APPLICATION OF GEO-PHYSICAL METHODS TO CHARACTERIZE SOLID WASTE LANDFILL: THE CASE OF REPI LANDFILL, SOUTH WEST ADDIS ABABA

A thesis submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Environmental Science

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This is to certify that the work is entirely my own and not of any other person, unless explicitly acknowledged (including citation of published and unpublished sources). The work has not previously been submitted in any form to any University or other institution for assessment of any other purpose.

Signed ___ __________________________________

Date __________________________________________

___ ____________________
Acknowledgments

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Biruk Birhanu
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<th>Description</th>
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<td>AACC</td>
<td>Addis Ababa City Council</td>
</tr>
<tr>
<td>AASBPDA</td>
<td>Addis Ababa Sanitation, Beautification and Parks Development Agency</td>
</tr>
<tr>
<td>AAWSA</td>
<td>Addis Ababa Water and Sewerage Authority</td>
</tr>
<tr>
<td>CBO</td>
<td>Community based organization</td>
</tr>
<tr>
<td>DC</td>
<td>Direct current</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital elevation model</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>m a s l</td>
<td>meter above see level</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-governmental organization</td>
</tr>
<tr>
<td>UNEP</td>
<td>United Nations Environmental Program</td>
</tr>
<tr>
<td>UNESCO</td>
<td>United Nations Education, Social and Culture Organization</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
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<td>VES</td>
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Abstract

Water quality degradation is one of the major environmental problems in Addis Ababa and municipal solid waste disposal sites can be sources of groundwater contamination as leachate may infiltrate and join the aquifer. In Addis Ababa, there is currently one landfill site at Repi in the South West of the city located 13kms away from the city center. The Repi landfill site was commissioned more than 40 years ago and the only factors that were considered in selecting this site were hauling distance and availability of the land. Geophysical surveys, involving 2-D resistivity imaging and vertical electrical sounding were conducted around the solid waste landfill for a hydro-geophysical assessment of contamination of groundwater. IRIS SYSCAL R1 Plus switch-72 multinode imaging unit was used to acquire data both for the imaging and VES survey. In general 3 traverses for imaging and 3 VES measurement points along a profile were used for the study.

The correlation between the 2-D resistivity imaging and the VES data is outstanding. The results clearly indicate that the underlying layers in this area around the landfill are weak incapable of preventing downward movement of the leachate from the landfill to the groundwater. Hence, the groundwater in this area may have been contaminated. Therefore, the usage of the landfill which is without geologically impermeable ground must be discouraged. It is also strongly recommended that a thorough study of any site must be done before any operation so as to know whether the aquifer is naturally sealed or not.

Keywords: 2-D resistivity imaging, VES, solid waste landfill, lecahate, chemical waste and groundwater.
CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

The management of solid waste landfills has been a major problem of our urban centers in Ethiopia and other developing economies worldwide. In these urban centers, wastes are generated daily and disposed indiscriminately in rivers and landfills without recourse to the underground environment, local geology and their proximity to living quarters.

Modern sanitary landfilling is not a common practice in Ethiopia. Some developing countries use simple landfilling methods by just dumping wastes in low-lying areas, which are prone to flooding. During rainy seasons, there is a possibility of surface water contamination due to flooding of these low lying-areas. Pollution of groundwater is also another threat posed by dumping of wastes as leachate may infiltrate and join the aquifer.

Leakage from municipal solid waste deposits is generally associated with high ion concentrations and hence results in very low resistivities of formations. This makes geoelectrical techniques most adequate for mapping the extent of leachate contamination around landfills (Bernstone and Dahlin, 1999). Landfill related geoelectrical surveys have been carried out by numerous investigators in the study of leachate contamination of soil and groundwater. Bernstone and Dahlin (1999), Christopher and Jones (1999), Keller and Frischescht (1999), Powers et al. (1999), Rosqvist et al. (2003), and Abdul Rahim et al. (2006), have used 2-D dc resistivity imaging and vertical electrical sounding to estimate the depth to the groundwater, identify and delineate the extent of contaminant leachate plume and migration paths below surface around landfills.

Percolating groundwater provides a medium through which wastes particularly organics can undergo degradation into simpler substances through biochemical reactions involving dissolution, hydrolysis, oxidation and reduction processes. This leachate, the liquid drains from the dump, mainly organic carbon largely in the form of fulvic acids (Taylor and Allen, 2001) migrate downward and contaminate the groundwater.

The importance of groundwater as a valuable source of potable water cannot be over emphasized. Groundwater forms the most important natural resources of any region and compliments surface sources in the provision of potable water for domestic and industrial
applications. The populace is also dependent on the abundance, fertility and integrity of the soils for agriculture, shelter, and other economic and industrial activities. Unfortunately, the quality of these natural resources have been impaired by the indiscriminate dumping of toxic waste materials in landfills in the municipality, with attended risk to the health of the people and damage to the environment.

When one considers the situation in Addis Ababa, the capital and by far the biggest urban center in Ethiopia, the open space dumping which has been in practice by the Addis Ababa City Municipality is major problem to the environment. In Addis Ababa, there is currently one landfill site at Repi in the South West of the City in Kolfe Keraniyo Kifleketema located 13 kms away from the city center. It has a surface area of 30 hectares. According to Region 14 Administrative Health Bureau (1997) The Repi landfill site was commissioned more than 40 years ago. The only factors that were considered in selecting this site were hauling distance and the availability of the land. There was no evaluation of the underlying soil structure and topography, climatological conditions, surface water hydrology or the geologic and hydro-geologic conditions of the area.

This work was intended to conduct geophysical surveys over the Repi landfill site to study the extent of invasion of the leachate from the solid waste to the groundwater system.

1.2 Solid Waste disposal

Disposal as the last functional element is the last option in the solid waste management system and the ultimate fate of all waste that is of no further value and use to the society. The safe and reliable long-term disposal of solid waste residues is an important component of integrated waste management (Tchobanoglous et al., 1977).

The use of landfills as a method of waste management is widely practiced all over the world; as such, landfill sites must be carefully selected, as it is a critical step in waste disposal. If improperly conducted, the overall efficiency of the waste management system is affected negatively as a result of generated leachate as well as landfill gas (LFG), which is a powerful greenhouse gas and thus results in a transfer of pollution. Uncontrolled landfill gas migration from the site cannot only damage the global environment but can also negatively impact human health and pollute the local environment.

It is possible through reduction, reusing, recycling and incineration of municipal solid wastes to significantly reduce the amount of wastes that need to be land filled. It is not possible to
totally eliminate the land burial of municipal solid wastes. Ultimately, something must be done with wastes that are of no further use. These wastes need to be land filled.

The current situation in Addis Ababa is the utilization of one landfill disposal site where all the collected waste is disposed off and has been giving service since 1968. Figure 1 below shows the Repi landfill.

![Figure 1: Landfill site of Addis Ababa (Repi)](image)

The site is known as “Rappi” or “Koshe” which is situated at the southwest part of the Addis Ababa in the sub-city of kolfé-keranyo. At the time of its establishment, the site was 13 km away from the center of the city. Anaerobic decomposition of organic solid waste produces landfill gas (LFG), which constitutes methane, carbon dioxide, and toxic gases. This is true of the Addis Ababa landfill site where the gases generated from the site sets the waste on fire and the toxic liquid produced from the site contaminates the surface and ground water (Hassen, 1998). Even though detail studies were not conducted the gas produced can be methane since it has fire of explosive nature and the liquid part is leachate, which escapes from the landfill due to the failure of the piping system. Studies show that this system can clog up in short period due to mud, silt, and chemical attacks. The danger from the site in the case of Addis Ababa is high, since the city has been expanding and developing towards the present landfill site, and it is now in the proper urban area surrounded by institutions, residential houses and schools (Yami, 1999).
Land filling is necessary for municipal solid waste disposal but every landfill has its own finite capacity. The most common approach to extending the life of landfill is to introduce recycling composting and incineration into the solid waste disposal system (Chang and Nishat, 2005).

Hence, the city council is planning to rehabilitate the existing landfill and an action to build one new landfill site at eastern part of the city is being implemented. Encouraging a greater participation in primary waste collection by micro and small enterprises as well as the participation of NGOs and CBOs is also under way (AASBPDA, 2003).

1.3 General Description of Addis Ababa

Topography and location

Addis Ababa, the capital city of Ethiopia, is located in the heart of the country. It is the country’s commercial, manufacturing and cultural center. Addis Ababa has grown at an astonishing speed since it was established in 1886.
Figure 2. Location map of the city of Addis Ababa and the landfill.

Today, it has a population of more than three million in a land area of 540 sq.Km of which 18.2 sq.Km are rural. The city had divided into ten sub-cities and 204 districts for administrative purposes (AACC, 2004) as shown in Figure 2. Its center is situated at 9° N and 38° 45’ E and lies between 2000 and 2800 meters above sea level on a well plateau surrounded by hills and mountains. The city is endowed with numerous streams that start from North West and north east running towards the south and draining to Awash River. The most important streams and rivers are Kebena, Ginflle, Bantyiketu, Buhe, Akaki and Kechene rivers (Region 14 Environmental Protection Bureau, 1997).

Climate

Despite its proximity to the equator, Addis Ababa enjoys a mild, Afro-Alpine temperate climate. The lowest and the highest annual average temperature are between 10 and 25°C. April and May are the driest months. The main rainy season occurs between mid-June and mid-September; this season is responsible for 70% of the annual average rainfall of 1400mm. It is characterized by intense rainfall of short duration. During the dry season, the days are pleasantly warm and nights are cool; in the rainy season, both days and nights are cool (Belachew Tolla, 2006).
1.4 Location and Brief History of Koshe

Koshe, the only open dump landfill of Addis Ababa, is located in the western part of the city around 13km from the center and it covers an area of 0.3km² (30 hectare). Figure 2 shows the exact location of the site.

According to Region 14 Administrative Health Bureau (1997) The Repi landfill site was commissioned more than 40 years ago. The only factors that were considered in selecting this site were hauling distance and the availability of the land. There was no evaluation of the underlying soil structure and topography, climatological conditions, surface water hydrology or the geologic and hydro-geologic conditions of the area.

Prior to that the city had no landfill for dumping wastes. Customarily, people used to dump their wastes in close proximity to their houses. Currently the major problems associated with the disposal site are: The site is over filled, surrounded by housing areas and institutions, nuisance and health hazard for people living nearby, more than 200 - 300 human scavengers per day work continuously and obviously living nearby the site and interfering the operation of the work for collection of salvageable materials such as wood, scrap metals and discarded food, no daily cover with soil, no leachate containment or treatment, no rainwater drain-off, no odor or vector control, no fence, no weigh bridge and inaccurate weighing of waste and poor record keeping, no liners, no gas venting, hence there is frequent fires, operated very close to rivers and streams, poor road conditions leading to the site and no proper and adequate access road, indiscriminate disposal of hazardous and industrial wastes, no proper maintenance of the bulldozers and compactor.

The present method of disposal is crude open dumping: hauling the wastes by truck, spreading and leveling by bulldozer and compacting by compactor or bulldozer (AASBPDA, 2003).

These types of disposal operations can pose health hazards as well as pollution of the air and water (Mantell, 1975). The wastes are exposed to wind and rain, as well as rat, houseflies, birds and other vermin. There are also people who spend their time sorting through the garbage for edible or recyclable materials in a very risky way to health.
1.5 Statement of the Problem

The open dump disposal site at Repi is characterised by varied and incompatible land use activities. These land use activities, coupled with environmentally unsustainable waste disposal system are believed to have exposed the local communities to great health risks and also the groundwater system to pollution. Therefore, ground water contamination is the main problem of interest of study.

1.6 Objectives of the Study

1.6. General Objective

The main objective of this study is to investigate the effect of municipal and other solid wastes on ground water system of the Repi area.

1.6.2 Specific Objectives

➢ To assess groundwater contamination near the Repi site landfill through the use of electrical geophysical methods.

➢ To assemble information on the groundwater condition in the study area.

➢ To map for the presence of subsurface structures that could act as conduits for the flow of groundwater.

➢ To determine the groundwater condition and its vulnerability to contamination from the solid wastes.

1.7 Significance of the Study

It is everyone’s everyday observation that solid waste dumped in different parts of the city in uncontrolled manner. The properly collected solid waste is dumped in the only open dump landfill of Koshe -this open dump has been serving the City of Addis Ababa for the past 45 years. Considering the growing size of waste that is dumped at Koshe due to the rapidly increasing population and the ill-designed nature of the open dumped landfill, it seems reasonable to hypothesize that the waste is causing environmental damages. Therefore, assessment of the extent of pollution that is caused by the growing size and poor management of the waste at Koshe and suggestion for more environmentally friendly strategies is believed
to contribute to the present and future endeavors aimed at a sound scheme for waste management in the city.

It is hoped that a research work like this type can provide useful information for policies and practices aimed at minimizing the environmental impact of the disposal of solid waste and can help create a healthy society and bring about environmentally sustainable development in Addis Ababa, which can be replicated in other parts of the country, that possibly share similar problem.

1.8 Structure of the Thesis

This thesis comprises of five chapters. The first chapter deals about the introduction part. Geological settings of the study area are included in chapter two. Chapter three consists of the theoretical frame work of electrical resistivity methods and data acquisition and processing. Chapter four incorporates interpretations of results and discussion of the different data presentations. Conclusions and recommendations are discussed in chapter 5.
CHAPTER TWO

2. GEOLOGY AND HYDROGEOLOGY

2.1 Regional Geology

Addis Ababa was founded at the southern border of Entoto ridge with elevation (3199m asl). This ridge presently marks the northern boundary of the city following the east-west trending major fault (Ambo-Kassam) (Zanettin et al., 1978). The other significant volcanic features surrounding the city are Mt. Wochacha with elevation (3385m asl) in the west, Mt. Yerer with elevation (3100m asl) in the southeast and Mt. Furi with elevation (2839m asl) in the southwest. These typical volcanic features are mainly built up of acidic and intermediate lava flows (UNEP/UNESCO/UN-HABITAT/ECA, Scientific report, 2003). Thus, they are characterized by rugged landscapes and steeper slopes. The centre of the city lies on an undulating topography with some flat land areas.

Based on Morton’s geological map (1974), the work of Kazmin and Seifemichael (1978), Hailesilassie and Getaneh (1989) proposed the volcanic succession of the area starting from Sululta to Nazareth. The suggested Miocene-Pleistocene volcanic succession in the Addis Ababa area from bottom to top are: Alaji basalts, Entoto silicics, Addis Ababa basalts, Nazareth group, and Bofa basalts.

The regional geology of the area is adopted from the work of Hailesilassie and Getaneh (1989).

Alaji Basalts

This volcanic rock is composed of basalts, which show variation from highly porphyritic to aphyric. Within this unit, there is an intercalation of welded tuff. The outcrop of Alaji basalt extends from the crest of Entoto (ridge bordering the northern parts of Addis Ababa) towards the north. This unit is underlain by tuffs and ignimbrites. The outcrop of this unit extends from the crest of Entoto north across the Sululta plain.
Entoto Silicics

The Entoto silicics composed of rhyolite and trachyte with minor amount of welded tuff and obsidian. This unit is uncomfortably overlain by Addis Ababa basalts on the foot hills of Entoto and underlain by Alaji basalts. The rocks outcrop on the crest of Entoto adjoining the E-W fault running from Addis Ababa to Ambo, and on the plain east of the town of Addis Ababa.

Addis Ababa Basalt

This basalt is porphyritic in texture, composed of labradorite – bytownite, olivine and augite as phenocrysts. This unit is overlain by Lower Welded Tuff of the Nazareth group and underlain by Entoto Silicics. These rocks outcrop within the city of Addis Ababa from the foot hills of Entoto up to Filwoha. The topography of this area shows a smooth dipping to the south of Filwoha (inclined by less than 300 towards the rift).

Nazareth Group

In this group three informal units are identified namely in ascending stratigraphical order; Lower Welded Tuff, Aphanitic Basalt and Upper Welded Tuff. The Nazareth group is underlain by Addis Ababa Basalts and overlain by Bofa Basalts. The rocks outcrop mainly south of the major Filwoha fault located NE – SW direction (Morton, 1974) and extend towards Nazareth.

Bofa Basalt

It is composed of labradorite, olivine (partially or completely iddinsitized) and augite that occur as phenocrysts. The ground mass is crystalline and composed of labradorite andesine, clinopyroxene and olivine (mostly idddinsitized) calcite exists replacing plagioclase and as veins. This rock out crops in the Akaki – Debrezeit area.
The Repi vicinity geology

Figure 3. Geologic map of Addis Ababa (after Mulugeta, 2007)
Local geology of Repi area

Repi basalt, ignimbrite and trachytic basalt are the main rock type found in the study area. Table 1 below shows the well log data of 196m deep borehole located at about 2 kms SE of the Repi landfill.

<table>
<thead>
<tr>
<th>Depth(m)</th>
<th>Lithologic description</th>
</tr>
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<tbody>
<tr>
<td>0 – 32</td>
<td>Brown soil</td>
</tr>
<tr>
<td>32 – 46</td>
<td>Highly weathered &amp; slightly fractured ignimbrite</td>
</tr>
<tr>
<td>46 – 58</td>
<td>Moderately weathered &amp; slightly fractured trachytic basalt</td>
</tr>
<tr>
<td>58 – 72</td>
<td>Fresh basalt</td>
</tr>
<tr>
<td>72 – 73</td>
<td>Paleosoil reddish</td>
</tr>
<tr>
<td>73 – 90</td>
<td>Moderately weathered trachytic basalt</td>
</tr>
<tr>
<td>90 – 114</td>
<td>Moderately fractured &amp; slightly weathered trachytic basalt</td>
</tr>
<tr>
<td>114 – 162</td>
<td>Highly weathered &amp; highly fractured scoracious trachytic basalt</td>
</tr>
<tr>
<td>162 – 168</td>
<td>Moderately fractured &amp; slightly weathered pumice</td>
</tr>
<tr>
<td>168 – 180</td>
<td>Highly fractured &amp; moderately weathered ignimbrite</td>
</tr>
<tr>
<td>180 – 186</td>
<td>Highly weathered &amp; moderately fractured ignimbrite</td>
</tr>
<tr>
<td>186 – 192</td>
<td>Slightly fractured &amp; moderately weathered ignimbrite</td>
</tr>
<tr>
<td>192 – 196</td>
<td>Fresh ignimbrite</td>
</tr>
</tbody>
</table>

Table1. Well Log Data at the Mekanisa borehole 19. (After AAWSA, 2007).

2.2 HYDROGEOLOGY

The groundwater circulation and the dispersion of pollutants depend on the hydrogeological characteristics of the material more specifically hydraulic properties such as porosity, permeability, transmissivity etc. The origin, flow and chemical constituent of groundwater is controlled by the type of lithology, distribution, thickness and structure of hydrogeological units through which it moves. Moreover, the stresses due to tectonism and weathering govern the hydrogeochemical characteristics of earth materials.

The Addis Ababa area is made up of Oligocene-Miocene and Quaternary volcanic rocks. The rock chemistry ranges from basic to acidic. The northern part of the city is made of rhyolites and trachytes of older age than the basaltic rocks of the southern sector. The main volcanic centers are Entoto, Yerer, Furi and Wachacha.
Volcanic rocks mainly basalts, rhyolites, trachytes, scoria, trachy-basalts, welded and unwelded tuffs are the dominant rock outcrops in the area. Besides, unconsolidated materials of different origin also occurred in Addis Ababa. These rocks are the major groundwater supply for large parts of Addis Ababa. Hydrogeological investigation in volcanic terrain needs emphasis in re-construction of the geologic and geomorphologic history of the area. In between successive lava flows physical disintegration and chemical decomposition of rocks exposed at the surface; subsequent erosion and deposition; and tectonic activity taken place that has modified significantly the geomorphologic set up of the area. The main porosity groups identified are fracture porosity and interstitial porosity.

The main aquifers in Addis Ababa area can be categorized into three groups:

1. Shallow aquifer: made of weathered volcanic rocks and alluvial sediments along the river valleys.
2. Deep aquifers: made of fractured volcanic rocks that tap fresh ground water.
3. Thermal aquifer: that is located at depth greater than 300m.

The main aquifer in the Repi area are highly weathered & highly fractured scoracious trachytic basalt (AAWSA, 2007).

**Groundwater Flow**

The present day landform of Addis Ababa is influenced by geological processes specially faulting and denudation. The layering of lava flows are dipping nearly southwards and similarly the unconformity surfaces. For this reason the general groundwater flow is from north to south. Hence, the central and the southern parts are subjected to pollution from waste waters upstream.
CHAPTER THREE

3. THEORY AND METHODOLOGY

3.1 ELECTRICAL GEOPHYSICAL TECHNIQUES

3.1.1 Introduction

The earth possesses naturally occurring electric fields and their variation can be mapped using the spontaneous potential (sp) method. However, the most important electrical geophysical techniques for environmental investigations are active systems in which direct or alternating current is applied to the ground surface and measurements made of the potential difference. Two active systems are electrical resistivity and induced potential (IP), the former being the more commonly used one.

Electrical surveys are especially useful when the presence (or absence) of fluids are being investigated. They have been used in such circumstances to:

- Locate potential sources of groundwater,
- Locate geological structures which control the movement of groundwater,
- Detect the position of former disposal sites,
- Investigation of waste disposal site for escaping effluent,
- Locate pollutant pathways,
- Map the extent of contaminant plume,
- Detect salt water intrusions
- Investigate the integrity of barriers of seepage.

Electrical resistivity has other applications including determining the depth to bedrock and the detection of cavities and cave systems. The resistivity method as it is the most widely used electrical technique in environmental investigations, is based on well established theoretical concepts and a number of computer programs have been developed to aid in the interpretation of resistivity data.
3.1.2 Fundamental Principles of DC Resistivity Method

DC Resistivity is an active method that employs measurements of electrical potential associated with subsurface electrical current flow generated by a DC, or slowly varying AC, source. Factors that affect the measured potential, and thus can be mapped using this method, include the presence and quality of pore fluids and clays. Resistivity technique is superior, at least theoretically, to all the other electrical methods, because quantitative results are obtained by using a control source of specific dimensions. Practically, as in other geophysical methods the maximum potentialities of the resistivity are never realized. The chief drawbacks are its high sensitivity to minor variations in conductivity near surface and the practical difficulty involved in dragging several electrodes and long wires through rough wooden terrain.

In 1827, George Ohm defined an empirical relationship between the current flowing through a wire and the voltage potential required to drive that current.

\[ V = I \times R \]  \hspace{1cm} (1)

Ohm found that the current, \( I \), was proportional to the voltage, \( V \), for a broad class of materials that we now refer to as ohmic materials. The constant of proportionality is called the resistance of the material and has the units of voltage (volts) over current (amperes), or ohms.

In principle, it is relatively simple to measure the resistance of a strand of wire. Connect a battery to a wire of known voltage and then measure the current flowing through the wire. The voltage divided by the current yields the resistance of the wire. In essence, this is how your multimeter measures resistance. In making this measurement, however, we must ask two crucial questions.

- How is the measured resistance related to some fundamental property of the material from which the wire is made?
- How can we apply this relatively simple experiment to determine electrical properties of earth materials?
The problem with using resistance as a measurement is that it depends not only on the material from which the wire is made, but also the geometry of the wire. If we were to increase the length of wire, for example, the measured resistance would increase. Also, if we were to decrease the diameter of the wire, the measured resistance would increase. We want to define a property that describes a material's ability to transmit electrical current that is independent of the geometrical factors.

Figure 4. Definition of resistivity

The geometrically-independent quantity that is used is called *resistivity* and is usually indicated by the Greek symbol \( \rho \).

\[
\rho = \frac{R \cdot A}{L}
\]

where \( \rho \) is the resistivity

In the case of a wire, resistivity is defined as the resistance in the wire, times the cross-sectional area of the wire, divided by the length of the wire. The units associated with resistivity are thus, ohm - m (ohm -meters). Resistivity is a fundamental parameter of the material making up the wire that describes how easily the wire can transmit an electrical current. High values of resistivity imply that the material making up the wire is very resistant to the flow of electricity. Low values of resistivity imply that the material making up the wire transmits electrical current very easily.
3.1.3 Resistivity of Earth Materials

Although some native metals and graphite conduct electricity, most rock-forming minerals are electrical insulators. Measured resistivities in Earth materials are primarily controlled by the movement of charged ions in pore fluids. Although water itself is not a good conductor of electricity, ground water generally contains dissolved compounds that greatly enhance its ability to conduct electricity. Hence, porosity and fluid saturation tend to dominate electrical resistivity measurements. In addition to pores, fractures within crystalline rock can lead to low resistivities if they are filled with fluids.

The resistivities of various earth materials are shown in Table 2. Like susceptibilities, there is a large range of resistivities, not only between varying rocks and minerals but also within rocks of the same type. This range of resistivities, as described above, is primarily a function of fluid content. Thus, a common target for electrical surveys is the identification of fluid saturated zones.

Table 2. Electrical resistivity and conductivity of earth materials (from L.Ledo 2007)
3.1.4 Potentials in homogenous media

Consider a continuous current flowing in an isotropic homogenous media. (This analysis will also apply ac if the frequency is low enough that displacement current is insignificant). If \( V \) is the volume of the media, \( S \) is the surface area, \( Q \) is the charge enclosed by the volume, \( I \) is the current through the media and \( J \) the current density in amperes per square meters. The flow of current through the volume is given by

\[
I = -\frac{\partial Q}{\partial t}
\]  

(3)

In terms of charge density \( q \) and current density \( J \), \( I \) and \( Q \) are given by,

\[
(I)_S = \oint J \cdot \partial s
\]  

(4)

and

\[
Q = \int q \cdot \partial v
\]  

(5)

where \( V \) is the volume enclosed by \( s \).

Substituting equation (3) and equation (5) in to equation (3)

\[
\oint J \cdot \partial s = -\frac{\partial}{\partial t} \int q \cdot \partial v
\]  

(6)

Using the divergence theorem,

\[
\oint J \cdot \partial s = \int (\nabla \cdot J) \partial v
\]  

\( S \)

So that equation (6),

\[
\int (\nabla \cdot J) \partial v = -\int \left( \frac{\partial q}{\partial t} \right) \partial v
\]

\( V \)

\[
\int \left[ (\nabla \cdot J) + \frac{\partial q}{\partial t} \right] \partial v = 0
\]  

(7)

Since equation (7) is for any volume,
\[ \nabla \cdot J + \frac{\partial q}{\partial t} = 0 \]  \hspace{1cm} (8)

Equation (8) is the law of conservation of charges in differential form. It is known as the continuity equation.

For Direct Current (DC), the stationary field is conservative and hence the electric field intensity \( E \) is related to the scalar function \( V \) as,
\[ E = \nabla \cdot V \]  \hspace{1cm} (9)

where \( V \) is the potential measured in volts.

Current density \( J \) and electric field \( E \) are related by Ohm’s Law as
\[ J = -\delta E \]  \hspace{1cm} (10)

where \( \delta \) is the conductivity.

Since resistivity is the reciprocal of conductivity \( (\sigma = 1/\rho) \)
\[ J = \frac{1}{\rho} E \]  \hspace{1cm} (11)

or
\[ J = -\frac{1}{\rho} (\nabla v) \]  \hspace{1cm} (12)

From equation 4 and 7, we have,
\[ \text{Div} \left(-\frac{1}{\rho} \nabla V\right) = 0 \]
\[ \nabla \frac{1}{\rho} \nabla V + \frac{1}{\rho} (\text{div} \nabla V) = 0 \]  \hspace{1cm} (13)

Equation (13) is the fundamental equation for electrical prospecting with direct current.

For homogenous media \( \rho \) is independent of coordinates (since \( \text{div} \nabla V = 0 \)) so that equation (13) reduces to
\[ \nabla^2 V = 0 \quad (14) \]

3.1.5: practical way of measuring resistivity

Using an experimental configuration where the two current electrodes are placed relatively close to one another and using two potential electrodes placed between the two current electrodes, we can estimate the resistivity of our homogeneous earth. The configuration of the four electrodes for this experiment is shown below. Let the distances between the four electrodes be given by \( r_1, r_2, r_3, \) and \( r_4 \), as shown in Figure 5.

![Figure 5. Practical way of measuring resistivity](image)

The voltage recorded by the voltmeter (\( \Delta V \)) is relatively small. That is, the difference in the potential at the locations of the two potential electrodes is small. We could increase the size of the voltage recorded by the voltmeter by moving the two potential electrodes outward, closer to the two current electrodes. For a variety of reasons, some related to the reduction of noise and some related to maximizing the depth over which our measurements are sensitive, we will typically not move the potential and current electrodes close together. Thus, a very sensitive voltmeter must be used. In addition to having large impedance, voltmeters need to be able to record voltage differences down to mV (10^{-3} volts). If the potential electrodes were moved closer to the two current electrodes, larger voltages would be recorded. For a variety of reasons, however, we will typically not do this in the field.

Knowing the locations of the four electrodes, and by measuring the amount of current input into the ground, \( i \) and the voltage difference between the two potential electrodes, \( \Delta V \), we can compute the resistivity of the medium, \( \rho \), using the following equation.
\[
\rho_a = \frac{2\pi \Delta V}{i} \left[ \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4} \right]
\] (15)

In this particular case, regardless of the location of the four electrodes, \( \rho_a \) will be exactly equal to the resistivity of the medium. The resistivity computed using the equation given above is referred to as the \textit{apparent resistivity}. We call it the apparent resistivity for the following reason. We can always compute \( \rho_a \), and we only need to know the locations of the electrodes and measure the current and voltage. If, however, the Earth does not have a constant resistivity (that is, if the resistivity varies with depth or horizontally), the resistivity computed by the above equation will not represent the true resistivity of the earth. Thus, we refer to it as an apparent resistivity.

As a final caveat, as written above, the difference between the apparent and the true resistivity of the medium is not a function of any noise that might be associated with the measurements we are attempting to record. The difference, rather, comes from the fact that our measurement, in some sense, averages the true resistivities of some region of the earth, yielding an apparent resistivity that may or may not represent the true resistivity at some point within the earth.

\subsection*{3.1.6 Sources of Noise}

There are a number of sources of noise that can affect our measurements of voltage and current from which we will compute apparent resistivities.

- \textit{Electrode Polarization} - A metallic electrode, like a copper or steel rod, in contact with an electrolyte other than a saturated solution of one of its own salts, like ground water, will generate a measurable contact potential. In applications such as SP, these contact potentials can be larger than the natural potential that you are trying to record. Even for the DC methods described here, these potentials can be a significant fraction of the total potential measured.
For DC work, there are two possible solutions.

1. Use no polarizing electrodes. These are electrodes that contain a metallic conducting rod in contact with a saturated solution of its own salt. Copper and copper sulfate solutions are commonly used. The rod and solution are placed in a porous ceramic container that allows the saturated solution to slowly leak out and make contact with the ground. Because these solutions are rather environmentally unfriendly, and because the method described below is easy to employ, these so-called porous pot electrodes are rarely used in DC work. They are, however, commonly used in SP and IP surveys.

2. A simple method to avoid the influence of these contact potentials is to periodically reverse the current flow in the current electrodes or use a slowly varying, a few cycles per second, AC current. As the current reverses, the polarizations at each electrode break down and begin to reverse. By measuring over several cycles, robust current and voltage measurements can be made with negligible polarization effects.

- **Telluric Currents** - Naturally existing currents flow within the earth. These currents are referred to as telluric currents. The existence of these currents can generate a measurable voltage across the potential electrodes even when no current is flowing through the current electrodes. By periodically reversing the current from the current electrodes, or by employing a slowly varying AC current, the effects of telluric currents on the measured voltage can be cancelled.

- **Presence of Nearby Conductors** - Electrical surveys cannot be performed around conductors that make contact with the ground. For example, the presence of buried pipes or chain-linked fences will act as current sinks. Because of their low resistivity, current will preferentially flow along these structures rather than flowing through the earth. The presence of these nearby conductors essentially acts as electrical shorts in the system.

- **Low Resistivity at the Near Surface** - Just as nearby conductors can act as current sinks that short out an electrical resistivity experiment, if the very near surface has a low resistivity; it is difficult to get current to flow more deeply within the earth. Thus, a
highly conductive* near-surface layer such as a perched water table can prevent current from flowing more deeply within the earth.

- **Near-Electrode Geology and Topography** - Any variations in geology or water content localized around an electrode that produce near-surface variations in resistivity could greatly influence resistivity measurements. In addition, rugged topography will act to concentrate current flow in valleys and disperse current flow on hills.

- **Current Induction in Measurement Cables** - Current flowing through the cables connecting the current source to the current electrodes can produce an induced current in the cables connecting the voltmeter to the voltage electrodes, thereby generating a spurious voltage reading. Keeping the current cables physically away from, a meter or two, the voltage cables can minimize this source of noise.

### 3.1.7 DC Resistivity Equipment

The equipment required for DC resistivity surveying consists of nothing more than a source of electrical current, an ammeter, a voltmeter, some cable, and electrodes. Given the nature of the measurements that we are making, however, there are some considerations that must be taken into account given the equipment used to perform the measurements.

- **Current Source** - A source of DC current is required. In general, batteries are not capable of producing the DC currents required, so that if a pure DC source is used, it has to be produced by a portable electric generator. If, as is commonly done to eliminate the effects of electrode potentials and telluric currents, a slowly varying AC current is used, portable, battery driven sources can be employed for DC resistivity surveys commonly used in engineering and environmental applications.

- **Ammeter** - A simple ammeter (a device for measuring electrical current) can be used. The only constraint is that the meter be capable of measuring amperage from a few mile Amperes to about 0.5 Amperes. Many of the modern instruments are regulated such that the user determines the amperage input into the ground and the instrument attempts to deliver it. If the instrument can not deliver the specified amperage, either because the subsurface is too resistive or the electrodes are too far apart, the instrument warns the user.
• **Voltmeter** - A simple voltmeter can also be used. To avoid problems with contact potential, a voltmeter with very high impedance, above 500,000 Ohms, should be used. The voltmeter must also be capable of measuring voltages from a few millivolts to a few volts.

• **Electrodes** - To avoid problems associated with electrode potentials sophisticated electrodes known as porous pots can be used. But, because spurious electrode potentials can be mitigated through the use of a slowly varying AC source, these electrodes are not commonly used for DC resistivity measurements. If the conditions in the survey are extremely dry and contact between the electrode and the ground cannot be maintained, one might consider using porous pots. For DC resistivity surveys, the most commonly used electrodes are nothing more than aluminum, copper, or steel rods about two feet in length. These rods are driven into the ground and connected with cables to the current source or the voltmeter. Under dry conditions, contact between the rod and wetting the ground surrounding the electrode can enhance the ground.

• **Cables** - To connect the electrodes to the various electrical components, cables must be employed. These cables are typically nothing more than insulated wires with stranded, copper-cored conductors. Although long cable lengths may need to be employed, given the high resistivity of the ground, resistance in the cables is typically negligible. A more significant problem is current induction in the cables used to make the voltage measurement from the current flowing in the cables going to the current electrodes. This source of noise is easily avoidable by simply keeping the voltage cables at a distance (a few feet) from the current cables. For easy deployment, cables are usually stored on reels.

### 3.1.8 Survey Types: Soundings and Profiles

Thus far we have begun to see how geologically relevant structure can affect electrical current flow and measurements of voltage at the Earth's surface. We've described how depth variations in resistivity can be detected by increasing current electrode spacing by estimating apparent resistivities for various current electrode spacing. We have not, however, described the specific field procedures used in resistivity surveying. Before describing these
procedures, there is an important point to note about the geologic structures considered thus far. Notice that the resistivity method represents the first method that we have described which can detect depth variations in a geologically relevant parameter. For example, if we conducted gravity or magnetic surveys atop structures that varied in density or magnetic susceptibility only with depth, we would observe no spatial variation in the Earth's gravity or magnetic fields. Thus, these methods are insensitive to changes in density and magnetic susceptibility that occur solely with depth.

- **Resistivity Soundings** - As we've already shown, the resistivity method can detect variations in resistivity that occurs solely with depth. In fact, this method is most commonly applied to look for variations in resistivity with depth. Surveys that are designed to determine resistivity variations with depth above some fixed surface location are referred to as *resistivity soundings*. An example of a problem for which one might employ resistivity soundings is the determination of depth to the water table. When doing resistivity-sounding surveys, one of two survey types is most commonly used. For both of these survey types, electrodes are distributed along a line, centered about a midpoint that is considered the location of the sounding. The simplest in terms of the geometry of electrode placement is referred to as a *Wenner* survey. The most time effective in terms of fieldwork is referred to as a *Schlumberger* survey.

For a Wenner survey, the two current electrodes and the two potential electrodes are placed in line with each other, equidistant from one another, and centered on some location as shown below.

**Figure 6. The arrangement of Wenner array**
The apparent resistivity computed from measurements of voltage, $\Delta V$, and current, $i$, is given by the relatively simple equation shown above. This equation is nothing more than the apparent resistivity expression shown previously with the electrode distances fixed to $a$. To generate a plot of apparent resistivity versus electrode spacing, from which we could interpret the resistivity variation with depth, we would have to compute apparent resistivity for a variety of electrode spacing, $a$. That is, after making a measurement we would have to move all four electrodes to new positions.

For a Schlumberger survey, the two current electrodes and the two potential electrodes are still placed in line with one another and centered on some location, but the potential and current electrodes are not placed equidistant from one another.

Figure 7. The arrangement of Schlumberger array

The apparent resistivity computed from the measurement of voltage, $\Delta V$, and the current, $i$, is given by simple equation shown below.

$$\rho_a = 2\pi a \frac{\Delta V}{i}$$

(16)

$$\rho_a = \frac{\pi \left( s^2 - a^2 \right)}{a} \frac{\Delta V}{i}$$

(17)
Resistivity Profiles - Unlike soundings, profiles employ fixed electrode spacing, and the center of the electrode spread is moved for each reading. These experiments thus provide estimates of the spatial variation in resistivity at some fixed electrode spacing. Surveys that are designed to locate lateral variations in resistivity are referred to as resistivity profiles. An example of a problem for which one might employ resistivity profiles is the location of a vertical fault.

3.1.9 The principle of Equivalence and suppression

In actual application of various interpretation methods to a particular field problem, limitations are set by maximum distance from the current source to which the electric field due to surface inhomogeneities. Furthermore, all measurements have finite accuracy. On account of all this causes, widely different resistivity distribution may lead to apparent resistivity curves, which, although they are not identical, cannot be distinguished in practice. This introduces ambiguity in the interpretation.

Mathematical formulation of two simple types of equivalence can be easily obtained. If we consider, for example, a relatively thin layer sandwiched between two layers whose resistivities are much larger than the sandwiched layer. Then the current flow in the earth will then tend to concentrate into the middle layer. The resistance of the elementary block of length, \( l \) and cross section, \( h \) & \( m \) to which a current flow is

\[
R = \frac{\rho}{h} \left( \frac{\Delta l}{\Delta m} \right)
\]  

(18)

and this will be unaltered if we have increase \( \rho \) and at the same time increase in the same proportion. Thus all such middle layers for which the ratio \( h/\rho \) is the same are electrically equivalent.

On the other hand, if the resistivity of the middle layer is much larger than that of the layers on either side of the middle layer, the electric current will tend to avoid it and take the shortest rout to the lower layer. The lines of the current flow will be almost perpendicular to the layer. The resistance of the elementary block will be
\[ R = \rho \left( \frac{h}{\Delta A} \right) \] (19)

where, \( A \) is the cross section. In this case, all layers for the product \( h \rho \) are the same are electrically equivalent, so that, \( h \) and \( \rho \) can not determined uniquely.

### 3.1.10 Electrical imaging / Tomography

Electrical imaging (EI) is a survey technique for developing continuous resistivity profiles of the subsurface. Features that will cause variations in the resistivity include changes in the type of soil or rock, voids, and changes in the moisture content of the subsurface.

Stainless steel electrodes are placed into the ground and cables fitted with addressable connections attached to them. The electrodes are attached to a control and resistivity measurement system, which collects high-density data, both laterally and with depth, typically in less than two hours per survey line.

The resulting data set is a pseudosection of apparent resistivity versus apparent depth beneath the survey line. These data are then run through a computer program that uses a non-linear least squares optimization technique to determine a two-dimensional resistivity model for the subsurface (Loke & Barker 1995; 1996). This geological model is used in conjunction with all the other geophysical and physical data to help interpret the structure the subsurface.
The SYSCAL-Type Resistivity Imaging Unit.

The SYSCAL resistivity imaging range of \textit{IRIS INSTRUMENTS} are fully automatic resistivity meters designed for intensive exploration of the ground with DC electrical methods. They allow studying the variations of resistivity with respect to depth (vertical electrical sounding) together with the lateral variations observed along a profile (electrical profiling). They also allow computing the chargeability (induced polarization) of the ground. An additional advantage in these instruments is that self potentials are also measured along with the resistivity measurements.

The instrument used in this survey is the SYSCAL R1 Plus Switch 72, 5 m spacing, i.e. the instrument uses 72 electrodes to a maximum electrode separation of 5 m giving a single profile length of 355 meters in the main sequence. There is an option with a roll-along sequence whereby 18 of the electrodes are moved forward for an additional distance of 90 meters.

The instrument is able to store in memory all the parameters like current, voltage, geometrical parameters, station number. A serial link permits to transfer the data to a PC for data processing and interpretation. The figure below give a typical apparent resistivity pseudo section and in inverted/interpreted true resistivity section when the system is used with 72 electrodes 5 m spacing.
Figure 9. A typical apparent resistivity pseudo section and true resistivity model section of the ground obtained with the SYSCAL Imaging unit.

By adding the roll-along sequence on either side of the section shown above, as required, it is possible to get a complete picture of the ground under the survey area. The instruments are, therefore, specially designed for medium depth exploration (in excess of 60 meters) and can be used in many civil engineering and groundwater projects to solve problems such as depth to bedrock determination, weathered bedrock areas localization, clay-gravel determination, shallow aquifer depth and thickness determination, salinity control and pollution monitoring.

Electrode configurations

There are different electrode arrangements with different applications used in electrical resistivity imaging survey. The most commonly known are Wenner ($\alpha$, $\beta$ and $\gamma$), Dipole-Dipole, Pole-Dipole, pole-pole and Wenner-Schlumberger arrays. The basic resistivity measuring technique is just similar to the conventional principles. Basically, four electrodes are required; two for current injection and two electrodes for potential measurement. The only difference with the conventional arrays is in the case of multi-electrode arrays, a large number of electrodes are spread along the survey line with constant electrode spacing. Each
array has their own advantages and drawbacks in data acquisition and processing works. But one might has better sensitivity and resolution power for vertical as well as lateral structural variations than the other. For instance, Wenner array in multi-electrode mode has good resolution power for horizontal structure having vertical variations but weak for horizontally variable geological structures. This array also characterized by less depth penetration and high signal strength. This is why because signal strength is inversely proportional to the geometric factor. The geometric factor of Wenner array \((=2\pi a)\) is the smallest of other array types.

Note that as the electrode spacing increases, the number of measurements decreases. The type of array used also matters the number of measurements to be obtained. The Wenner array gives the smallest number of possible measurements compared to the other common arrays used in 2-D surveys. The survey procedures followed in the pole-pole array are similar to that used for the Wenner array, whereas, survey procedures of dipole-dipole, Wenner-Schlumberger and pole-dipole arrays are slightly different. Wenner-Schlumberger array which is the emphasis of this paper will be discussed more.

**Wenner-Schlumberger array**

Among the multi-electrodes arrays, the Wenner-Schlumberger array has better resolution and high sensitivity for vertical and horizontal geological variations. The Wenner-Schlumberger array is a technique where different combinations of an electrode spacing ‘a’ and a factor ‘n’ can be used. The factor ‘n’ is the ratio of the distance between the C₁-P₁ (or P₂-C₂) electrodes to the spacing between the P₁-P₂ potential pair. It has value 1 for the first sequence of measurement and 2 for the next, and so on.

Wenner-Schlumberger is a recent array crossbred from the Wenner and Schlumberger arrays for better 2-D imaging survey. The classical Schlumberger array is one of the most commonly used array for resistivity sounding surveys. On the other hand, Wenner array is the successful procedure for profiling survey. The spacing between adjacent electrodes is ‘a’. The first sequence of measurements is carried out, this array, with electrode spacing of ‘1a’. In this sequence of measurement, the first measurement is made with electrodes 1, 2, 3 and 4. In this case, electrodes 1 and 4 are used as the current electrode C₁ and C₂ respectively, and electrode 2 and 3 act as the potential electrode P₁ and P₂ respectively. For the second measurement, electrodes number 2, 3, 4 and 5 are used for C₁, P₁, P₂ and C₂ respectively. This is repeated down the line of electrodes until the last set of electrodes, 69, 70, 71 and 72, are used for the last measurement with ‘1a’ spacing. For instance, a system of measurement with 72 electrodes will have \((72 − 3) = 69\) possible measurements with ‘1a’ spacing. This configuration has just the classical Wenner array.
The next sequence of measurement is made by choosing a current electrode spacing e to be ‘2a’ and the spacing between two potential electrodes is set to be ‘a’ (may be a fractional number) to get Schlumberger depth of investigation. In this case ‘n’ factor have a value 2.

First measurement is made using electrodes 1, 3, 4 and 6, and then the second measurement uses electrodes 2, 4, 5 and 7 for C₁, P₁, P₂ and C₂ respectively for each. But normally only one either of the two trends is taken. This process is repeated down the line until electrodes 67, 69, 70 and 72 are used for the last measurement with spacing ‘2a’. The same process is repeated for measurements with ‘3a’, ‘4a’, ‘5a’, ‘6a’ and so on. To understand more, a good figurative illustration of Wenner-Schlumberger electrode configuration is presented in the Figure (10) below.

Figure 10. The Wenner-Schlumberger ‘2-D’ imaging array procedure.

Wenner-Schlumberger array is quite sensitive to both horizontal and vertical structures and is better applicable for areas where both types of geological structures are expected. The signal strength for this array is smaller than that for the Wenner array, but it is higher than the dipole-dipole array. The median depth of investigation (zₑ) for the Wenner – Schlumberger array is moderately deeper than the dipole-dipole and Wenner arrays.
3.2 DATA ACQUISITION AND PROCESSING

3.2.1 Data acquisition

Instrument used and field procedure

2-D resistivity imaging:

Two-dimensional resistivity surveys were conducted using the SYSCAL R1 PLUS Switch-72 multinode resistivity imaging unit. The field layout was designed to use the main sequence and then roll along technique for survey lines 1 and 2, since the two survey lines were very long. This roll-along method has advantage to remove the data gap created when two (or more) main sequence were deployed in sequence. Therefore, roll along method is better than to use another main sequence which create undisputed gap between the two sequences.

Survey lines were selected based on the topography of the area so that the maximum depth of investigation could show the potential source of ground water aquifer. Figure shows the 90m resolution Digital Elevation Model of the study area.

Figure 11. DEM of Repi area enclosing the waste disposal site
GPS coordinates and the elevations of end points and junction points for each survey lines are tabled as below. The extended profiles are indicated by the roll along measuring points.

<table>
<thead>
<tr>
<th>Survey-Line numbers</th>
<th>Measuring points</th>
<th>coordinate</th>
<th>Northing</th>
<th>Easting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey Line-1</td>
<td>South West end</td>
<td>08°58'229”</td>
<td>38°42'452”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Box-1</td>
<td>08°58'470”</td>
<td>38°42'474”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Main center</td>
<td>08°58'510”</td>
<td>38°42'505”</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roll along-1</td>
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<tr>
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<td></td>
<td>North East-end</td>
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<td>VES-3</td>
<td>08°58'227”</td>
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Table 2. GPS locations of profile lines ,VES points, and some points along the profiles of the survey area.
Survey profile 1 consists of one main sequence and one roll along sequence covering 450 meters and is located at the western edge of the landfill (figure 12).

Survey profile 2 is located at the Southern-edge of the landfill (figure 12) and is the longest profile line consisting of one main sequence and two roll-along sequences and has a total length of 540 meters.

Survey profile 3 is located on the Eastern edge of the landfill and consists of one main sequence covering a length of 360 meters.

The equipment for the survey consist of the main instrument (in a box), four specially designed fiber optic cable reels, 72 short stainless steel electrodes, 72 connectors and two connecting boxes. In addition to the two internal rechargeable batteries, the instrument requires an external 12 V (60 ampere-hour) normal car battery while working in the tomography mode. The main instrument and all ancillary equipment are light weight and easy to transport.

This automated resistivity system perform stationary surveys with the electrode cable laid along the horizontal line. It features an internal switching board for 72 electrodes and an internal 200W power source. Four strings of cables with 18 electrode take-out each 5 m spacing are connected to electrodes plugged in to the ground. The output current is automatically adjusted to optimize the input voltage values and ensure the best measurement quality. Its typical resistivity accuracy is 0.5% and performs noise reduction through continuous stacking selectable from 1 to 255 stacks. In the resistivity meter itself are located the relays which ensure the switching of those electrodes according to a sequence of reading predefined and stored in the internal memory of the unit. The various combinations of transmitting (A, B) and receiving (M, N) pairs of electrodes construct the mixed profiling section. In the field data analysis was conducted as it allows on-the-spot determination of the optimum survey parameters and an assessment of the degree of success of the instrument (Max et al 1995).

ELECTRE II software permits to load a preset sequence of measurement (Schlumberger-Wenner, in this case) into the internal memory of the resistivity meter. This program displays the theoretical depth of penetration reached by the sequence (65m in this case).

The acquired data is transferred from the SYSCAL Unit to PC by PROSYS software, which also performs an automatic filtering such as noise elimination and topographic correction. After performing all necessary correction and filtering under PROSYS software environment,
data are exported to RES2DINV Inversion software which performs pseudo-section inversion to true resistivity 2D section.

**Vertical electrical sounding:**

Three vertical electrical sounding (VES 1, VES 2 and VES 3) were also carried out at the landfill site using the same IRIS SYSCAL R1 Plus switch. The VES points were sited on the Western edge of the landfill (figure 12) and ran parallel to the imaging line 2 but ran perpendicular to the imaging lines 1 and 3. A maximum AB/2 distance of 750m and MN/2 distance of 45m were occupied. The VES points are oriented nearly along North west to South east direction. The station separation between VES-1 and VES-2 is about 230m, between VES-2 and VES-3 is 400m. The profile consisted of the 3 VES points is parallel to image line 2.

Current was injected into the ground using two current electrodes, A and B, placed a distance L (AB) apart; and the potential drop that occurs between two other electrodes, M and N placed near the center of the current electrodes was measured. The current electrode separation, L, is progressively increased in steps so as to increase the depth of investigation, and at each step the measured current and potential reading are used to obtain the apparent resistivity of the ground. A record of the variation of the apparent resistivity of the subsurface with depth for the survey was obtained using Schlumberger field array.

The sounding curve which is a log-log plot of the apparent resistivity versus half the distance between the current electrodes (AB/2) is readily plotted in the field so that any erroneous measurements could be detected and taken care of.
Figure 12. Sketch of the Location of the Dump Site Where the Study was Carried Out showing Distribution of VES points and locations of imaging survey lines.
3.2.2 Data processing and presentation

2D - Resistivity Imaging:

The measured 2D resistivity imaging data were processed using the RES2DINV inversion software (Loke, 1999). This program automatically subdivide the subsurface into a number of blocks and then uses a least –squares inversion scheme to determine the appropriate resistivity values for each blocks so that the calculated apparent resistivity values agrees with the measured apparent resistivity values from the field survey.

The results are displayed as inverted model resistivity sections versus depth of the subsurface along the three profiles (Figure 13).

Vertical Electrical Sounding (VES) Data:

3 VES data with a maximum AB/2 separation of 750 m were obtained and the raw resistivity data was entered to the excel sheet and prepared for other software. The mapping software used to prepare the pseudo-depth sections is known as SURFER-7 and the one dimensional modeling of the VES was done using resistivity modelling softwares Resix-IP and Winresist. The values of the modelled VES (resistivity and depth of each layer beneath the VES points) were used in AutoCAD to make the geo-electric section.

The results of resistivity sounding survey are presented in the form of apparent resistivity pseudo-sections and in terms of the resistivities, thicknesses and depths of the geo-electric section for the three VES positions.
CHAPTER FOUR

4. INTERPRETATION AND DISCUSSION OF RESULTS

4.1 2D - Resistivity Imaging:

As discussed in the preceding section, the measured 2D resistivity imaging data were processed using the RES2DINV inversion software (Loke, 1999).

The results are displayed as inverted model resistivity sections versus depth of the subsurface along the three profiles (Figure 13). The pseudo sections, consistently show similar structures with variation on the detail level with depth and were visually inspected to delineate areas of anomalously high or low resistivity related to subsurface structures.
Figure 13: Interpreted 2-D pseudo sections of the survey profiles (1-3)
Survey Profile 1: This profile is located along the western edge of the landfill and as such runs in a SW-NE direction (Figure 13). Low resistivity zones (<15 Ωm) were isolated near the surface with depths of between 1.25m to 9.94m. These are interpreted to be contaminant leachate plume mixed with decomposing waste which indicates the contamination of the surrounding soil. Underlying these low resistivity there is zone of relatively high resistivities (>942 Ωm) to the South West of the section with depths between 9.94m to 49.9m. This was interpreted to be fresh basalt rock.

In the middle of the section, weak zones of low resistivities are observed. These weak zone can serve as a path for the downward movement of leachate to the groundwater.

About 300m from the SW end of the section at depth of 26.2m there exists oval shaped bluish zone. This structure indicates the presence of weak zone and downward movement of low-resistivity material which may indicate ionized fluid from the landfill which has penetrated the underground water. This bluish zone is the ground water.

Survey Profile 2: Profile 2 is located at the Southern edge of the landfill and also perpendicular to profile 1 (Figure 12). There exists an isolated zones of high resistivity (>40 Ωm) to the South West of the section with depths between 9.94m to 26.2m. The structure match with the high resistivity structure that was delineated in survey profile 1 indicating the continuity of the structure. This same structure was identified in the second layer of VES 1 as high resistivity layer.

Low resistivity zones were isolated at the South East of the section near the surface between 1.25m to 9.94m.

There exists a weaker zone of low resistivity in the middle of the section in all depth. This was interpreted as highly weathered and fractured basalt. The shape of this structure indicates the path for the downward movement of contaminating fluid.

Bluish zone identified at south east end of the section at depth grater than 57.4m is interpreted as groundwater.

Survey Profile 3: Profile 3 is located at the Eastern edge of the landfill parallel to profile 1 and perpendicular to profile 2 (figure 12). Low resistivity zone was isolated near the surface with depth of between 1.25m to 17.3m at South East end of the section which is continuation of low resistivity contaminate leachate that was delineated in profile 2. This is because of the
leachate from a small stream that passes down to the South near the Eastern edge of the landfill. The effect of this highly polluted small stream has been clearly seen in the second and third survey profiles.

Good aquifer structures exist at depth greater than 26.2m. This impermeable layer can prevent the vertical migration of the leachate from the landfill.

4.2 Vertical Electrical Sounding (VES) Data:

The results of resistivity sounding survey are presented in the form of apparent resistivity pseudo-sections, for the purpose of qualitative assessments and vertical geo-electric section, permitting quantitative interpretations.

4.2.1 Apparent resistivity pseudo-section along survey Profile 2

As shown in figure 12, survey profile 2 is made by aligning three vertical electrical soundings, namely VES-1, -2 and -3, in a SW-SE direction.

From the pseudo-section, figure 14, the top most portion of the section generally characterized by low apparent resistivity in the range of (25-55 ohm-m). Between VES-2 and VES-3 this low resistivity value slowly decreases and extends to a large depth and seems to be due weathered and fractured volcanic rocks. At the location near to VES 2, high resistivity values are viewed (75-95 ohm-m). These patches may reflect fresh basalt rock and match with the resistive zone that was delineated in image survey 2. At bottom in the location of VES -3 low resistivity values (< 25 ohm-m) surrounded by relatively resistive portion on the left also may a reflection of downward movement of leachate from the small stream near VES 3.
The detailed analysis of the apparent resistivity data beneath the Three VES points along line 2 (Figure 15) resulted in the production geo-electric section. The section provides composite quantitative information on the distribution of litho-electrical parameters at depth.

### 4.2.2 Geoelectric Section along line 2

The geoelectric section has been constructed using the layer parameters resulted from inversions of the data from the VES’s (Figure 16) and show four major layers and a very small depth (thin) top layer. The first layer is characterized by resistivity range of 6-9 Ohm-m and the thickness variation are from 1.7-2.5m and may be attributed to the top soil mixed with decomposing solid waste.

The second layer has resistivity values ranging from 22 to 42 ohm-m. The thickness variation is from 19-28 m. This layer likely reflects highly weathered and slightly fractured ignimbrite. A resistive layer is detected at the location of VES 1 (72.9 Ohm-m) and most probably represents fresh basaltic rock.

The third layer is marked by high resistivity values ranging from 102 to 308 ohm-m. The resistivity of this layer shows a decreasing pattern near VES 3. The thickness variation is from 44-89 m. This layer likely reflects slightly fractured basalt.
From geoelectrical point of view, the fourth layer in the sequence seems to be more promising for its ground water potential. The resistivity signature, within this section, ranges from 15 to 20 Ohm-m and is thought to be a response of the water bearing formation. The likely litho-compositional interpretation is that; this layer may comprise highly weathered and highly fractured scoraceous trachytic basalt.
Figure 15:  Resistivity sounding curves along line 2

Figure 16:  Geoelectric section along line 2
CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusion

The results of the combined investigation of leachate plume contamination of the groundwater aquifer system using 2-D resistivity and VES data is quite revealing. It shows that the surrounding groundwater around the landfill may have been contaminated.

Weak zone identified in the imaging survey line-1 and -2 revealed that there is a chance for downward movement of leachate to the groundwater.

A resistive impermeable layer was identified and mapped around the landfill in image line 3 at depth between 17m-60m. This impermeable layer may prevent the downward and movement of the leachate.

The results of 2-D DC resistivity imaging with those of the VES measurements, compares favourably well how the groundwater resource around the landfill is exposed to contamination.

5.2. Recommendation

There is a need to monitor leachate migration process to safeguard the groundwater resources. It is strongly recommended that a thorough study of any waste disposal site be done before any operation so as to know whether the aquifer is naturally sealed or not. And the presence of impermeable layer above the aquifer must be sought for before choosing any site for waste disposal.

The usage of the Repi waste disposal site which is without a geologically permeable ground like clay above the groundwater aquifer must be discouraged.

More detailed integrated studies involving geochemistry, drilling of monitory boreholes, and chemical analysis of water samples are recommended to ascertain the nature of pollutants.
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