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A Review on Groundwater Contamination Assessment by Geophysical Method

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Abstract *— To assess groundwater contamination, a geophysical investigation method using Wenner Array was carried out at the Moshi dumping site in Pune, India. Three profiles and fifty-four station measurements were carried out on the selected site. The data obtained from the study area were modeled using RES2DIVN software, which automatically interprets the apparent resistivity data. The inverse section of profile one in the vicinity of a test site reveals a homogenous high electrical resistive zone (>155 Ohm-m) at depths ranging from 1-16 m across the model. Due to the zone's high resistivity response, it is clear that the area is uncontaminated by leachate and ideal for groundwater development. From the surface to about 3.75 m depth, a horizontal zone thickens to the profile end having a resistivity response ranging from 45-200 ohm-m. This is interpreted as unpolluted topsoil. At 72 m - 82 m from the base of the point is highly re-up to give up to depth h of 3.75m it contains a signifying zone of highly decomposing waste saturated with highly conductive leachate(2.994 – 6.03 ohm-m) The link between this zone and the polluted zone underground suggests leachate infiltration from east to west. Thus, the surface of the landfill reveals the various extent stent of waste decomposition. The second inversion shows the low resistivity zone same as graph no. first (0-72 m) but the depth is up to 5.55 m (45.5 - <155 ohm-m). From the surface, 59 m – 66 m at a depth ranging from m depth of 0-10.2 m (Sand saturated with rain water zones) has resistivity of 13.1-17.50 ohm. From the surface, 39 m- 59 m and 5.68 m depth below it contain clean sand-saturated water of resistivity of 1.5 – 3.5 ohm- of resistivity up to a depth of 5.12 m. The third inversion shows at 19 m - 80 m it a zone of 0.322 – 13.1 ohm–m Soil saturated with rainwater and some contaminated waste water) up to a height of 3.75 m from downward. The zone is interpreted as clayey material with low hydraulic conductivities and is thus responsible for protecting the underlying auriferous layer from leachate invasion from the surface*
Keywords— *Geophysical investigation, Groundwater, leachate, Contaminant, Aquifer.*

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I. INTRODUCTION

A Municipal Solid Waste Landfill is a designated area where solid or liquid wastes are disposed of, and over time, the waste undergoes decomposition, resulting in the production of leachate that has the potential to contaminate underlying groundwater. The extensive use of natural resources and the high volume of waste produced in modern society pose a significant risk to the quality of groundwater and have already led to numerous incidents of contamination. To address this issue, proper waste management strategies must be implemented to reduce landfills' potential environmental impact. The quality of groundwater can deteriorate over vast areas due to diffuse or point sources. Diffuse sources, such as deep percolation from highly cultivated fields, can result in the degradation of groundwater quality over large areas. On the other hand, point sources, including septic tanks, garbage disposal sites, cemeteries, mine spoils, and oil spills, can cause localized contamination of groundwater. Accidental entry of pollutants into the underground environment can also lead to the degradation of groundwater quality. Proper management and regulation of these sources are essential to ensure groundwater quality protection and prevent further contamination.

Groundwater contamination can also occur through line sources, such as seepage from polluted streams and intrusion of saltwater from the ocean. Due to the slow movement of groundwater, it may take several years before the effects of pollution become noticeable in a well. Similarly, even after the source of pollution has been eliminated, it may take many years to restore contaminated aquifers fully. Therefore, it is crucial to prevent contamination from occurring in the first place by implementing effective management strategies and regulations. Timely detection and remediation of contaminated groundwater are also critical to protect public health and the environment. Leachate that emanates from landfills is a type of wastewater that contains acute and chronic toxicity. If left untreated, this wastewater can permeate the groundwater or mix with surface waters, causing contamination of soil, groundwater, and surface water. In addition to this, the presence of leachate can also result in the production of malodorous smells and aerosols, although these effects are typically localized and temporary.

It is essential to address this issue by implementing effective waste management strategies, such as proper landfill design and the installation of appropriate liners and leachate collection systems, to prevent leachate from contaminating the environment. Regular monitoring and remediation efforts are also crucial to prevent the spread of pollutants and protect public health. The composition of the contaminant plume can exhibit sequential and regional variations, with significant concentrations of various contaminants. This poses a significant challenge for landfill operators and local authorities, particularly regarding constituents, ammonia, and heavy metals in leachate.

This helps to prevent the contamination of aquifers and the potential harm to the health of people, the environment, and the economy that depends on it. Without proper management of buried waste at landfills, there is a significant risk of groundwater contamination, which can have severe and long-lasting effects on the surrounding ecosystem. Therefore, it is critical to implement effective waste management strategies and regulations to prevent further pollution of the aquifer. Doing so can protect the environment and public health while ensuring sustainable economic development.

II. Literature review

Indiscriminate waste disposal has been identified as a significant cause of pollution in developing nations, as noted by multiple sources including Tijani et al. (2004), Olayinka and Olayiwola (2001), and Ariyo et al. (2013). Improper waste disposal is a common practice in many areas and is often done for the sake of convenience rather than environmental, geological, or engineering considerations. Open landfills and abandoned mineral workings are frequently used for waste disposal due to their proximity to the waste source (Desa et al. 2009; Jhamnani and Singh 2009). Unfortunately, such sites may pose a risk of groundwater contamination and other environmental hazards (Chambers et al. 2006; Perozzi and Holliger 2008). When rainfall infiltrates

into landfill, it combines with the biochemical and chemical breakdown of the wastes to produce leachate that contains high levels of suspended solids and varying organic and inorganic contents. If the leachate enters the surface or groundwater before sufficient dilution occurs, it can cause serious contamination incidents (Desa et al. 2009). Wastes are often dumped in open landfill and abandoned mineral workings for convenience or proximity to the waste source, rather than considering the potential environmental, geologic, or engineering consequences, such as bedrock and groundwater contamination (Chambers et al. 2006; Perozzi and Holliger 2008). This disregard for such considerations can lead to hazardous outcomes (Olayinka and Olayiwola, 2001; Ariyo et al. 2013).

Infiltration of rainfall into landfills along with the biochemical and chemical breakdown of wastes generates leachate that contains high levels of suspended solids and varying amounts of organic and inorganic constituents. Serious contamination incidents may occur if the leachate enters the surface face or groundwater before sufficient dilution (Desa et al. 2009). Over the past few decades, disposal sites have been filled with household and various types of potentially hazardous industrial waste in an uncontrolled manner, posing a significant risk to the environment and serving as the prisourceurces of groundwater contamination (Adeoti, L. 2011). Several geophysical surveys can be conducted to explore leachate flow paths the and time-dependent transport of contaminants (Behshad Jodeiri Shokri 2015). A well-known reclaimed dumpsite in north central Nigeria used geophysical techniques like vertical electrical sounding (VES), 2D electrical resistivity profiling (2D ERP), and very low frequency electromagnetic (VLF-EM) to determine the extent of leachate contamination in nearby rocks. This investigation was carried out in separate studies conducted by W.O. Raji in 2016 and Ugwu N.U. in 2016.

The application of Wenner and Schlumberger array configurations of electrical resistivity techniques was used to image the subsurface resistivity within the study area using ABEM SAS 300 Terrameter, as reported by Cyril N. NWANKWO in 2020. The vulnerability of overburdened aquifers located near a municipal dumpsite was investigated within the survey site, which is located within the Niger Delta basin of South-eastern Nigeria and bounded by longitude 7°5'20"E and 7°5'52"E and latitudes 6°13'35"N and 6°13'52"N, as reported by Egwuonwu Gabriel N in 2020. The impact of open landfills on soils, the biosphere, and groundwater has become a significant concern in many parts of the world. A study conducted by Fahmida Parvin et al. in 2021 investigated an uncontrolled landfill located in the Tadla Plain, Morocco’s main agricultural region. The leaching of organic and inorganic waste materials deposited in landfills and open dumpsites can lead to serious degradation of the environment, causing contamination of aquifers, as stated by Ndifreke I. Udosen in 2022

The electrical resistivity images of these three lines will be discussed and compared to resistivity values obtained from laboratory measurements for landfill and other earth materials as shown in Table 1

Table 1

Sampled material	**Resistivity (ohm.m)**
Leachate only	2.994
Sand saturated with leachate	4.97-5.04
Fresh Waste (Plant materials, rubber stands, and saturated with leachate)	6.03-7.16
Soil saturated with leachate	3.15-4.00
Rain water only	73.88
sand saturated with rainwater	14.36- 1750
Fresh waste (Plant materials, rubber strands, and saturated with rainwater	19.71- 22.50
Soil saturated with rainwater	9.30-10.57
Clay saturated with brackish water	0.12-0.20
Clean and saturated with seawater	1.5-3.5
Fresh sandstone	600
Hard rock	>600
Clayey	1-30
Laterite	50-350
Coarse sand	2400-10^8
Limestone	50-10^7
Dolomites	350-5000

III. STUDY AREA

Moshi is located in Pune District, Maharashtra, with a Pin code of 412105. It has a latitude of 18°39'23"N and a longitude of 73°51'24"E. For the past three decades, the Pimpri-Chinchwad Municipal Corporation (PCMC) has been using the Moshi garbage depot, situational 81-acre land on the Pune-Nashik Highway on the outskirts of the city, as a dumping site for the city's waste. The officials have stated that the landfill at Moshi is full and no longer has any space to accommodate any more waste. The PCMC Moshi Kachara Depot, located in Pimpri-Chinchwad, Pune, has a 45-acre dumping site. However, due to insufficient treatment and ineffective land use practices, there is a shortage of space and sanitary conditions in the vicinity of the site.

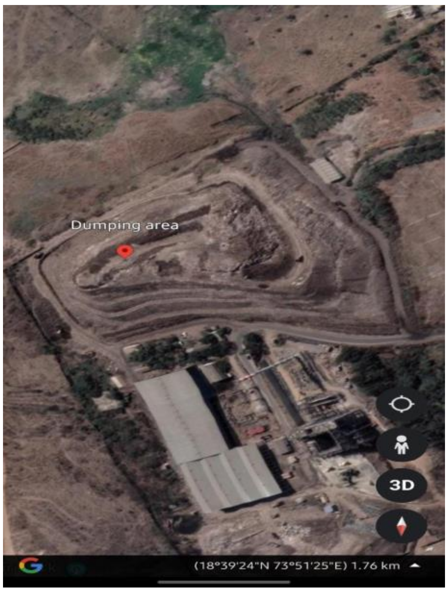


Fig no. 1 Dump Site

IV. METHODOLOGY

The electrical resistivity method is employed to assess potential variances at specific locations on the Earth's surface generated by the passage of direct current through the subsurface. The movement of charges or currents through a conductive wire characterizes this current flow.

$I = Q \backslash t$ (1)

The resistivity meter utilized in the research, an Ohmega, was assembled and prepared with all necessary accessories. The electrodes were evenly spaced along the measurement line, maintaining their equilibrium. Cables were connected to the C1 and C2 ports of the machine to provide current to the subsurface.

In the first measurement, electrodes 1, 2, 3, and 4 were employed Referring to Figure 5, electrodes 1 and 2 functioned as the initial current electrode (C1) at 0 m, electrode 3 as the second potential electrode (P2) at 10 m, and electrode 4 as the second current electrode (C2) at 15 m. The same pattern was repeated for the second measurement with electrodes 2, 3, 4, and 5 positioned at 5 m, 10 m, 15 m, and 20 m, respectively. This process was repeated along the 200 m profile line with intervals of 1a, 2a, 3a, 4a, and 5a, obtaining corresponding spacing measurements. Following the technique outlined in reference (14), the measured apparent resistivity of the study area (as shown in Table I) was calculated by multiplying the measured resistance (R) with the corresponding geometric factor value (Gw).

$$J = I / A \quad (2)$$

From Ohm's law,

$$I = V/R \quad (3)$$

R is the resistance, and V is the voltage.

One immediate issue is that resistance is affected by the material's size as well as its composition.

$$R = \rho * (L/A) \quad (4)$$

In electrical resistivity surveying, the objective is to determine the potential difference between two points, similar to how we measure it in electrical circuits. The arrangement of electrodes on the Earth's surface is depicted in Figure 1. The potential differences were measured using the inner potential electrodes, P1 and P2, in conjunction with the two outer current electrodes, C1 and C2.

Therefore, the potential difference ΔV equals

$$\Delta V = V_{P1} - V_{P2} \quad (5)$$

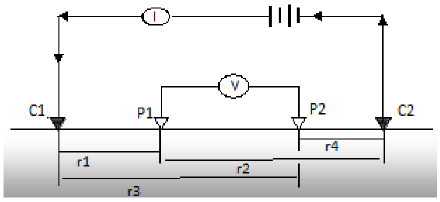


Fig. 1 Diagram used to determine the potential difference between two points Inserting (3) and (4) into (5), then

$$\Delta V = [(I\rho/2\pi r_1) - (I\rho/2\pi r_2)] - [(I\rho/2\pi_3) - (I\rho/2\pi r_4)] \quad (6)$$

$$\Delta V = 1\rho/2\pi\,(1/r_1 - 1/r_2 - 1/r_3 + 1/r_4) \quad (7)$$

The 2D electrical resistivity method typically involves the introduction of current into the ground to measure the resulting potential difference, which enables the determination of soil or common rock resistivity. Therefore, the resistivity ρ in equation (3) is obtained.

$$\rho = 2\pi\Delta V/I\,(1/(1/r_1 - 1/r_2 - 1/r_3 + 1/r_4)] \quad (8)$$

Resistivity ρ is thus given as

$$\rho = 2\pi\Delta V/I.\ G = RG \quad (9)$$

Where *G;*

The geometric constant represents the electrode configuration chosen for the survey. In this study (refer to Fig. 2), the four electrodes A, M, N, and B were positioned along a profile according to the inner configuration, resulting in the following arrangement.

AM=MN=BN= AB/3 (10)

This distance AB/3 is called the electrode spacing (a)

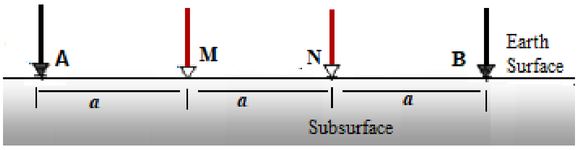


Fig. 2 The Wenner electrode configuration

The current electrodes in the setup are A and B, while the potential electrodes are M and N. By comparing Figs. 1 and the obtained apparent resistivity ρa for a specific electrode spacing value, we can deduce the following relationship: (a) becomes:

$r_1=a,\ r_2=2a,\ r_3=2a,\ r_4=a$ (11)

Then the equation for resistivity (8) becomes:

$\rho = 2\pi\Delta\ V/I\ \{(1/a-1/2a)-(1/2a-1/a)\}$ (12)

The apparent resistivity ρ_a measured at a particular value of electrode spacing, (a) becomes:

$\rho_a= 2\pi\Delta\ V/I$ (13)

$\rho_a= G_{w.}\ \Delta V/I= G_W.R$ (14)

In the adopted configuration of this study (Fig. 2), there are four electrodes planted along a profile: A, M, N, and B. The measured resistance in Ohms denoted as R, and the geometric factor for the Wenner array, represented by Gw ($2\pi a$), are related as follows:

V. SOFTWARE INFORMATION

Two-dimensional (2D) electrical imaging surveys have become a popular method for mapping areas of geology that are moderately complex and require more than the traditional 1D resistivity-sounding surveys. To produce a 2D model of the subsurface from apparent resistivity data, the RES2DINV program uses the smoothness-constrained least-squares method inversion technique developed by Sasaki in 1992. This method is completely automated, and the user does not need to provide a starting model. The RES2DINV program is capable of inverting a single pseudo section on a Pentium-based microcomputer within minutes. It supports a variety of array configurations, including Wenner (a p.y), Schlumberger, pole-pole, pole dipole, inline and equatorial dipole-dipole, gradient, and non-conventional arrays. The program automatically selects the optimal inversion parameters for a given dataset, but users can modify these parameters if desired. Three variations of the least-squares method are provided, including a very fast quasi-Newton method, a slower but more accurate Gauss-Newton method, and a moderately fast and accurate hybrid technique. The smoothing filter in the RES2DINV program can be altered to highlight resistivity differences in either the vertical or horizontal directions. Additionally, the filter can be tweaked to create models with rounded edges, like chemical plumes, or sharp edges, like fracture zones. To constrain the inversion process, resistivity information from boreholes and other sources can also be incorporated. The program offers three different techniques for topographic modeling, as developed by Loke in 2000. Figure 1 depicts an example of an electrical imaging survey conducted in an area with complex subsurface geology and significant surface topography. The survey was performed across a circular mound that is believed to contain significant Irish archaeological burial chambers, according to Waddell and Barton in 1995. The data set includes 67 electrode positions and 339 data points, and the inversion process on a 3.4 GHz Pentium 4 computer took approximately 24 seconds.

VI. INPUT DATA

The input data mainly involves the geophysical survey parameters and the location topographical details as mentioned in Table 2.

Table 2 Input data

Dumpsite.Dat File	**Comment**
Dumpsite Survey Line	Name OF Survey Line
5	Unit Electrode Spacing
1	Array Type, 1 For Wenner Array
54	Number Of Datum Points
54 70.000 20.000 7.9	Position Of Mid-Point Array
0.00 And 100.00	Minimum And Maximum Electrode Locations
5	Minimum Electrode Spacing
7.5 5 80.34	Frist Data Point
17.5 5 28.23	Third Data Point
70 20 7.89	Last Data Point
0,0,0,0,0	Ends With Few Zero. Flags For Other Options
Topographic Data	
21	Topographical Datum Point
4	Total Number Of Data Level
21	Total Number Of Electrodes
0	First Electrode Located
100	Last Electrode Located

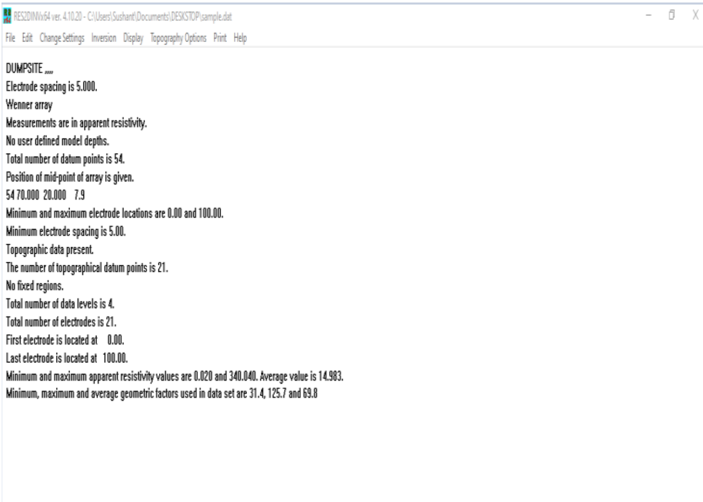
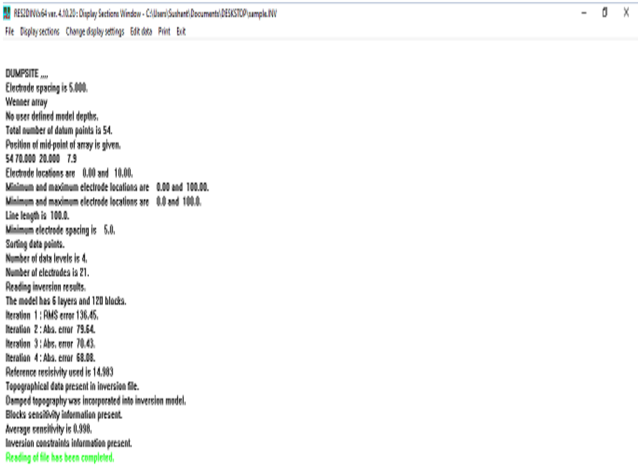


Fig. 4 Input Data in Res2Dinvx64



RES2DINVx64 ver. 4.10.20 : Display Sections Window - C:\Users\Sushant\Documents\DESKSTOP\sample.INV

File Display sections Change display settings Edit data Print Exit

DUMPSITE ....
Electrode spacing is 5.000.
Wenner array
No user defined model depths.
Total number of datum points is 54.
Position of mid-point of array is given.
54 70.000 20.000 7.9
Electrode locations are 0.00 and 10.00.
Minimum and maximum electrode locations are 0.00 and 100.00.
Minimum and maximum electrode locations are 0.0 and 100.0.
Line length is 100.0.
Minimum electrode spacing is 5.0.
Sorting data points.
Number of data levels is 4.
Number of electrodes is 21.
Reading inversion results.
The model has 6 layers and 120 blocks.
Iteration 1 : RMS error 136.45.
Iteration 2 : Abs. error 79.64.
Iteration 3 : Abs. error 70.43.
Iteration 4 : Abs. error 68.08.
Reference resistivity used is 14.983
Topographical data present in inversion file.
Damped topography was incorporated into inversion model.
Blocks sensitivity information present.
Average sensitivity is 0.998.
Inversion constraints information present.
Reading of file has been completed.

Fig.5Inversion data

VII. RESULTS AND DISCUSSIONS:

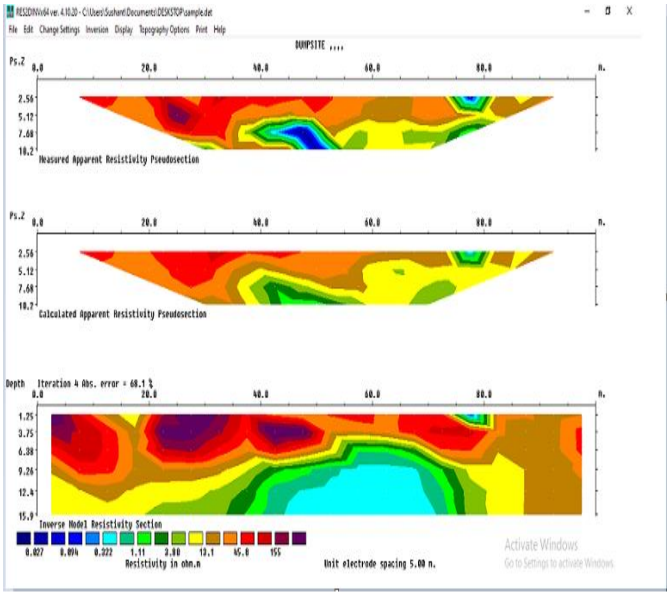


Fig 5 Inversion Graph Image

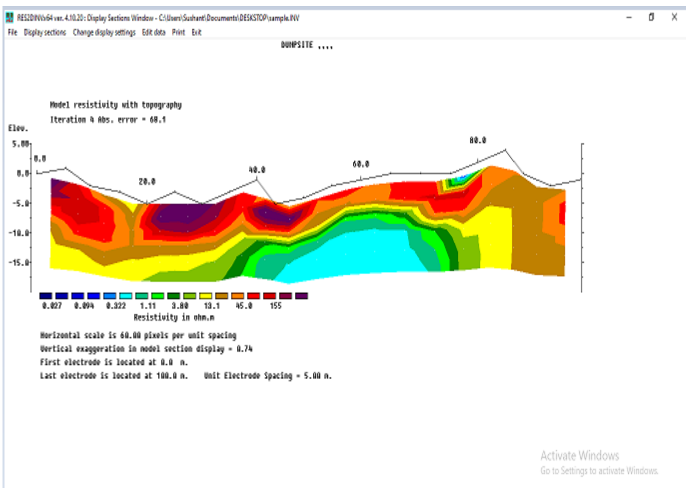


Fig 6 Topographic Inversion Graph Image

VIII. DISCUSSION

The Res2dinv software, specifically the x64 version, was utilized to process the field data gathered. This software automatically produces the inverse resistivity model section, where the horizontal distance represents the profile and the vertical axis corresponds to the depth of investigation. Each inverse section of the profile was then analyzed in terms of geology, as presented in Table 1, and other related information.

The inverse section of profile one, as shown in Figure 5, displays the resistivity model results along traverse 1 (control) in the vicinity of a test site located 80m from the dump site. The model illustrates a homogenous high electrical resistive zone (>155 Ohm-m) at depths ranging from 1-16 m across the model. The area is free of leachate contaminations and ideal for groundwater development based on the high resistivity response of this zone. A horizontal zone with a resistivity response ranging from 45-200 ohm-m thickens from the surface to about 3.75 m depth, extending to the end of the profile. This is interpreted as unpolluted topsoil. However, a local zone of low resistivity response is observed at 0 to 72 m from the base point on the surface of this traverse. Table 1 provides information on the electrode electroactivity of Earth Materials for this traverse, which shows a large conductive zone with uniform resistivity of less than >3.80 ohm-m (Clay saturated with brackish water) at a depth of 7.68 m from the top of the landfill. This zone occupies most of the area of the model section and is interpreted as a possible polluted zone due to leachate infiltration from the landfill. At a distance of 72 m to 82 m from the base of the point, the zone is highly conductive, giving a resistivity response of 2.994 – 6.03 ohm-m up to a depth of 3.75m, signifying a zone of highly decomposing waste saturated with highly conductive leachate. The link between this zone and the polluted zone underground suggests leachate infiltration from east to west. Thus, the surface of the landfill reveals the various extents of waste decomposition.

The results of the second inversion indicate a low resistivity zone, similar to the first graph, with a depth of up to 5.55 m (45.5 - <155 ohm-m) from the surface ranging from 0-72 m. Between 59 m to 66 m from the surface and at a depth ranging from 0-10.2 m, zones of sand saturated with rainwater show resistivity values of 13.1-17.50 ohm. At a depth of 5.68 m below the surface, the zone between 39 m to 59 m contains clean sand saturated with seawater with resistivity values of 1.5-3.5 ohm-m. Finally, from the surface, the zone between 74 m to 81 m has a resistivity range of 0.322-3.80 ohm-m up to a depth of 5.12 m. The Third Inversion results reveal a zone between 19 m and 80 m with resistivity ranging from 0.322 to 13.1 ohm-m, which is interpreted as soil saturated with rainwater and some contaminated wastewater. This zone extends up to a depth of 3.75 m from the surface and is likely composed of clayey material with low hydraulic conductivities. It is believed that this layer acts as a barrier, protecting the underlying auriferous layer from leachate invasion from the surface. Therefore, the narrow, horizontal layer does not represent a contaminated aquifer, but rather a clay layer that prevents pollution from affecting the underlying aquifer.

REFERENCES

[1]. Alex, A.B., Igor, N.M., Vladimir, A.S., 2002. Automated and Semi-automated Interpretation of Vertical Electrical Sounding and Induced Polarization Data Obtained from A Variety of Popular Arraysused in Electrical Prospecting, IPI2Wi. Geological and Geophysical Department, Moscow State University.

[2]. Annor, A.E., Olasehinde, P.I., Pal, P.C., 1987. Basement fracture pattern in the control of river channels. An example from central Nigeria. J. Min. Geol. 26 (1), 5–11.

[3]. Beamish, D., 1994. Two-dimensional, regularized inversion of VLFdata. J. Appl. Geophys. 32, 357–374. Beamish, D., 2000. Quantitative 2D VLF data interpretation. J. Appl. Geophys. 45, 33

[4]. Billman, H.G; (1992). Offshore Stratigraphy and Paleontology of the Dahomey Embayment, West African. NAPE Bulletin Vol. 7 (2) pp.121 – 130.

[5]. Bureau de Recherches Geologiques et Minieres (1979): Pre-drilling hydrogeological report area 18 and 19 submitted to the federal Department of Water Resources, Lagos, NNigeria pp.1-60

[6]. Billman, H.G; (1992). Offshore Stratigraphy and Paleontology of the Dahomey Embayment, West African. NAPE Bulletin Vol. 7 (2) pp.121 – 130.

[7]. Bureau de Recherches Geologiques et Minieres (1979): Pre-drilling hydrogeological report area 18 and 19 submitted to the federal Department of Water Resources, Lagos, Nigeria pp.1-60

[8]. Chambers JE, Kuras O, Meldrum PI, Ogilvy RD, Hollands J (2006) Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site. Geophysics 71(6):231–239

[9]. Desa ND, Mejus L, Abd Rahman M, Samuding K, Mostapa R, Dominic JA (2009) Study on subsurface contamination flow path distribution using Electrical Resistivity Imaging (ERI) technique at the waste disposal site, Taiping, Malaysia. In: Proceedings of SEG Houston 2009 international exposition and annual meeting

[10]. Elueze, A.A. and Nton, M.E., (2004). Organic geochemical appraisal of limestones and shales in part of eastern Dahomey basin, southwestern Nigeria. Journal of Mining and Geology, vol. 40, No. 1 pp. 29-40

[11]. Jones, H.A. and Hockey, R.D. (1964). The geology of part of Southwestern Nigeria. Geological Survey of Nigeria. Bull. 31,87p

[12]. Jhamnani B, Singh SK (2009) Groundwater contamination due to Bhalaswa Landfill site in New Delhi. Int J Environ Sci Eng 1(3):121–125

[13]. Loke, M.H. and R D Barker, (1996). Practical techniques for 3D resistivity surveys and data inversion. Geophysical Prospecting, 44, pp.499-523

[14]. Oladapo MI, Mohammed MZ, Adeoye OO, Adetola BA (2004)Geoelectrical investigation of the Ondo State Housing Corporation

Estate, Ijapo Akure, Southwestern Nigeria. J Min Geol 40(1):41–48

[15]. Olayinka AI, Olayiwola MA (2001) Integrated use of geoelectrical imaging and hydrochemical methods in delineating limits of polluted surface and groundwater at a landfill site in Ibadan Area, South West Nigeria. J Min Geol 37:53

[16]. Perozzi L, Holliger K (2008) Detection and characterization of preferential flow paths in the downstream area of a hazardous landfill. J Environ Eng Geophys 13(4):343–350

[17]. Tijani MN, Jinno K, Horoshiro Y (2004) Environmental impact of heavy metals distribution in water and sediments of Ogunpa River, Ibadan Area, Southwestern Nigeria. J Min Geol 40(1):73–79