol. 50, pp. 1095-1103, 2006.

[43] E. Al-Tarazi, J. Rajab, A. Al-Naqa, and M. El-Waheidi, "Detecting leachate plumes and groundwater pollution at Ruseifa municipal landfill utilizing VLF-EM method", *J. Applied Geophysics*, vol. 65, pp. 121-131, 2008.

[44] T. Dahlin, H. Rosqvist, and V. Leroux, "Resistivity-IP mapping for landfill applications", *First Break*, vol. 28, pp. 101-106, 2010.

[45] F. Walraven, D. Grobler, and R. Key, "Age equivalence of the Plantation Prophyry and the Kanye Volcanic Formation", *South African J.Geology*, vol. 99, pp. 223-228, 1995.

[46] J. McNeill, *Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers*, Tech. Note TN-6, Geonics Ltd., Mississauga, Canada, 1980.

[47] T. Dahlin, "2D resistivity surveying for environmental and engineering applications", *First Break*, vol. 14, pp. 275-284, 1996.

[48] T. Dahlin, and C. Bernstone, "A roll-along technique for 3D resistivity data acquisition with multi-electrode arrays", in *Proc SAGEEP'97*, pp. 927-935, 1997.

[49] D. Griffiths, J. Turnbull, and A. Olayinka "Two-dimensional resistivity mapping with a computer controlled array", *First Break*, vol. 8, pp. 121-129, 1990.

[50] J. Brunell, H. Gurrola, and K. Mickus, "Frequency domain electromagnetic and ground penetrating radar investigation of ephemeral streams: case study near the Southern High Plains, Texas", *Envir. Geology*, vol. 55, pp. 1169-1179, 2008.

[51] M. Loke, and R. Barker, "Rapid least-squares inversion of apparent resistivity pseudosections by quasi-Newton method", *Geophysical Prosp.*, vol. 44, pp. 131-152, 1996.

[52] C. deGroot-Hedlin, and S. Constable, "Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data", *Geophysics*, vol. 55, pp. 1613-1624, 1990.

[53] L. Conyers, and D. Goodman, *Ground Penetrating Radar: An Introduction for Archaeologists*. Walnut Creek, California , AltaMira Press, 1997.

[54] P. Hutchinson, and L. Barta, "Geophysical applications to solid waste analysis", in *Proc. 16th Intern. Conf. Solid Waste Tech. and Management*, pp. 66-78, 2000.