DETERMINATION OF THE EXTEND OF GROUNDWATER CONTAMINATION WITHIN THE VICINITY OF KIPKENYO DUMPSITE IN ELDORET MUNICIPALITY, UASIN GISHU COUNTY, KENYA

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DECLARATION

Declaration by the student

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DEDICATION

I dedicate this thesis to my wife Irene Barno and daughters' Sharon and shanice for their unwavering encouragement and prayers throughout my studies.

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I extend my deepest gratitude to the Almighty God for His unfailing love, care, protection and wisdom that have guided me throughout this research journey. His grace has been my source of strength and perseverance, enabling me to overcome challenges and complete this study successfully.

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ABSTRACT

The increasing demand for groundwater as a primary source of water supply has raised concerns about its vulnerability to contamination, particularly in areas surrounding unmanaged dumpsites. Kipkenyo Dumpsite in Eldoret Municipality, Uasin Gishu County, Kenya, presents a potential risk of leachate infiltration into groundwater, threatening water quality and public health. This study aimed to evaluate the impact of leachate contamination in groundwater quality by integrating geoelectrical resistivity surveys and physicochemical analyses. The specific objectives were to determine the physicochemical characteristics of groundwater contamination, map the spatial distribution of leachate contaminant plumes using geoelectrical methods, analyze the vertical and horizontal flow dynamics of leachate, and assess the hydrogeological and environmental factors influencing leachate migration and contaminant transport. This study was anchored in Dacy's Law developed Darcy's Law in 1856 which is based on experiments that studied the flow of water through sand filters. The study was conducted in the Kipkenyo Dumpsite vicinity, focusing on shallow wells and boreholes used by the local community. A descriptive research design incorporating both geophysical and laboratory analyses was adopted. The sample size comprised groundwater samples were collected from selected wells, with sampling points determined through stratified random and purposive sampling techniques. Physicochemical parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), nitrates, chlorides, phosphates, sodium and potassium, were analyzed using standard laboratory procedures. The geoelectrical resistivity survey employed two-dimensional (2D) and three-dimensional (3D) resistivity imaging to map subsurface contamination zones. Data analysis involved statistical techniques such as one-way ANOVA to assess spatial variations in water quality parameters, and geophysical inversion modeling to interpret resistivity variations indicative of leachate infiltration pathways. Results indicated that groundwater quality parameters varied across different wells, with pH levels ranging from 5.94 to 11.70, electrical conductivity from 42 to 113 μS/cm, total dissolved solids from 21 to 57 ppm, nitrate from 0.01 to 0.67 mg/L, chloride from 1.90 to 4.40 mg/L, phosphate from 0.26 to 1.04 mg/L, sodium from 5 to 10 mg/L, and potassium from 6 to 58 mg/L, suggesting potential leachate contamination. Further, the findings revealed significant variations ($p<0.05$) in physicochemical parameters across different wells, with some locations exhibiting elevated ion concentrations linked to leachate percolation. While most parameters remained within World Health Organization (WHO) and National Environment Management Authority (NEMA) limits, localized areas displayed elevated levels of pH and ion concentrations, indicating contamination hotspots. Geoelectrical resistivity imaging identified subsurface zones with low resistivity values, suggesting potential leachate infiltration pathways and groundwater contamination zones. The findings further indicated that groundwater contamination was not uniform across the study area, with hydro geological conditions influencing contaminant transport and distribution. The study concluded that leachate infiltration from Kipkenyo Dumpsite may pose a potential risk to groundwater quality, with localized contamination requiring continuous monitoring. The study recommended the implementation of proper waste management strategies, regular groundwater quality assessments and the establishment of protective buffer zones to mitigate contamination risks. Additionally, future research should incorporate seasonal variations to better understand leachate dynamics under different climatic conditions.

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ABBREVIATIONS AND ACRONYMS

ABEM:	American Board of Emergency Medicine
APHA:	American Public Health Association
AWWA:	American Water Works Association
BOD:	Biological Oxygen Demand
CIDP:	Chronic Inflammatory Polyneuropathy
DC:	Direct Current
DO:	Dissolve Oxygen
EC:	Electrical Conductivity
EPA:	Eicosapentaenoic Acid
GDWQ:	Guidelines for Drinking-Water Quality
GoK:	Government of Kenya
HI:	Hanna Instrument
KEBS:	Kenya Bureau of Standards
NTU:	Nephelometric Turbidity Units
pH:	Hydrogen Potential
SAS:	Special Air Current
TDS:	Total Dissolved Solids
UNEP:	United Nations Environment Programme
VES:	Vertical Electrical Sounding
WHO:	World Health Organization
WRMA:	Water Resources Management Authority

DEFINITION OF TERMS

Geographic Information System (GIS) is a system designed to collect, organize, alter, evaluate, supervise, and present spatial or geographic data According to (Anderson, 2011).

EarthImager 1D software serves as an inversion modeling software application utilized for interpreting one-dimensional electrical resistivity data to unveil a layered model of subsurface geology. Additionally, it is capable of processing vertical electrical sounding (VES) data obtained through Schlumberger, Wenner, dipole-dipole, and other array configurations.

Landfill age describes the time spent depositing solid trash, which affects how quickly waste breaks down in landfills. Over time, leachate builds up in layers and becomes dangerous. Recent landfill leachate has high levels of BOD and COD, which progressively decrease in later strata (Sasane & Kote, 2020). When undesirable materials or contaminants are released into the atmosphere, they can make their way into subterranean water supplies and contaminate them, making them unfit for human use.

Shallow well is a vertical well that is dug to get water that is less than 15m deep (Okuyade, Abbey, Onyebueke, & Ibeawuchi, 2024).

Aquifer is a subterranean rock that contains water and has the ability to store and transfer groundwater (Morris, Lawrence, Chilton, Adams, Calow, & Klinck, 2003).

Flame photometry is an analytical tool used to measure the concentrations of Na^+ and K^+ in a solution.

CHAPTER ONE

INTRODUCTION

1.1 Introduction

This chapter presents the background information, statement of the problem, specific research objectives, research questions, justification, significance of findings, theoretical framework and its scope and limitations.

1.2 Background Information

Groundwater is a major source of freshwater globally, supplying approximately 36% of potable water, 42% of water for irrigated agriculture and 24% for industrial use (United Nations, 2022). It constitutes 99% of all liquid freshwater on Earth, making it an indispensable resource for sustaining human livelihoods and economic activities (Margat & Van der Gun, 2013). The global demand for groundwater has risen sharply over the years, driven by population growth, agricultural expansion and industrial development. In the last five decades, groundwater abstraction has at least tripled, reflecting the increasing reliance on this resource (K'oreje et al., 2022; Bierkens & Wada, 2019). Currently, at least 2.5 billion people depend exclusively on groundwater to meet their basic needs (K'oreje et al., 2022). Additionally, per capita groundwater use has surged from 124 m^3 in 1950 to 152 m^3 in 2021, further illustrating the growing dependence on this finite resource (Loaiciga & Doh, 2024). Despite its significance, groundwater remains poorly understood, often undervalued, mismanaged and subject to overexploitation (United Nations, 2022).

Ground water can become contaminated from natural and anthropogenic sources. Groundwater contamination is defined as the addition of undesirable substances to groundwater caused by human activities (Li et al., 2021). Many of the contaminants in groundwater are of geogenic origin as a result of dissolution of the natural mineral deposits within the Earth's crust. Elements such as iron, manganese, arsenic, chlorides, fluorides, sulfates and radionuclides can dissolve into groundwater due to geochemical interactions, while organic matter can migrate as particulate matter (Smedley & Kinniburgh, 2017). Research in India and Bangladesh has documented widespread arsenic contamination in groundwater due to natural mineral dissolution, affecting millions of people and leading to severe health issues such as arsenicosis (Shankar et al., 2014). Similarly, fluoride contamination in groundwater has been reported globally, with concentrations exceeding World Health Organization (WHO) limits, contributing to dental and skeletal fluorosis (Ali et al., 2016; Podgorski & Berg, 2022). Sulfate contamination, often linked to natural weathering of sulfate-rich minerals, has been observed in regions with high evaporite deposits, such as parts of North Africa and the Middle East (Appelo & Postma, 2005). Additionally, radionuclides such as uranium and radon are commonly detected in groundwater in areas with granitic bedrock, posing long-term carcinogenic risks (Egbueri et al., 2025). Empirical studies have also extensively documented anthropogenic sources of ground water pollution. Industrial activities contribute through the discharge of hazardous chemicals and improper waste disposal. Studies have shown that heavy metals such as lead (Pb), cadmium (Cd), chromium (Cr), and arsenic (As) infiltrate aquifers due to leachate from industrial waste dumps and improper wastewater management (Evans, 2019; Awoyemi, 2024; Jagaba et al., 2024). Research in China by Zhang et al. (2019) found that over 60% of groundwater near industrial zones exhibited contamination levels exceeding World Health Organization (WHO) standards due to chemical effluents. Similarly, studies in India and Nigeria have linked industrial waste discharge to increased concentrations of toxic metals in groundwater, affecting both drinking water quality and agricultural productivity (Evans, 2019; Izah et al., 2016; Bhutiani et al., 2016).

Agricultural practices, including excessive use of fertilizers, pesticides, and livestock waste, are major contributors to groundwater pollution. Nitrate contamination, in particular, has been widely reported due to agricultural runoff and leaching of nitrogen-based fertilizers (Shukla & Saxena, 2020). Empirical studies in the United States and Europe have demonstrated that regions with intensive agriculture exhibit nitrate levels in groundwater exceeding safe drinking limits (Hamlin et al., 2022). Research in Kenya by K'oreje et al. (2022) found that nitrate concentrations in agricultural zones surpassed WHO-recommended limits, leading to concerns over drinking water safety. Furthermore, pesticide residues have been detected in groundwater, with studies in Bangladesh confirming the persistence of organochlorine and organophosphate pesticides in aquifers (Rahman et al., 2020).

Poorly managed domestic and municipal waste significantly contributes to groundwater contamination. Leachate from open dumpsites, landfill seepage, and septic tank effluents introduce biological and chemical pollutants into groundwater sources (Ali et al., 2020). Studies in sub-Saharan Africa indicate that uncontrolled waste disposal is a primary cause of microbial contamination in urban groundwater supplies, leading to increased incidences of waterborne diseases such as typhoid and cholera (Adelana et al., 2008).

Mining operations, particularly those involving heavy metal extractions pose serious threats to groundwater quality. Empirical evidence from South Africa and Ghana demonstrates that acid mine drainage (AMD) significantly elevates sulfate, iron, and heavy metal concentrations in groundwater systems (Abiye & Ali, 2022). In Ghana, research by Owusu et al. (2024) found that artisanal gold mining contributed to mercury contamination in groundwater, with severe health implications for local communities relying on boreholes for drinking water. Further, fluoride contamination in the Rift Valley region has been extensively documented, with concentrations exceeding WHO guidelines, causing dental and skeletal fluorosis (Gevera & Mouri, 2018; Mwiathi et al., 2022).

In Kenya, groundwater contributes in meeting the water demand, particularly in urban and peri-urban areas where surface water sources are unreliable or insufficient (K'oreje et al., 2022). However, groundwater resources are increasingly threatened by contamination from various sources, including industrial effluents, agricultural runoff, and municipal solid waste leachate (Kinuthia et al., 2020). The rising population and rapid urbanization have exacerbated waste management challenges, leading to the proliferation of uncontrolled dumpsites, which are major contributors to groundwater pollution (Mogaka et al., 2021). Leachate is a highly poisonous liquid formed when water permeates solid waste in landfills and open dumps, dissolving inorganic and organic contaminants, including heavy metals, nutrients, and pathogens (El-Saadony et al., 2023; Alao, 2024). As leachate permeates into the soil, it is able to make its way into underlying groundwater aquifers, highly contaminating water and posing extreme health risks to adjacent communities (Kamboj et al., 2020). In Kenya, open dumpsites are a common waste disposal method due to their low cost, but they lack proper containment mechanisms, leading to severe groundwater contamination (Calvo, 2005). Several studies have documented the impact of leachate contamination of groundwater quality across Kenya. Karimi et al. (2023) found that groundwater sources in informal settlements of Kisumu contained coliform bacteria due to leachate infiltration from poorly managed waste disposal sites. Similarly, research by Kinuthia et al. (2020) in Nairobi revealed elevated levels of lead, mercury, and cadmium in groundwater near industrial zones, attributing the contamination to leachate from adjacent dumpsites and industrial runoff. In Mombasa, Mwaguni, (2002) reported that improper solid waste disposal contributed to high concentrations of nitrates and heavy metals in groundwater, affecting its suitability for human consumption. Thus, monitoring and implementation of effective management strategies are key in safeguarding groundwater resources as well as enhancing sustainable water supply.

1.3 Statement of the problem

Groundwater contamination in Kenya is a growing environmental and public health concern, particularly in rapidly urbanizing areas where unregulated waste disposal is common. Municipal Solid Waste (MSW) from residential, commercial, industrial and institutional sources is often disposed of in open dumpsites, leading to the generation of leachate. This leachate percolates through soil layers and reaches groundwater reservoirs, posing a significant threat to water quality. When groundwater is contaminated with hazardous substances beyond permissible limits, it becomes unfit for human consumption and other essential uses. Poor solid waste management in Kenya has contributed to widespread groundwater pollution, particularly in urban and peri-urban areas where open dumpsites serve as the primary waste disposal method.

The Kipkenyo dumpsite, located on the outskirts of Eldoret Municipality in Uasin Gishu County, is one such unregulated waste disposal site that receives diverse waste streams, including hazardous industrial and medical waste. Situated in a water catchment area with streams and a shallow groundwater table, this dumpsite presents a high risk of groundwater contamination through leachate infiltration. The geology of the area, primarily composed of igneous rocks, influences the subsurface flow of leachate, but the extent and direction of leachate movement remain largely unknown.

Furthermore, most inhabitants of Eldoret rely on shallow wells for their daily water needs due to deficiencies in the municipal water supply system. The potential contamination of these groundwater sources raises significant health concerns, given that unsafe drinking water is a leading cause of diseases such as cholera, typhoid, and other waterborne illnesses in Kenya.

Despite the evident risks associated with leachate contamination, limited studies have been conducted to assess the extent of groundwater pollution in the vicinity of Kipkenyo dumpsite. While previous research in other regions of Kenya has confirmed the presence of heavy metals, pathogens, and organic pollutants in groundwater near open dumpsites (Kinuthia et al., 2020; Karimi et al., 2023), no comprehensive study has been conducted to integrate both geoelectrical and physicochemical methods in evaluating contamination levels in Eldoret Municipality. Given the increasing dependence on groundwater for domestic, agricultural, and industrial purposes in Uasin Gishu County, there is an urgent need to evaluate the extent of leachate contamination in groundwater resources.

1.4 Main Objective

The main objective of this study is to evaluate geoelectrical and physicochemical aspects of leachate contamination in groundwater quality within the vicinity of Kipkenyo Dumpsite, Eldoret Municipality,Uasin Gishu County, Kenya

1.4.1 Specific Objectives

1. To determine the levels physicochemical parameters in the study area.
2. To map the spatial distribution of leachate contaminant plumes in the subsurface

using geoelectrical methods.

3. To analyze the vertical and horizontal flow dynamics of leachate within the subsurface and its interaction with groundwater.
4. To identify and evaluate the hydrogeological and environmental factors influencing leachate migration and contaminant transport in the study area.

1.4.2 Research Questions

1. What are the physicochemical characteristics of groundwater in the study area, and to what extent has leachate infiltration affected its quality?
2. How the leachate contaminant plumes are spatially distributed in the subsurface, and what patterns can be observed using geoelectrical methods?
3. What are the vertical and horizontal flow dynamics of leachate within the subsurface, and how does it interact with groundwater?
4. What hydro geological and environmental factors influence leachate migration and contaminant transport in the study area?

1.5 Justification of the study

Kipkenyo Dumpsite is an open, unregulated waste disposal site, making it a potential source of groundwater contamination due to the generation and infiltration of leachate. The site is located near residential areas where many households rely on shallow wells for their daily water needs due to the limited supply of piped water. As a result, leachate percolation from the dumpsite poses a serious risk to groundwater quality, potentially leading to health hazards for the local community. Contaminated groundwater has been linked to the spread of waterborne diseases and long-term exposure to toxic substances, which can cause severe health complications.

Hence the findings of this study may contribute to several United Nations Sustainable Development Goals (SDGs) by addressing groundwater contamination caused by leachate infiltration from the Kipkenyo Dumpsite. Sustainable Development Goal 6 aims on ensuring universal access to safe and clean water. The study will provide empirical data on groundwater contamination levels, aiding efforts to improve water quality and prevent contamination. The findings will also guide policymakers and stakeholders in developing strategies for sustainable water resource management, ensuring that groundwater remains a reliable and safe source for drinking and other domestic uses.

This research also aligns with SDG 3 by addressing the health risks associated with contaminated groundwater. Polluted groundwater can expose local communities to harmful substances that lead to waterborne diseases, including cholera, typhoid, and heavy metal poisoning. The findings can be used to advocate for better waste management practices and enhanced environmental sanitation, reducing exposure to hazardous contaminants. Furthermore, the study supports SDG 11 by providing information that can inform urban waste management policies and sustainable city planning. Poorly managed dumpsites pose long-term environmental and public health hazards, particularly in rapidly growing towns like Eldoret. The research findings will contribute to the development of sustainable waste disposal mechanisms, promoting environmentally friendly urban planning that minimizes pollution and enhances the quality of life for urban residents. Lastly, in SDG 15, the study will support conservation efforts aimed at restoring land affected by waste contamination, promoting sustainable land use and environmental rehabilitation.

Under the Environmental Management and Waste Control under Environmental Pillar, Vision 2030 emphasizes the need for efficient solid waste management systems to minimize pollution and protect natural resources. This study will provide scientific evidence on the extent of contamination from Kipkenyo Dumpsite, which can be used to improve waste disposal practices and reduce environmental degradation. The Uasin Gishu County Integrated Development Plan (CIDP) emphasizes the need for environmental conservation, sustainable water resource management, and improved public health. This study aligns with these priorities and provides valuable data to inform county policies and decision-making processes.

1.6 Significance of the study

From a scientific perspective, the research will generate essential data on the physicochemical characteristics of groundwater within the Kipkenyo Dumpsite vicinity, offering information into contamination trends. Additionally, the application of geoelectrical techniques will provide a deeper understanding of subsurface contaminant transport, an area that has received minimal research attention in Kenya. These findings will contribute to advancing knowledge in hydrogeology and environmental science, supporting efforts to improve water quality assessment methodologies.

In terms of public health, the findings of this study may be instrumental in evaluating the potential health risks associated with consuming contaminated groundwater. Through identifying pollutants and their concentrations, the research may create awareness among local communities and relevant stakeholders regarding the dangers of groundwater contamination. Moreover, the findings may inform the development of preventive measures and intervention strategies to reduce the prevalence of waterborne diseases linked to leachate infiltration.

Regarding environmental and policy implications, this study may provide valuable information to environmental agencies, policymakers, and local government authorities, aiding in the implementation of better waste disposal practices and enhancing environmental monitoring efforts. The research may also contribute to the enforcement of regulations aimed at reducing groundwater pollution while promoting sustainable waste management strategies.

The study will also provide community and economic benefits. Identifying contamination sources and pathways may help to inform decisions regarding the suitable locations for boreholes and water wells, ensuring safer water access for residents. Additionally, by mitigating groundwater contamination, the study may contribute to lowering healthcare costs associated with waterborne diseases and improving the overall well-being of the local population. These long-term benefits will not only enhance the livelihoods of residents but also support the sustainable development of Eldoret Municipality and beyond.

1.7 Scope of the Study

This study determined the extend of leachate contamination in groundwater quality in the vicinity of Kipkenyo Dumpsite, Eldoret Municipality, Uasin Gishu County, Kenya. A comprehensive approach was employed, integrating both geoelectrical resistivity surveys and physicochemical analyses to assess groundwater contamination levels and their spatial distribution. The investigation was conducted within Kipkenyo Dumpsite and its surrounding areas, focusing on shallow wells and boreholes that served as primary water sources for the local community. The area was selected due to its proximity to the dumpsite and the potential risks posed by leachate percolation on groundwater quality.

To achieve the study's objectives, two primary investigative techniques were utilized. The geoelectrical resistivity survey involved two-dimensional (2D) and three-dimensional (3D) resistivity imaging to identify subsurface contamination zones. Variations in apparent resistivity values provided insights into potential leachate infiltration pathways. The physicochemical analysis of groundwater samples from various wells within the study area assessed key water quality parameters, including pH, electrical conductivity (EC), total dissolved solids (TDS), nitrate and chloride levels, as well as phosphates, sodium, and potassium concentrations. These parameters helped determine the extent of contamination and its potential sources. Furthermore, statistical techniques, including one-way ANOVA, were employed to analyze significant variations in physicochemical parameters across different well locations.

The study was conducted within a specific timeframe to establish baseline contamination levels. While seasonal variations were not explicitly addressed, they were recommended for future studies to assess how wet and dry seasons influenced leachate percolation and groundwater quality dynamics. The research also evaluated groundwater quality in comparison to World Health Organization (WHO) standards and National Environment Management Authority (NEMA) guidelines for safe drinking water.

1.8 Theoretical Framework

This study was guided by Dacy’s Law. Henry Darcy developed Darcy's Law in 1856 based on experiments that studied the flow of water through sand filters. The law states that for laminar flow through saturated soil or porous media, the discharge rate is proportional to the hydraulic gradient (Darcy, 1856). This principle has become fundamental in hydrogeology, influencing groundwater studies and the assessment of contaminant transport in subsurface environments. Darcy's law provides an equation that describes the movement of fluids through porous media and has been extensively applied in environmental engineering, hydrogeology, and groundwater contamination studies (Bear, 1972). This law forms the basis of groundwater flow modeling, which is critical in assessing leachate migration from landfills and dumpsites. Studies have empirically validated Darcy’s law in real-world scenarios, especially in cases of groundwater contamination due to leachate infiltration (Freeze & Cherry, 1979). For example, research conducted by MacDonald et al. (2005) on groundwater flow in African aquifers confirmed that Darcy’s law effectively models water movement through fractured and porous rock formations, highlighting its applicability in subsurface contamination studies. Furthermore, Darcy’s law is analogous to Ohm’s law in electrostatics, as it linearly relates the volume flow rate of fluid to the hydraulic head difference via hydraulic conductivity (Todd & Mays, 2005). In the context of landfill leachate contamination, understanding the hydraulic conductivity of the subsurface material is essential in predicting the extent of groundwater pollution. Studies on waste disposal sites, such as those conducted by Christensen et al. (2001), have shown that leachate migration is largely controlled by subsurface permeability, reinforcing the significance of Darcy’s law in environmental assessments. Recent research has expanded the applications of Darcy’s law beyond simple flow through homogeneous media to more complex, heterogeneous conditions. For instance, investigations on landfill sites in Kenya, such as those by Wechuli (2022), have demonstrated how variations in soil permeability influence the spread of contaminants. Hence, the theory helps in understanding how leachate from the Kipkenyo dumpsite migrates through the subsurface and contaminates groundwater.

1.9 Conceptual Framework

A conceptual framework is a structured representation of how a researcher understands the key variables in a study and their relationships. It serves to clarify the presumed interactions among these variables using relevant literature and empirical findings (Maxwell, 2013). Unlike a theoretical framework, which provides a broad philosophical or theoretical lens, a conceptual framework is more practical, integrating both established theories and the researcher's emergent ideas (Ravitch & Riggan, 2017). In this study, the conceptual framework describes the interaction between geoelectrical and physicochemical factors influencing groundwater contamination from leachate within the vicinity of Kipkenyo dumpsite in Eldoret Municipality, Uasin Gishu County. The relationship is also controlled by intervening and moderating factors such as rainfall patterns, land use, soil type, and natural attenuation processes. The study employs geoelectrical and physicochemical analysis to assess groundwater levels of contamination.

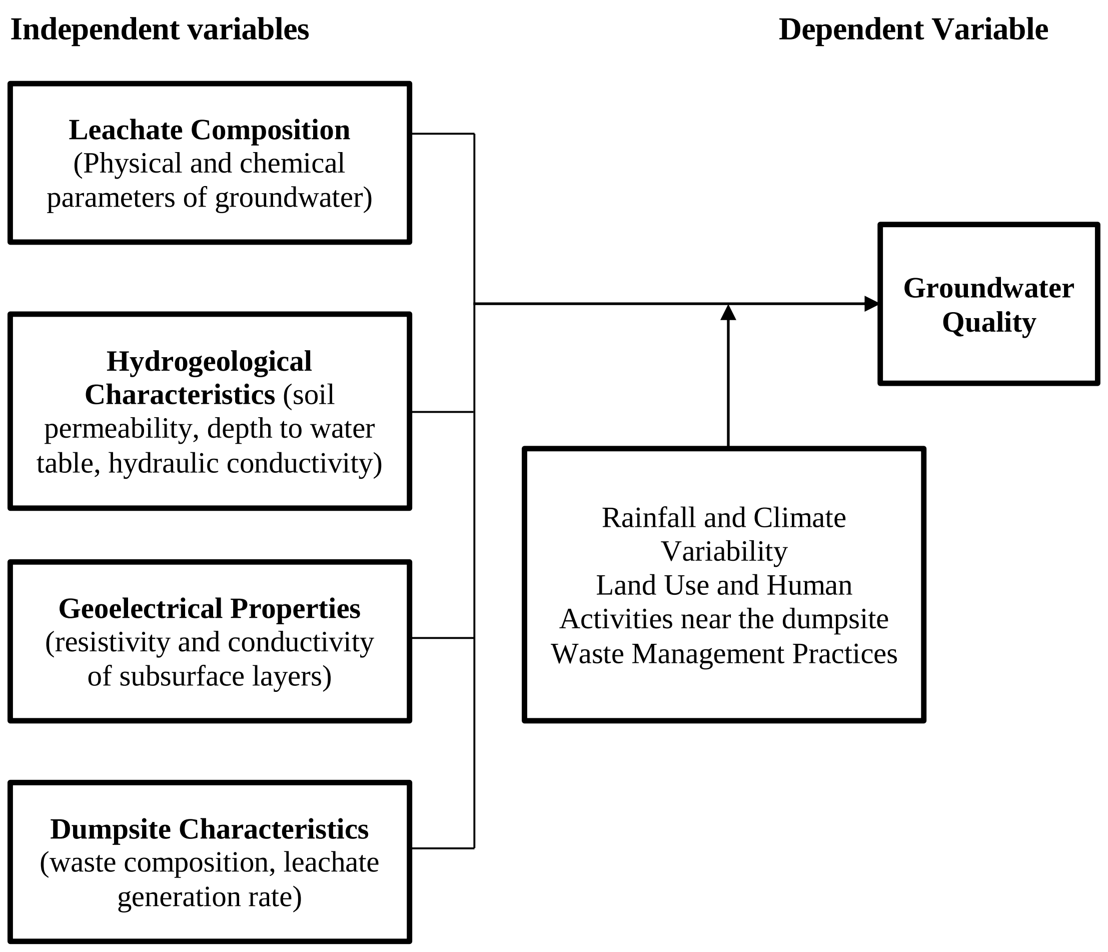

Figure 1.1: The Conceptual Model of the Study

1.10 Limitation of the Study

The study encountered several limitations that affected data collection and analysis. One significant constraint was the use of geophysical equipment with long AB/2 cables, which limited the extent of the resistivity soundings. Ideally, the AB line should remain straight during measurements, but this was sometimes difficult to achieve due to the uneven topography of the study area. Additionally, the effectiveness of geophysical instruments was restricted by their inherent design limitations, including the spatial resolution they provide and the background noise levels that could interfere with readings.

Another limitation was the temporal aspect of the study. Since groundwater quality was assessed at a specific point in time, the results did not capture seasonal variations in leachate migration and contamination patterns. The ability to detect long-term trends was further constrained by financial and time constraints, which limited the frequency and scope of measurements.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter reviews relevant literature on groundwater contamination caused by leachate infiltration, focusing on the physicochemical characteristics of contaminated water, geoelectrical methods for mapping subsurface contaminant plumes and the hydrogeological factors affecting leachate transport. The review also examines regulatory frameworks and standards set by institutions such as the World Health Organization (WHO) and the National Environment Management Authority (NEMA) for safe drinking water.

2.2 Groundwater Resource

Water is a critical natural resource, indispensable to life, human progress, and environmental sustainability (Makanda et al., 2022). Its availability and control are key determinants of health, economic development, and ecological balance (Quan et al., 2024). However, the dual character of water is such that not only its lack but also its abundance can create severe issues, e.g., droughts, and floods (Jain et al., 2007). Groundwater, or water beneath the Earth's surface in saturated zones, comprises a significant portion of the Earth's freshwater reserves. It has been estimated that roughly 30.1% of the worlds freshwater is tied up as groundwater, an indication of its significance compared to surface waters (Kretschmer et al., 2023). This underground water is stored in rock formations known as aquifers, which possess variable capacity and permeability and regulate groundwater flow and availability. Globally, groundwater is a valuable source of freshwater for drinking water, agriculture, and industry. It is the world's most extracted raw material, with withdrawal rates approximated at some 982 cubic kilometers per year (Abhinav Reddy et al., 2023). In the African continent, groundwater is particularly important, and aquifers hold an estimated 0.66 million cubic kilometers of water. This exceeds 100 times the annual renewable freshwater resources trapped in rivers and lakes on the continent, indicating groundwater potential in enhancing water security. However, groundwater reliance varies across the continent depending on climate, infrastructure, and socio-economic standing (Turhan, 2021).

Groundwater in Kenya plays a significant role in meeting Kenya's water needs, especially in semi-arid and arid regions. In areas like Nairobi, groundwater supplies roughly 60% of the water need, serving over 6 million residents (Fankhauser et al., 2022; Ngare et al., 2024). Kenya's total potential groundwater resource stands at around 619 million cubic meters, with a safe abstraction rate of 193 million cubic meters annually. But issues such as over-extraction have led to precipitous declines in groundwater levels, with studies indicating a median decline of six meters per decade beneath Nairobi since 1950.

2.3 Groundwater Contamination

Groundwater quality is affected by various factors, including recharge sources, lithology, hydrodynamic setting, mineralization of watersheds, water-rock interaction, such as mineral dissolution, ion exchange, redox, and human impacts (Masood et al., 2019; He et al., 2021). Various studies have been conducted worldwide to assess the sources associated with groundwater pollution. Industrial and agricultural activities are major contributors to groundwater contamination worldwide. A study by Alam et al. (2024) on groundwater nitrate pollution due to excessive use of N-fertilizers in rural areas of Bangladesh, found that excessive use of fertilizers and pesticides led to high nitrate concentrations in groundwater, posing health risks to consumers. Similarly, Khan et al. (2022) examined Occurrence, source apportionment and potential risks of selected PPCPs in groundwater used as a source of drinking water from key urban-rural settings of Pakistan and identified a high presence of antibiotics and personal care products in groundwater due to improper disposal of medical waste.

In Africa, Afolabi et al. (2021) assessed industrial pollution in Lagos, Nigeria, and found elevated levels of heavy metals such as lead, cadmium, and chromium in groundwater due to untreated industrial effluents. These findings underscore the role of industrialization and agriculture in groundwater pollution across different regions.

Leachate from landfills and improper waste disposal has also been identified as critical sources of groundwater contamination. Singh et al. (2018) investigated the impact of landfill leachate on groundwater quality in New Delhi, India, and found increased levels of ammonia, chloride, and organic pollutants in wells near landfills. In Africa, Oyeku and Eludoyin (2019) studied urban groundwater pollution in Nigeria and discovered that poor waste management practices led to bacterial contamination, increasing the prevalence of waterborne diseases. These findings emphasize the need for proper waste disposal and landfill management to prevent groundwater contamination.

Septic tanks and sewage leakage further contribute to groundwater pollution. Graham et al. (2017) conducted a study in rural areas of the United States and found that poorly maintained septic tanks were a primary source of groundwater contamination, with high levels of coliform bacteria and nitrates. In China, Jiang et al. (2021) reported significant microbial contamination in groundwater due to sewage system leakage, leading to the presence of Escherichia coli and fecal coliforms. Similar patterns have been observed in Africa, where inadequate sanitation infrastructure results in groundwater contamination and increased health risks.

2.4 Physiochemical Parameters of Groundwater

According to Ontumbi, (2020), the essential physical and chemical characteristics of groundwater are temperature, pH, electrical conductivity, turbidity, total dissolved solids, dissolved oxygen, total hardness and total alkalinity. The essential chemical characteristics are magnesium, calcium, sodium, potassium, fluoride, chloride, nitrate, and phosphate.

A vast variety of compounds can be suspended or dissolved in water due to their special chemical properties. Water thus becomes less pure as a result of absorbing contaminants from its surroundings. According to Umeh, Chukwura, Ibo, and Uba, (2020), polluted particles from storm runoff and flooding at the borehole site sink into the soil and reach a shallow depth of the aquifer, resulting in poor water quality.

(a) Calcium Ions

According to Muraga, (2019), Drinking Water containing 100 mg/L of calcium ions is the maximum allowable limit. Among the most prevalent elements in nature are calcium ions and salts (Ackah, Agyemang, Anim, Osei, Bentil, Kpattah & Hanson, 2011). They could originate from artificial sources like Waste from industry and sewage, or they could arise from other natural sources and soil evaporation. One of the main elements that typically contribute to hardness is calcium. When carbon dioxide is available, calcium compounds in water remain stable. However, when calcium carbonate precipitates as a result of rising water temperatures, photosynthetic activity, and pressure- induced carbon dioxide loss, the concentration of calcium compounds decreases.

(b) Sodium Ions

Since sodium ions are thought to have no negative health effects, they are a necessary component of human growth (Mbura, 2018). According to KEBS, (2010), there is a 200 mg/L maximum allowable recommendation level for drinking water; any amount above this overwhelms the kidneys' capacity to function and may result in renal failure (Marian & Ephraim, 2009). Natural water has some sodium in it; one of the constituents that are abundant on Earth is sodium, which is also highly soluble in water (Chapman, Capo, Stewart. Kirby, Hammack, Schroeder & Edenborn, 2012) Industrial and sewage effluents can contribute to elevated salt concentrations in surface water.

Depending on the local geology and wastewater flows, sodium concentrations in natural surface waters can vary significantly. In natural brines, values can vary from less than 1 mg/L to 10^3mg/L (Chapman, et al, 2012). Sodium in irrigation fluids is a particular cause of harm to crops and can negatively impact the structure of soils as well as slow down the speed with which water travels through and into soils (Bond, 2022). Vegetables and row crops under drip and furrow irrigation are not damaged by sodium and chloride unless the irrigation water has a very high saline level (Grattan, 2002). Ayers & Westcot, (1994) claim that irrigating sensitive crops from above can result in toxicities that are not experienced when irrigating from the surface.

(c) Magnesium Ions

These ions could come from natural sources such as granitic-bearing rocks, which are closely associated with hardness (Murhekar Gopalkrushna,2011) and have a high concentration of the element magnesium (Kumar & Kumar, 2013). Natural waters frequently contain magnesium, which together with calcium contributes to the hardness of the water (Welsh, Lipton, Chapman, & Podrabsky, 2000). Certain carbonate rocks and rocks containing Ferro magnesium minerals are the main sources of magnesium. Water does not affect magnesium metals while it is at room temperature. Although magnesium reacts slowly in general, its reactivity rises with oxygen content. Moreover, magnesium hydroxide and hydrogen gas are produced when they combine with water vapor; equation 1 describes this chemical process shown by equation (1) below.

$Mg(OH)_2 + H_2 (aq) = Mg (s) + 2 H_2O (g)$……………………………Equation (1)

Non-calcium hardness is the distinction between calcium hardness and overall hardness. Magnesium accounts for the majority of non-calcium hardness, although there are also zinc, manganese, iron, aluminum, and strontium salts (Kuutondokwa, 2008). The natural concentration of magnesium in freshwater can range from 1 mg/L to less than 100 mg/L, depending on the kinds of rocks in the watershed (Welsh,et al, 2000). KEBS, (2010) states that the permissible limit of non-toxic magnesium ions in water is 100 mg/L.

(d) Phosphate

It happens in groundwater as a result of leaching from detergents and domestic sewage (Mbura, 2018). Moreover, fertilizer-laden agricultural effluents and industrial wastewater can cause it to appear in the sea. Therefore, an elevated phosphate concentration indicates the presence of tainted groundwater, (Ontumbi, 2020). Nonetheless, pure water phosphate levels are low.

(e) Nitrates

Contamination of groundwater results from nitrate from the surface leaching (Kumar & Kumar, 2013). Nitrate in water has a legal maximum of 10 mg/L (KEBS, 2010), and concentrations beyond this limit. Has been connected to blue baby syndrome in infants and stomach cancer in humans (Ayesha, WHO, Jain & Agarwal, 2012), According to Jacob. Breuer, Butterbach-Bahl., Pelster, and Rufino, (2017), total nitrogen is the sum of nitrogen from organic matter, nitrate and ammonia. There are four types of nitrogen found in aquatic environments Nitrate (NO^{3-}), nitrite (NO^{2-}), ammonium ion, and ammonia (NH_4^+). The total concentration of nitrogen remains unchanged as nitrogen is converted from one form to another (Lutz, 2004).

As the sole nitrogen component in aerobic waters that is thermodynamically stable, in natural waterways, nitrate is the last oxidation product in the nitrogen cycle (Akoto, 2008). Both natural and artificial fertilizers such as manure need nitrates to function. An average surface water supply would have a mean nitrate concentration of between 1 and 2 mg/L (Webb, 2004) Nitrates are essential nutrients for the growth of phytoplankton and algae. The natural process of eutrophication is significantly accelerated when nitrates are released into surface water bodies (Shao & Wang, 2003). Depletion of oxygen and generally low water quality are caused by algal blooms. This raises the price of treating surface water for municipal use, causes fish kills, destroys riparian habitat, kills valuable aquatic insects, and causes difficulties with taste and odor two harmful consequences of nitrate in drinking water on health are the probable creation of carcinogenic nitrosamines and the induction of methemoglobinemia, particularly in babies (Webb, 2004). The WHO recommends 10 mg/L of nitrate in drinking water.

(f) Chloride Ions

According to (Mbura, 2018) Irrigation water drainage, sewage discharge, saline intrusion, and refuse leachate contamination are the causes of chloride ions found in groundwater. Elevated levels of chloride hurt vegetation growth and make metals more corrosive. A higher than agreed-upon level of chloride produces a salty taste and may lead to physiological harm. According to KEBS, (2010), drinking water with a chloride content of up to 250 mg/l is permissible; if this level is exceeded, it becomes harmful to human health (Ayesha, 2012), and those who are exposed to such high amounts of chloride may experience laxative effects (Murhekar, 2011).

(g) Potassium Ions

Rock erosion causes these ions to naturally end up in groundwater, but wastewater discharged around wells could be the cause of the greater quantities in contaminated water (Mbura, 2018). Since it is an essential part of the human diet, intoxication from ingestion is rare due to its rapid elimination. However, a high potassium ion diet overloads the kidney's homeostatic functions, potentially leading to renal failure and death (Nkansah & Ephraim, 2009). KEBS, (2010) states that the permissible level is 50 mg/L for drinking water

(h) pH

The pH scale, according to Mesner, (2005), shows how basic (alkaline) or acidic a solution is. The chemical and biological processes that take place in a body of water, along with all water treatment-related operations and supply, are intimately related to the pH of the water (Chapman, 1996). The pH 7.0 scales, which spans from 1.0 to 14.0, is regarded as neutral and goes from higher for more basic solutions to lower for more acidic ones. Every full unit on the scale represents a multiplication factor of 10. Hence; Water with a pH of 5.0 is 100 times more acidic than water with a pH of 7.0, according to UNEP & Mesner, (2005) while pH in water is usually not a problem in and of itself, it can be a sign of other issues such as carbonates and sodium.

As pH rises, calcium carbonate ($CaCO_3$) and other mineral scales are more likely to precipitate, while water becomes more corrosive as pH falls. Irrigation water normally has a pH of 7.2 to 8.5, which makes it more alkaline. There is a greater chance of salt issues when irrigation water pH rises above 8.2 (Westcot & Ayers, 1994). Masaba, (2020) States that the pH of the water can affect a number of things, such as the solubility and biological availability of components in the water, the pH range of 6.5 to 8.5 is said to be excellent for freshwater aquatic fish growth and reproduction.

(i) Temperature

Temperature plays a crucial role in controlling the concentration of soluble gases in water (Nirmala, 2012). KEBS, (2010) states that the acceptable range is 28–32°C.Water contaminated by wastewater raises its temperature and decreases its dissolved oxygen content (Murhekar, 2011). Along with regular climate oscillations, water bodies experience temperature shifts (Chapman, 1996). Seasonally and in some aquatic bodies throughout 24 hours, these fluctuations take place. Latitude, altitude, and Surface water temperature are influenced by flow depth, cloud cover, season, and air circulation. While hot spring temperatures can reach over 40 degrees Celsius, surface water temperatures typically vary from 0 to 30 degrees Celsius (Chapman, 1990) affecting the internal metabolic processes of any living organism (Murhekar, 2011).

The rate of organic matter breakdown and oxygen consumption in aquatic animals are directly associated with temperature; in warm waters, respiration rates increase. The speeds of chemical reactions usually double for every 10 °C rise in temperature (Webb, 2004). Temperature affects how much $CaCO_3$ dissolves; at higher temperatures, less $CaCO_3$ dissolves and an overabundance of precipitate could clog hot water pipes (Webb, 2004). In aquatic systems, temperature matters because it affects the solubility of dissolved oxygen (DO) and other elements like ammonia, which is toxic to fish, as well as the ability to cause mortality (Olatayo,2014).Webb, (2004) states that temperature has a significant impact on the removal of turbidity by metal-ion coagulants, Lower temperatures cause decreased removal, and they also have an impact on the coagulation and flocculation process by changing the solubility of the coagulant, raising water viscosity, and slowing down the rate of hydrolysis reactions.

(j) Turbidity

It is a measurement of a liquid's purity and is brought on by materials that are suspended in water. It degrades the water's quality by altering its hue and promoting the development of microorganisms (Otieno, Olumuyiwa, & Ochieng, 2012). According to studies, the main cause of turbidity is the deposition of silt into the aquifer, which is linked to greater levels in the wet seasons and a lesser level in the dry ones (Oluyemi, 2014). (KEBS, 2010) states that turbidity may be allowed up to 5 NTU how much suspended particles cause the transparency of the water to diminish is measured by a process called turbidity (Chapman, 1996). Plankton and other microscopic organisms, silts, clay, and finely divided organic and inorganic debris are examples of suspended particles that can induce turbidity in water (AWWA, 1990).

(k) Dissolved Oxygen

Dissolved oxygen is an indicator of the physical, chemical, and biological activities taking place in water, according to (Murhekar, 2011). Although dissolved oxygen standards are not specified in the (KEBS, 2010), research suggests that it is important for water to have a sufficiently high content of dissolved oxygen. Water with less oxygen indicates that its chemical composition is degrading, which increases the temperature (Otieno, et al, 2012). Dissolved oxygen (DO) is a measurement of the quantity of oxygen gas dissolved in water and available to aquatic and plant life (WHO, 2006). The amount of oxygen in natural water is influenced by several variables, including temperature, salinity, turbulence, air pressure, photosynthetic activity of plants and algae and others (Chapman, 1996). Surface interaction causes oxygen gas to spontaneously combine with water; fast-moving waters usually have a higher DO as a result of the air mixing with the water as it hits logs and boulders. While the concentration of oxygen is normally close to but less than 10 mg/l in uncontaminated waters. It should be around 100% saturation in naturally occurring running waters, or between 9 and 11 mg/L depending on temperature (SEED, 2003). Eisler, (2003). States that while drinking water with dissolved oxygen concentrations below a certain point does not negatively impact human health; fish and other aquatic life require access to sufficient dissolved oxygen. In uncontaminated waterways, the minimum dosage of DO require for fish to survive varies depending on their size and species and is often less than or equal to 10 mg/L.

(l) Total Dissolved Solids

This important statistic measures the total number of mobile charged ions dissolved in a given volume of water. Water with higher TDS than the 1200 mg/L permissible limit according to KEBS 2010, on the other hand, irritates the digestive tract and alters the taste, hardness, and corrosiveness of water. High levels of mineralization in water are evidenced by high TDS, which may be due to the presence of hard-to-dissolve rock components such as sulfate and chlorides, and minerals including calcium and magnesium that may exist locally in the area. Magnesium may also be the source of an increase in total dissolved solids in water, which makes hard water unfit for human consumption. Surface runoff components include bicarbonates, chlorides, nitrate, salt, potassium and calcium because it does not create lather; it is insufficient for bathing and washing (Olumuyiwa, Kumar & Kumar, 2013). Total dissolved solids, or salts that make soil and irrigation water salinous are commonly referred to as TDS. The unit of TDS for salinity is mg/L. It is often measured by the widely used measurements of electrical conductivity, or EC. In drinking water, levels higher than about 1000 mg/L are associated with a significant loss of taste. Generally speaking, the water with less than 600 mg/L TDS is fairly acceptable in palatability. Too high TDS concentration is also unsafe for users, considering the serious scaling in water pipes, heaters, boilers, and domestic appliances. According to health guidelines, TDS does not yet have a permissible limit value.

2.5. Resistivity in Pollution Mapping

Municipal solid waste leaks are typically linked to high ion concentrations and extremely low resistivities. Because of this, mapping the three-dimensional extent of contamination surrounding landfills using geoelectrical imaging techniques is particularly fascinating (Loke, Chambers, Rucker & Wilkinson, 2013). Used 2D electrical resistivity imaging and vertical electrical sounding to determine the depth of the groundwater table, detect and map the size of the pollution plume, and follow the migration pattern below the surface surrounding the dumpsite. Abdullahi, (2011) carried out integrated geophysical surveys at the Unguwan Dosa municipal solid waste disposal site in Kaduna, northwest Nigeria, using seismic refraction tomography, very low-frequency electromagnetic induction method, and 2D electrical resistivity to investigate groundwater contamination. Enikanselu, (2008) utilized the electrical resistivity approach to look at the effects of the dumpsite on the aquifer units in the Giwa- Okerodo area of Ogun State.

It was concluded from the findings that the well water in the region was tainted. Adebayo, (2015) used a geophysical technique in Ede Town, Southwest Nigeria, to locate pollution plumes. They evaluated the extent of pollution in some hand-dug wells and delineated the subsurface pollution plumes in Ede Town, southwest Nigeria, utilizing geochemical and electrical resistivity techniques (Olagunju & associates 2017), conducted research on the environmental effects of open dumpsites using geochemical and geophysical methods. The findings indicated that the river and the hand-dug wells near the refuse dump were polluted. The research presented here accordingly uses electrical resistivity tomography and vertical electrical resistivity sounding to study the impact of leachate on the groundwater at Gashua in Nigeria.

These methods are highly relevant for the study given that subsurface electrical resistivity can vary greatly between organic and inorganic constituents. Electrical imaging can identify the low resistivity that accompanies contaminated soil and groundwater; hence, it is a nonintrusive and nondestructive technique to delineate pollution plumes from solid waste disposal sites. The electrical resistivity approach is one of the quick, somewhat inexpensive, and non-destructive geophysical methods for shallow subsurface anomaly imaging. The approach of resistivity survey deals with various problems concerning groundwater evaluation, research, exploration, and salinity.

This method can be used to determine the following: the depth, thickness, and boundary of different aquifer layers (Zohdy, 2007); the boundary between fresh and saline water (El-Waheidi & Choudhury, 2001); and the presence of groundwater contamination (Kelly, & Kaya, 2001). The electrical resistivity of clean water frequently drops as ion concentrations rise as a result of pollution (Lashkarripour, 2003). To investigate and determine the suitability of groundwater for various purposes, several researchers and writers have looked at the relationship between geo-electrical parameters and aquifer properties like transmissivity and conductivity, among other parameters (Kelly,1996) (Aleke, Ibuot & Obiora, 2018). According to geophysical studies, the resistivity technique is crucial for evaluating groundwater in alluvial soils. Resistivity assessments also show great effectiveness in settling wells in areas with hard rock terrain (Patra, Adhikari, Kunar, Patra, Adhikari & Kunar, 2016).

The electrical resistivity method can be used to solve a wide range of groundwater issues, such as monitoring aquifer boundaries, strata, depth, and thickness; estimating the boundaries between fresh and saline water zones (Hago,2000); locating high-yield potential zones in an aquifer (Oseji, 2005); and examining groundwater quality (Arshad, 2007). In groundwater exploration, many geophysical methods have been employed to identify favorable sites for productive boreholes. One often-used method is the electrical resistivity approach, which comprises VES and Horizontal Profiling (HP) (Omosuyi, 2008). This galvanic method, more commonly known as the VES method due to (Emmanuel, 2011) its reliability and ease of use, has proved quite useful in studies related to groundwater. Electrical resistance in rock depends on its lithologies and its fluid content. According to (Ilevbare & Ogundana, 2022), there is the possibility that the amount and thicknesses of the geoelectric units measured by VES in any place are not exactly geological. Sometimes, the main purpose of running VES is to obtain, without drilling the well itself, an actual resistivity log which has a similar resemblance to the induction log of a nearby well.

2.6. Physio-Chemical Effects to Groundwater

Studies conducted in India showed that the physico-chemical parameters of the groundwater were well above the recommended limits as defined by (WHO's, 2008). The results showed that a high value of total dissolved solids measured as 3780 mg/L, electrical conductivity, 5906 µS/cm, chlorides, 1230 mg/L, fluoride, 1.8 mg/L and nitrates, 162 mg/L (Jain & Agarwal, 2012).

The following qualities of Akot, India's groundwater was reported to exist: 5.4 to 9.5 pH range, 1590 µS/cm electrical conductivity, 1500 mg/L total dissolved solids, 13.4NTU turbidity, 687mg/L total hardness, 263 mg/L sulfate, up to 472mg/L calcium, up to 162 mg/L magnesium, up to 274 mg/L sodium and up to 308 mg/L chloride concentration (Murhekar, 2011).

It is estimated that 60 million people have been exposed to highly fluoridated groundwater; these come out as deformed bones in children when, in cases where the levels of fluoride as high as 2.5 mg/L above the set limits by WHO, (2008), have been found. The groundwater was assessed and found to have levels of fluoride ions, total dissolved solids, electrical conductivity, and hardness above the permissible limits recommended by WHO (2008), hence not suitable for human consumption. (PRASAD, 2014) carried out in Nigeria, as high as 35.4 mg/L, it recorded the groundwater nitrate while the phosphate concentration was above the permissible limit as stated by WHO (2008). Onwugharal, (2012) reports that approximately 385000 deaths among children every year due to water contaminated with a level of fluoride above threshold given by WHO's 2008 is 1.5mg/L.

On the physio-chemical analysis of the groundwater of Kiambu County, research has indicated that this water is not fit for human consumption because its turbidity, total dissolved solids, and electrical conductivity were found to be higher than the criteria of (KEBS, 2010) as reported by Gichuki & Gichumbi, (2012). High levels of fluoride in some of the analyzed groundwater samples indicated that the groundwater in the area was not fit for consumption. This was established by a study carried out in Tharaka Nithi County on the evaluation of tap water and groundwater quality in villages surrounding Chuka town.

In Kenya, studies showed that high levels of calcium, magnesium and salt make Mombasa groundwater hazardous for consumption. High levels of the minerals make water more aggressive. Maximum allowable limits were exceeded in terms of salinity, total dissolved solids, electrical conductivity and chloride. It was also noted that the concentration of nitrate was higher in the rainy than in the dry season, according to Muraguri, (2016).

Fluoride levels as high as 5.2 mg/L were discovered in groundwater tested from boreholes in the Kajiado district. This raised the risk of dental fluorosis and the formation of brown teeth. Baringo, Nakuru, and Naivasha regions have also provided reports on this (Chandeka, 2013).

2.7 Open dumpsite Age

The length of time solid waste is disposed of in open dumpsite affects waste breakdown. Leachate builds up in layers over time and becomes dangerous (Asadi, 2008). High quantities of BOD and COD have been found in recent open dumpsite leachate, these values progressively drop in the lower strata. Asadi, (2008) Carbon-containing compounds decompose faster than inorganic ones as they age. Chang, (2001) Inorganic chemicals are no longer as dangerous as they formerly were because rainwater infiltration eliminates them (Chiang, 2001). When sulfate is transformed into sulfide by infiltration, heavy metals precipitate (Adhikari, 2013). The leachate quality in landfills becomes dangerous as organic materials are stable (Adhikari, 2013).

2.8 Leachate Formation

Municipal leachate is composed of both organic and inorganic components. This is the outcome of the several sources of solid trash that were deposited. Most developing countries lack the technology necessary to control the generation and disposal of solid waste, hence solid waste management is still in its infancy in these countries (Tatsi & Zouboulis, 2002). Inadequate solid waste management practices put water and soil resources at risk of depletion. Leachate contamination is one of the primary challenges facing the municipality in managing its waste. Anions (HCO_3^-, Cl^- and SO_4^{2-}) cations (Ca^{2+}, Mg^{2+}, Na+, K^{+}, Fe^{2+}, Mn^{2+}, and NH_4^+) make up the majority of municipal solid waste. The distribution of ions affects leachate toxicity differently (Christensen, 2001).

2.9. Water Quality Standards and Guidelines

The protection of aquatic life and the health of the general public are the major goals of water quality standards and guidelines. Each country establishes guidelines and recommendations specific to controlling the maximum levels of pollutants allowed in its different water bodies Onemano & Otum, 2003. These include the designated uses of water bodies, anti-degradation rules to protect high-quality water bodies, and water quality standards that protect users and determine whether they are being met. The World Health Organization is one of the various organizations that have taken notice of the deteriorating quality of water and are trying to advance a global response to it. The WHO Guidelines for Drinking Water Quality (GDWQ) tackles the physical, chemical, and microbiological parameters of water quality (WHO 2006).

Once the guidelines are revised through scientific research and consultations with various stakeholders and professions, revisions are provided periodically (WHO, 2011) the third and fourth editions of the guidelines were published in 2004–2008 and 2011, respectively. WHO recommended GDWQ are not legally enforceable limits; rather, they are intended to serve as a framework for individual nations to define and control their national water quality standards and guidelines within the context of local or national environmental, social economic and cultural contexts. Drinking water sources are safe when the WHO criteria are properly followed, which eliminates or reduces contaminants in water that are known to be hazardous to human health to a minimal allowable concentration (WHO, 2011).

2.10. Effects of Solid Waste on the Environment

Uncontrolled solid waste disposal exposes city people to contaminated water, filthy food supplies, and contamination of the air, land, and vegetation, especially for those who live close to dumpsites. Ecosystems are harmed, the environment deteriorates, and there are serious health risks to individuals who improperly manage and dispose of solid waste. Solid waste accumulations also put city people's health at risk (UNEP, 2005). Numerous environmental problems, including noxious odors, water and soil contamination, health hazards, and ugly appearances, are brought on by solid waste. All of this contributes to the degradation of our environmental quality (Abdus, 2011).

Most dumpsites are situated adjacent to residential areas and wetlands. Often, the dumpsites are not technologically positioned to take in hazardous pollutants. Consequently, they become susceptible to the Release of contaminants into nearby water bodies and the atmosphere through leachates or dumpsite gases, respectively (Kulikowska & Klimiuk, 2008). It has been determined that many water resources are hazardous to people and other living things (Moh, 2012).

The majorities of unregulated disposal sites are established and dispose of waste improperly. The environment is greatly impacted by these dumping sites. Solid waste is a major hazard to the well-being of terrestrial, marine, and aerial environments, according to Arthur, (2024). Below the surface of the Earth, groundwater can be found in the pore spaces and fissures in rocks and sediments. It starts as snow or rain. It seeps into the groundwater system through the soil profile. Drilling wells eventually find its way back to lakes, streams, and seas. In many parts of the world, groundwater resources are an essential component of water delivery systems and are widely used for agricultural, commercial and residential purposes. The water supply is widely accessible, moderately priced, dependable, and has a lower chemical and microbial quality than surface water, according to Morris, (2003).

2.11. Anthropogenic Activities

The type of human activity in the area has an impact on groundwater safety as well. For example, agricultural practices can contaminate groundwater in several ways. Typical instances include handling fertilizer and pesticide spills, cleaning pesticide sprayers or other chemical application equipment close to shallow wells, and enriching the soil with organic manure that resembles animal dung Chemicals that seep through the aquifers and flow into the groundwater are another way that economic activities like transportation and industrial processes contaminate groundwater. Domestic garbage is especially very dangerous since it can contaminate groundwater by leaching when it is released close to wells (Murhekar, 2011).

2.12. Natural Substances

The kinds of naturally occurring contaminants found in groundwater are determined by the geological materials the water passes through en route to the aquifer. As water travels through soils and rocks and descends to aquifers, it may be impacted by the components of the rocks. It might therefore contain a range of minerals, some of which might be present in significant concentrations. The effects of these naturally occurring ground contamination sources on the quality of water are determined by the types and amounts of pollutants present. Although contaminants in water are dangerous to human health and life, they are considered safe for ingestion when found in amounts below the permissible limit (Murhekar, 2011).

2.13. Effects of Pollutants on Health

Under normal circumstances, silt, sand, and bacteria are among the impurities that water naturally contains, along with trace levels of dissolved minerals like zinc, calcium, and magnesium. These levels are considered safe for human consumption; but, when they are above specific criteria, the water becomes contaminated (Christensen, 2001). Metal ions and their complexes can be exceedingly harmful to living beings, ranging from sub-lethal to death, depending on the temperature and length of exposure. For example, the heavy metals Pb, Zn, Mn, Cd, As, Ni, and Hg are quite dangerous even at low concentrations (Sangarika, 2010). Continuous exposure to lead can cause significant disturbances of hemoglobin biosynthesis and/or anemia, kidney damage, hypertension, brain damage, miscarriages, disruption of the neurological system and damage to male sperm.

Lead and cadmium represent major health concerns to humans. Mercury exposure can cause damage to the kidneys and brain, as well as neurological disorders and hemoglobin regeneration (GSADH, 2005). Water supplies become contaminated when these pollutants are haphazardly dumped in landfills because the leachate that is left behind either seeps into groundwater or is carried by surface and stream water. Water bodies can get zinc from man-made sources such as burning garbage, steel industry wastes, and coal-fired power plants (Damodharan, 2013). Trace levels of zinc can be detected in commercial industry effluents, smelting processes, fertilizers, and mine-leaching effluents.

The measured pH values of the samples are merely markers of their acidity; they do not indicate the hydrogen ions' (H^+) potential activity levels. The neutral pH value is 7.0, and the measuring range is 0–14. A pH of greater than 7.0 is considered basic, whereas less than 7.0 are considered acidic. Because different species require different levels of acidity to survive, PH levels can be used as indicators of a water supply's possible implications on human health. Any level of acidity in the water makes metals or chemicals that come into touch with it more harmful (Moh, 2012).

2.14. Electrical Resistivity Survey

If the return current electrode is positioned far from the source and the surface of the current source electrode is made of a uniform material with constant resistivity ρ, there will be a radial flow of currents away from the electrode. This ensures that the current is distributed uniformly across the electrode-centered hemispherical surface.

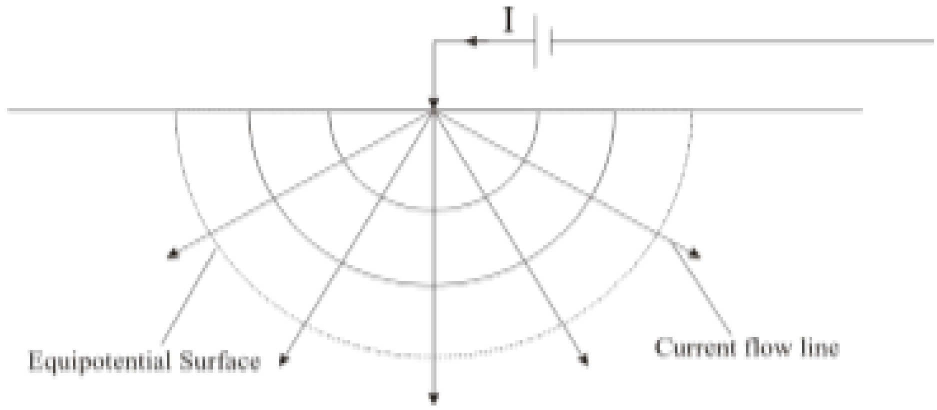

Figure 2.1: Current flow from a single surface electrode

When the hemispherical shell is separated from the source electrode, its surface area is when a linear isotropic medium is used;

At a distance r from the source electrode, the hemispherical shell has a surface area, the current density 'j' which is a ratio of current 'I' to the surface area. Ohm's law asserts that, field strength E,

$E = pj$……………………………………………………………………Equation (2)

Equation (3) is substituted into equation (4), resulting in the field strength E becoming

$E = \frac{Pl}{2\pi r^2}$.. Equation (3)

Current density and field strength are related by

$E = \frac{dv}{dr}$..Equation (4)

σ can be expressed as follows: σ is the resistivity (ρ) divided by the negative partial derivative of the field potential E, V, and the potential gradient (∂v/∂r) connected to the current density.

$\frac{\partial V}{\partial r}$=- pj=-$\frac{pl}{2\pi r^2}$.. Equation (5)

By integrating dv/dr with respect to r, one may get the potential Vr at a distance r from the current source. This becomes

$\int \frac{dv}{dr} = -\int pl = \int \frac{p}{2\pi r^2}$..Equation (6)

When a point electrode is r distances from an infinite homogenous and isotropic medium of resistivity, ρ, the electric potential Vr at any point P produces an electric current I. is determined by:

$Vr = \frac{pl}{2\pi r}$...Equation (7)

This is the most basic model of an earth for a semi-finite medium that has point electrodes for both current and potential at the surface.

$p = \frac{\Delta v}{l}$ .G=R.G...Equation (8)

Where R is the measured resistance and G is the geometric constant, which varies depending on the electrode configuration used for the survey (Anthony, 2006)

2.15. Agricultural activities

Both highly mechanized, large-scale farming with significant amounts of external input and small-scale farming with little external input characterize the County's agricultural industry. The main crops grown in the County are corn, wheat, beans, Irish potatoes, and horticultural goods such avocados, coffee, macadamia nuts, and passion fruits. The greatest locations to plant maize are Kesses, Kapseret, Turbo, and Ainabkoi, yet any of these crops may be grown anywhere in the county. Meanwhile, wheat grows well in the county's drier regions, like Moiben and Ziwa, and Irish potatoes flourish in the Ainabkoi region.

All animals are raised across the county, although the areas of Ainabkoi, Kapseret, and Turbo are especially good at raising dairy cattle pure breeds make up about 20% of dairy cattle herds, crossbreds make up 70%, and native cattle make up 10%. The increased demand for white meat and the subsector's support of fish farming have led to a recent large increase in the County's fish production. Tilapia, catfish, and ornamental fisheries which are gaining popularity are common fish species. Catfish, which do not reproduce in fish ponds or other captivity, find natural breeding grounds in streams, rivers, springs, marshes, and dams.

2.16. Drainage

The main water sources in kipkenyo ward are rivers, springs, boreholes, dams, and shallow wells. There are 250 dams and ponds that were constructed during the colonial era and are mostly silted, in addition to the five principal rivers, Moiben, Sergoit, Kipkarren, Chepkoilel, and Sosiani. The rural populace is mostly dependent on the abundant and superior-quality groundwater that they access through hand-dug wells, shallow wells and springs (Kalama, 2016).

The seven gazetted water systems in the County are Eldoret Water and Sanitation (ELDOWAS), Turbo, Moi's Bridge, Burnt Forest, Sambut, Sosiani, and Kipkabus. While ELDOWAS is a publicly traded company, the County administration is in charge of six of the seven. The ungazetted Ngeria water system and 260 community water supplies are also located within the County. Eldoret and the surrounding area currently produce 36,000 M^3 of water per day which is less than the 60,000 M^3 required daily.

It is necessary to invest in water supply to close this gap. The Elgarini Water Project, which the County and the Lake Victoria North Water Services Board are now developing, will contribute 9,000 M^3 per day. Additionally, plans are to build the Kipkaren water treatment facility, which will produce an extra 24,000 M^3daily. Since the closest water point is often 500–1 km away in the county's rural sections and 0–500 m away in its urban areas, residents don't have to spend an excessive amount of time gathering water for their families' requirements (Calvo, 2005) this distance can be reduced even further with the implementation of appropriate water supply and management strategies.

Getting portable, clean water is still a challenge, even with the County's abundance of water sources. This means that new water supply plans must be created and existing ones must be updated in addition to sustaining community water sources. Water will first be distributed to homes, communities, and government facilities. The County is also responsible for maintaining water catchment areas, desalting dams, and fixing water towers. Eliminating garbage in cities and towns can be challenging, despite the County's best efforts to reduce pollution and environmental harm the primary causes of sanitation problems in cities and metropolitan areas are a broken sewage infrastructure and poor solid waste management. To improve garbage disposal, it is necessary to build sewage systems, waste storage facilities, solid waste disposal sites, and a recycling plant at the Kipkenyo dumpsite (Creswell, 2002).

2.17 Spatial Distribution of Contaminant Plumes

Different substances may be present in groundwater at different amounts, depending on the local geology and human activity. The bulk of the soluble material in groundwater comes from minerals found in rocks and a soil very little comes from the atmosphere or sources of surface water. The majority of the ions in groundwater are composed of significant cations and anions such as sodium, potassium, calcium, and magnesium, along with cations like nitrate, sulfate, bicarbonate, chloride, and fluoride. These ionic interactions among the species tend to salinized the water, making it more mineralized and so contains more total dissolved solids as determined (Sundaram 2009).

2.18 Magnitude and Impacts of Contamination

It sets up the susceptibility of groundwater pollution, showing the combination of those characteristics that are more dangerous in terms of groundwater pollution compared to other combinations. According to Demetrious, (2008), surrounding land surfaces are hydraulically connected through interlaced pore fringes with groundwater aquifers. It determines the susceptibility of an aquifer to pollution. Land-surface-derived groundwater may be considered the most vulnerable compared to other groundwater, which receives water and contaminants more slowly and in lesser quantities. The quality of groundwater is dependent upon the proportional quantity of contaminants reaching the aquifer, the time that elapses for contaminants to travel the system and the attenuating ability of the geological system.

The degree of attenuation occurring is dependent upon rock and soil type, the type of contaminant involved, and the activity in question. Reduction or stoppage of pollution of any surface and groundwater requires, as a first step, full comprehension of the intrinsic natural characteristics of the targeted aquifer regarding its susceptibility to contamination, as well as the history of activities which have taken place there. Normally, water contains minute or trace quantities of dissolved minerals such as zinc, calcium and magnesium and impurities like silt, sand, and microorganisms. While these quantities are within the threshold limit set as safe for human consumption, when they exceed the threshold limits, the water is said to be contaminated (Christensen, 2001).

2.19 Leachates Flow Both Directions Vertical and Horizontal Movements

Apart from this percolation of rainfall, (Taylor & Allen 2006) attribute this to the generation of leachate by degradation processes acting within the garbage. In any case, the leachate produced by the dump or landfill will flow outward and downward due to the increased hydraulic head that is developed. This downward flow puts underground groundwater supplies in danger. Poor-quality water in nearby boreholes/wells shows that the leachate is being generated and migrating. The directions of surface water flow direction and groundwater flow direction could be different. But through the gaps in the rock and soil, groundwater flows steadily and slowly.

There was a contamination plume if groundwater is contaminated by a landfill. Wells within that plume was contaminated, but if they are outside of it, other wells including those near the landfill might not be impacted. Furthermore, variations in leachate concentrations and groundwater flow directions control the behavior of the leachate pollution plume produced in the groundwater zone Christensen, (1995). Lee & Kitanidis, (1993) noted that the type of waste, hydrogeology, geochemistry, and climate can all have an impact on leachate migration from disposal sites. It is a difficult undertaking to do a thorough analysis that accounts for each of these variables.

2.20 Relationship between Contaminant Flow Parameters and Geology

The types of natural contaminants in groundwater depend on the geological material from which the water enters the aquifer. When water passes through rocks and soil and enters the aquifer, it is affected by the composition of the rock and contains a variety of minerals, some of which may be present in high concentrations. The impact of these natural sources of contamination on groundwater quality depends on the type of contaminant and its concentration in the water. The presence of contaminants in water is harmful to health and poses a threat to human life, but its presence within the permissible concentrations is considered not harmful to human health (Murhekar, 2011).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter provides a detailed description of the study area, sampling procedures, data collection instruments, laboratory analysis techniques, and statistical methods used for data interpretation employed to assess the impact of leachate contamination in groundwater quality in the vicinity of Kipkenyo Dumpsite, Eldoret Municipality, Uasin Gishu County, Kenya.

3.2. Study area

The study was conducted in Kipkenyo dumpsite (Figure 3.1) situated at outskirts of Eldoret Town, Uasin Gishu County. The county lies between longitudes 340 50’ East and 350 37’ West and latitudes 00 03’ South and 00 55’ North. The county shares common borders with Trans Nzoia County to the North, Elgeyo Marakwet County to the East, Baringo County to the South East, Kericho County to the South, Nandi County to the South West and Kakamega County to the North West. It covers a total area of 3,345.2 Km2.

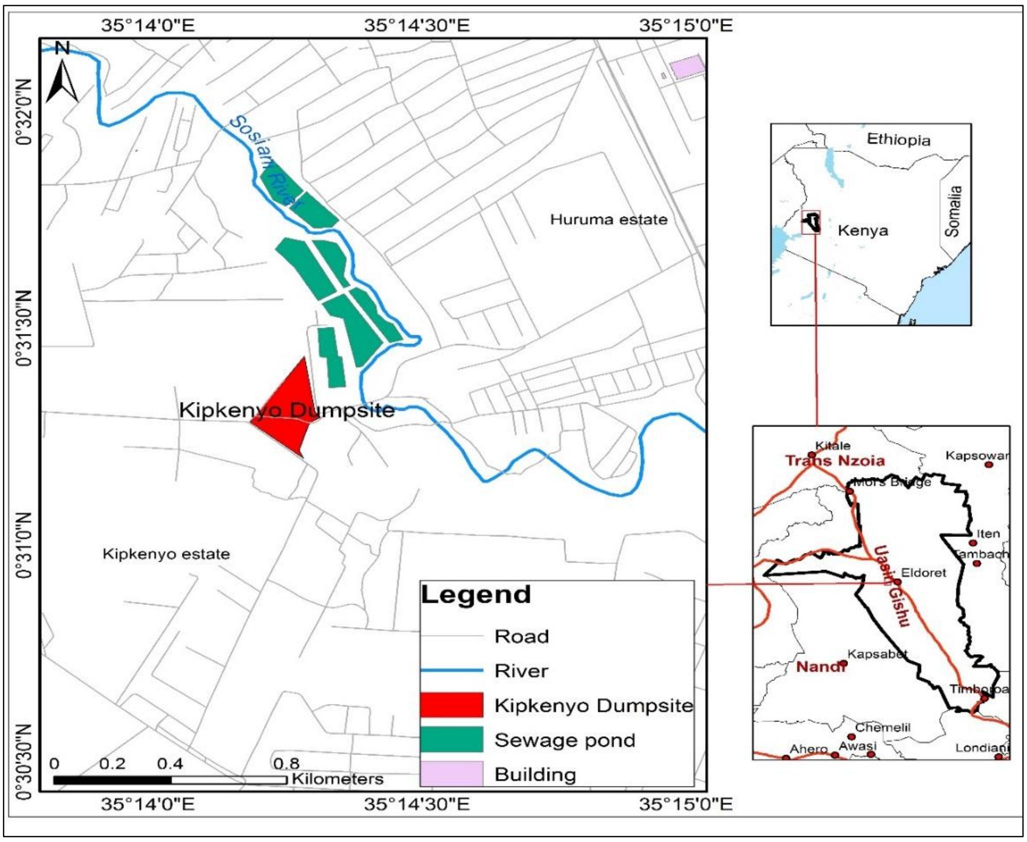

Figure 3.1: Map of the Study Area

Figure 3.2 Kipkenyo open dumpsite solid waste (http://www.alamy.com/)

3.2.2 Climatic Characteristics

Uasin Gishu County experiences a temperate climate with much cooler temperatures compared to other regions in Kenya. The county's temperatures generally range between 18°C and 21°C, though variations can occur, with minimum temperatures dropping to around 7°C and maximum temperatures reaching 29°C (Uasin Gishu County Integrated Development Plan, 2023).

Rainfall in Uasin Gishu County is both high and reliable, with an annual average precipitation of approximately 1,500 mm. The rainfall distribution follows a bimodal pattern, with two distinct peaks occurring between March and September and another between May and August. The county experiences four distinct seasons: January to March is the warm dry season, April to June marks the long wet season, July to September is the cool dry season, and October to December is the short wet season. Dry spells are most common between November and February; although they are not prolonged enough to significantly hinder agricultural activities (Uasin Gishu County Integrated Development Plan, 2023).

The favorable climatic conditions in Uasin Gishu support extensive agricultural production. The region is a key producer of staple crops such as wheat and maize, making it one of Kenya's leading grain-producing counties. Additionally, the moderate climate supports the cultivation of cash crops, including coffee, flowers, pyrethrum, vegetables, and horticultural crops. The reliable rainfall also enhances livestock farming, particularly dairy and beef production, as well as fish farming in suitable areas. Overall, the county's climatic conditions make it a prime agricultural hub, contributing significantly to Kenya's food security and economic growth (Uasin Gishu County Integrated Development Plan, 2023).

3.2.3 Geology and Soil Composition

Uasin Gishu County is predominantly underlain by igneous rock formations, which contribute to the diverse soil types found in the region. The four most common soil types in Kipkenyo include red clay, brown loam, red loam, and brown clay soils. Red loam soils are primarily found in Turbo, Moi's Bridge, and the lower Moiben region in northern Uasin Gishu. These soils are well-drained and highly fertile, making them suitable for the cultivation of staple crops such as maize and wheat. Red clay soils, on the other hand, are mostly found in the border areas of Soy, upper Moiben, and Nandi. They exhibit similar agricultural potential to red loam soils, supporting a variety of crops and vegetation (Uasin Gishu Integrated Development Plan, 2013).

Dark clay soils dominate the upper Lessos plateau, particularly on high-altitude areas where they contribute to soil moisture retention. These soils are commonly found on plateaus and are significant for their water-holding capacity, which is essential for agricultural sustainability. Rich brown loam soils, ideal for dairy farming, forestry, and crop cultivation, are widespread in high-altitude areas such as Ainabkoi and Kaptagat.

One of the key factors affecting soil performance in Kipkenyo, especially in relation to dumpsites, is the hydraulic conductivity of the soil. This parameter is crucial in determining infiltration rates and the stability of open dumpsites. Proper soil assessment is necessary to ensure effective leachate management and prevent groundwater contamination (Sivapullaiah, 2000).

3.2.4 Topography and Hydrology

Kipkenyo is characterized by a plateau landscape with varying elevations. The terrain gradually slopes from approximately 2,700 meters above sea level in Timboroa (eastern part of Uasin Gishu) to about 1,500 meters above sea level in Kipkaren (western part). Eldoret town serves as a significant geographical marker, dividing the county into two major physiographic regions. The eastern region is relatively steep, while the western part exhibits gentler slopes. The plateau nature of the county provides favorable conditions for infrastructure development, including road construction, as well as efficient mechanized farming (Uasin Gishu Integrated Development Plan, 2013).

Uasin Gishu County falls within the Lake Victoria Basin catchment area, with several key rivers flowing through it. These include Moiben, Sergoit, Kipkarren, Chepkoilel, and Sosiani. These water bodies serve various purposes, including industrial use, residential consumption, and livestock farming. The availability of surface water resources plays a vital role in sustaining the county's agricultural activities and supporting economic development (Uasin Gishu Integrated Development Plan, 2013).

3.2.5 Vegetation and Forest Cover

The natural vegetation of Uasin Gishu County consists primarily of grasslands interspersed with scattered trees and shrubs. The county has a total forest cover of approximately 29,801.92 hectares, with 56% consisting of indigenous tree species while the remainder comprises exotic plantations. The forested areas contribute to climate regulation, biodiversity conservation, and soil stability. Additionally, these forests support local economic activities such as timber production, beekeeping, and eco-tourism (Uasin Gishu Integrated Development Plan, 2013).

3.2.6. Population Growth and Demographic Trend

According to the 2019 Kenya Population and Housing Census (KPHC), Uasin Gishu County had a population of 1,163,186, comprising 580,269 males, 582,889 females, and 28 intersex individuals. This population was projected to grow to 1,232,563 by 2022, with 611,529 males and 621,034 females. The growth trend is expected to continue, with estimates reaching 1,306,865 in 2025 and 1,355,385 by 2027. The county's inter-censual population growth rate stands at 3.8%, significantly higher than the national average of 2.2% (Kenya National Bureau of Statistics [KNBS], 2019).

The high population growth in Uasin Gishu County is driven primarily by a fertility rate of 3.0%, coupled with significant immigration. The county's strategic location, with Eldoret as its economic hub, attracts people from different regions seeking employment and business opportunities. Eldoret, being one of Kenya's fastest-growing towns, serves as a commercial and industrial center, drawing in skilled and unskilled labor from neighboring counties and beyond. The presence of institutions of higher learning, such as Moi University, also contributes to population growth as students and academic staff settles in the region (KNBS, 2019).

The rising population presents both opportunities and challenges. On the positive side, the growing labor force supports industrialization, agribusiness, and service sectors, contributing to economic development. However, increased population growth also places pressure on essential services such as healthcare, education, housing, water and sanitation. The demand for urban housing has led to the expansion of informal settlements, while public infrastructure struggles to keep pace with the rising population density. To sustain the county's economic and social development, there is a need for strategic planning in urban development, resource allocation, and job creation to accommodate the rapidly increasing population effectively.

3.3 Research Design

A research design is the general plan that a researcher/s adopts to integrate different parts of a study in a consistent and systematic manner so that the research problem is appropriately dealt with. It specifies the collection, measurement, and analysis of data and it provides a structured method of conducting a study (Creswell, 2014). The selection of a research design ought to be guided by the type of study, the research objectives, as well as the kind of data required. Therefore, this study employed a descriptive research design to systematically collect and analyze data to determine the extent and nature of leachate contamination and its impact on groundwater quality without manipulating any variables. A descriptive research design focuses on what exists rather than why it exists, making it ideal for studies that seek to provide a detailed account of a phenomenon (Mugenda & Mugenda, 2003). Descriptive research design applies various data collection methods, including surveys, observations, case studies, and content analysis. It has the ability to utilize both quantitative and qualitative methods, which allows researchers to form numerical data for statistical analysis, as well as descriptive data for additional insight (Saunders, Lewis, & Thornhill, 2019). The key benefit of descriptive research design is that it can provide an accurate and thorough description of any circumstance. It is, however, limited in its ability to establish causal relationships since it neither manipulates independent variables nor controls extraneous variables (Creswell & Creswell, 2018). Despite this limitation, descriptive research remains a valuable tool for giving baseline information and informing policy.

3.4. Reagents, Instrumentation and Apparatus

For the physicochemical analysis of groundwater samples, several reagents were used to test key water quality parameters. pH measurements required buffer solutions to calibrate the pH meter, while electrical conductivity (EC) and total dissolved solids (TDS) were measured using standard conductivity calibration solutions. Nitrate levels were determined using reagents such as sodium salicylate and sulfuric acid, while chloride concentrations were analyzed using silver nitrate titration. Phosphates were measured using ammonium molybdate and ascorbic acid reagents, while sodium and potassium concentrations were determined using flame photometry, which required specific standard solutions for calibration.

The instrumentation used in the study included a digital pH meter for measuring water acidity or alkalinity and a portable electrical conductivity meter for assessing ion concentration in the groundwater samples. A spectrophotometer was employed for the colorimetric determination of nitrates and phosphates, while a flame photometer was used to measure sodium and potassium concentrations. Additionally, a turbidity meter was used to determine water clarity, providing further insights into potential contamination.

For geoelectrical resistivity surveys, the study employed a resistivity meter with electrode cables and stainless steel electrodes for measuring subsurface resistivity variations. Two-dimensional (2D) and three-dimensional (3D) resistivity imaging techniques were applied to identify zones of potential contamination and trace leachate migration pathways. The resistivity meter was connected to long AB/2 cables, allowing for measurements at various depths and lateral distances. The collected data were processed using specialized geophysical software to generate resistivity profiles and subsurface contamination maps.

Additional apparatus used in the study included sampling bottles for groundwater collection, which were pre-cleaned and labeled to prevent contamination. A GPS device was used to record the exact locations of sampling points and geoelectrical survey sites, ensuring spatial accuracy in data analysis. Glassware such as beakers, flasks, and pipettes were used in laboratory procedures, while a centrifuge was employed where necessary to separate particulates from water samples before analysis. Safety equipment, including gloves, lab coats, and goggles, was also used to maintain proper laboratory hygiene and prevent exposure to hazardous substances.

3.4.1 Instrumentations

3.4.2 Physiochemical Parameters Sampling Procedures

Permission was obtained from well owners before sampling. Water samples were collected using a sterilized plastic bucket tied to a rope. Care was taken to minimize contamination during collection. The samples were stored in sterilized polyethylene bottles, ensuring that no air bubbles were trapped inside. In total, 10 groundwater sampling sites were selected to ensure a representative analysis of contamination levels. The study employed purposive sampling to select groundwater sampling sites within the 1.5-kilometer radius of the Kipkenyo dumpsite, ensuring a representative analysis of contamination levels. Ten shallow wells (SW1–SW10) were sampled based on their proximity to the dumpsite and potential exposure to leachate contamination. The depths of the wells varied between 68 m and 290 m, and their distances from the dumpsite ranged from 110 m to 450 m.

Groundwater samples were collected between 8:00 a.m. and 11:00 a.m. to maintain consistency. For each well, two duplicate samples (e.g., SW1a and SW1b) were collected to ensure accuracy. 200 ml polyethylene bottles were used for sample collection, pre-rinsed three times with distilled water and then with sample water before final collection. The bottles were tightly corked to prevent vaporization and biodegradation of the analytes.

To preserve sample integrity, the collected water samples were immediately stored in a cool box with ice packs and transported to the laboratory, where they were refrigerated at 4°C until analysis, following standard water quality testing protocols (Gichuki & Gichumbi, 2012).

Figure 3.3: Samples of water collected in the field for analysis at a biotechnology laboratory

3.4.3 Geoelectrical Survey

A total of 26 Vertical Electrical Sounding (VES) measurements were conducted using a ABEM Terameter SAS 1000 Schlumberger electrode configuration, with a maximum electrode spacing of 50 meters (AB/2). The electrode spacing was progressively increased at intervals of 1.6 m, 2.0 m, 2.5 m, 3.2 m, 4 m, 5 m, 6.3 m, 8 m, 10 m, 13 m, 16 m, 20 m, 25 m, 32 m, 40 m, and 50 m to capture subsurface resistivity variations effectively.

The Global Positioning System (GPS) device (GERMIN 12-channel personal navigator) was used to locate each VES station, with coordinates recorded in Universal Transverse Mercator (UTM) space. The ABEM SAS 1000 Terrameter was employed for data acquisition, following standard geophysical survey protocols. The

Schlumberger array configuration was used to collect data from the study area, utilizing current electrodes (A and B) and potential electrodes (M and N) to determine subsurface resistivity.

The collected resistivity data were analyzed using Earth Imager 1D software, which facilitated automated inversion modeling to generate a layered geoelectrical model of the subsurface. The results provided insights into the extent of potential leachate contamination plumes and their impact on groundwater quality.

3.5 Sample Analysis

3.5.1 Physicochemical Parameters Measurement

To assess the impact of leachate contamination of groundwater quality, both in-situ measurements and laboratory analyses were conducted on selected physicochemical parameters. The in-situ parameters included temperature, electrical conductivity (EC), pH, and total dissolved solids (TDS), while laboratory analyses focused on nitrate ((NO_3), chloride (Cl^-), phosphate ($P0_4$), sulfate ($S0_3$) , total hardness (TH), calcium (Ca), sodium (Na), potassium (K), and biological oxygen demand (BOD). These analyses were carried out at the University of Eldoret Biotechnology Laboratory, following standard procedures for water quality assessment (APHA, 2017; WHO, 2017).

3.5.1.1 Temperature

Temperature readings were taken using the Hanna Instrument (HI) Model HI991301 digital meter (Figure 3.3). Prior to each measurement, the instrument was calibrated according to the manufacturer's guidelines to ensure accuracy. The temperature probe was first rinsed thoroughly with distilled water to remove any residual contaminants from previous measurements.

The temperature sensor of the probe was immersed in water to a depth of 10cm and was held in place until the temperature reading stabilized, at which point the measurement was recorded in degrees Celsius (°C).

After each reading, the probe was carefully removed, wiped with clean lint-free tissue paper, and rinsed again with distilled water before proceeding to the next sample. To minimize measurement errors, three replicate readings were taken for each water sample, and the average value was recorded as the final temperature measurement.

The temperature data were analyzed to assess variations across different sampling locations. Since temperature influences biochemical reactions, solubility of gases, and microbial activity in groundwater, the recorded values were compared with standard guidelines, including WHO (2017) and KEBS (2018) drinking water quality standards. High-temperature values were indicative of potential contamination from leachate infiltration, which could lead to increased bacterial activity and chemical reactions in the water.

Figure 3.4: Hanna Instrument (HI) Model HI991301 equipment used for taking temperature readings

3.5.1.2 Electrical Conductivity

Electrical conductivity (EC) was measured in situ using the Hanna Instrument (HI) Model HI991301 meter. Prior to each measurement, the probe was thoroughly cleaned with distilled water to eliminate any residual contaminants that could affect accuracy. The instrument was also calibrated according to the manufacturer's specifications using standard conductivity solutions to ensure precise readings (APHA, 2017). The conductivity probe was immersed in water to a depth of 10cm, allowed to stabilize and conductivity read in micro siemens per centimeter (µS/cm).

After each measurement, the probe was carefully removed, rinsed with distilled water, and wiped with lint-free tissue paper before being used for the next sample. To enhance accuracy, triplicate measurements were taken for each sample, and the average value was recorded (APHA, 2017).

Electrical conductivity is a key parameter in water quality assessment as it indicates the presence of dissolved ions such as chlorides, sulfates, nitrates and heavy metals that may originate from leachate contamination (WHO, 2017). Elevated EC levels suggest high ionic concentrations, often associated with groundwater pollution from landfill leachates (Tchobanoglous et al., 2014). The measured values were compared against the recommended standards by the World Health Organization (WHO, 2017) and the Kenya Bureau of Standards (KEBS, 2018) to determine potential contamination risks.

3.5.1.3 Total Dissolved Solids

The Total Dissolved Solids (TDS) in groundwater samples were measured in situ using the Hanna Instrument (HI) Model HI991301 water quality meter. This device is widely recognized for its accuracy and reliability in field measurements of TDS, pH, electrical conductivity, and temperature (Hanna Instruments, 2020).

Before taking any measurements, the probe was thoroughly rinsed with distilled water to eliminate residual contaminants and prevent cross-contamination between samples (APHA, 2017). A 50 mL groundwater sample was then carefully transferred into a sterilized 100 mL beaker to ensure a clean testing environment. The sample was gently stirred to maintain uniformity, ensuring the accurate representation of dissolved solids within the water column.

The TDS probe was immersed in the sample without touching the beaker's sides or bottom. The instrument was allowed to stabilize, and the TDS value was recorded in parts per million (ppm). To enhance accuracy, three replicate readings were taken per sample, and the average value was computed (WHO, 2017).

Between successive measurements, the electrode was rinsed with distilled water and wiped with lint-free tissue paper to prevent contamination and ensure accurate readings. The obtained TDS values were compared against the World Health Organization (WHO, 2017) and Kenya Bureau of Standards (KEBS, 2018) guidelines for drinking water quality.

Total Dissolved Solids (TDS) is a critical indicator of water quality, as it represents the concentration of dissolved inorganic and organic substances in the water. Elevated TDS levels can indicate contamination from leachate, agricultural runoff, or industrial effluents, affecting water potability and usability for domestic and agricultural purposes (Tchobanoglous et al., 2014).

3.5.1.4 Nitrate

The Brucine method was used to determine the concentration of nitrate ions (NO_3^-) in the groundwater samples collected from shallow wells. This method is based on the principle that nitrate ions react with brucine in the presence of concentrated sulfuric acid (H_2SO_4) to form an orange-red complex, which can be measured spectrophotometrically at 420 nm (Colman, 2010). To ensure accuracy, a blank sample of 25 mL filtered distilled water was set aside for use with reagents during color development. A calibration curve was prepared using standard solutions to quantify nitrate levels in the water samples. The procedure was carried out as follows: A 1L volumetric flask was used to prepare a 250 ppm nitrate standard solution by dissolving 0.3427 g of sodium nitrate ($NaNO_3$),) in distilled water. Serial dilutions were performed in 50 mL volumetric flasks to obtain standard concentrations of 0, 5, 10, 15, and 20 ppm for calibration. 2 mL of the water sample was measured into a clean test tube. 0.2 mL of 2% brucine solution was added and mixed thoroughly. The brucine solution was prepared by dissolving 1.0 g of brucine in 50 mL of concentrated sulfuric acid (95–97%) using a magnetic stirrer (APHA, 2017). 3 mL of concentrated sulfuric acid was then added and mixed well for one full minute to initiate the reaction. The solution was left in the dark for 30 minutes to allow the orange-red color to develop. The UV-Vis spectrophotometer was set to a wavelength of 420 nm, and a blank solution was used to set the instrument to zero absorbance. The absorbance of each sample was measured, and nitrate concentrations were determined using the previously prepared calibration curve (Rodier et al., 2009). The color intensity of the solution was directly related to the nitrate concentration, and results were compared to World Health Organization (WHO, 2017) and Kenya Bureau of Standards (KEBS, 2018) guidelines for drinking water safety.

Figure 3.5: Laboratory analysis of nitrates using brucine method

3.5.1.5 Chlorides

The Mohr method was employed to determine chloride (Cl^-) concentration in groundwater samples. This technique is based on the precipitation titration of chloride ions (Cl^-) with silver nitrate ($AgNO_3$) in the presence of potassium chromate as an indicator. The formation of a reddish-brown silver chromate precipitate indicates the endpoint of the titration (APHA, 2017). A 50 mL groundwater sample was pipetted into a 250 mL conical flask, and NaOH solution was added to adjust the pH to a neutral or slightly alkaline level. Two drops of phenolphthalein indicator were introduced to confirm pH neutrality. To begin the titration, 1 mL of potassium chromate indicator was added, imparting a yellow color to the solution. The sample was then titrated against 0.0141 M silver nitrate ($AgNO_3$) solution, which was gradually added drop by drop from a burette while swirling the solution. As $AgNO_3$ was introduced, chloride ions (Cl^-) reacted with silver ions (Ag^+) to form a white precipitate of silver chloride (AgCl), following the reaction: $Ag^+ + Cl^- \rightarrow AgCl(s)$. The titration continued until the endpoint was reached, indicated by a color change from bright yellow to light pinkish-yellow, signifying the formation of silver chromate when all chloride ions had reacted.

To ensure accuracy, a blank titration was conducted using distilled water in place of the sample, and the volume of $AgNO_3$ used was recorded and compared with a reference sodium chloride (NaCl) solution to determine chloride concentration in the sample.

Figure 3.6 Laboratory analysis of chlorides using Mohr method

3.5.1.6 Phosphates

The ammonium molybdate method was employed to determine the concentration of phosphates in the water samples, following the procedures outlined by APHA (2005). The necessary reagents, including ammonium molybdate reagent, stannous chloride reagent, stock phosphate solution, and standard phosphate solution, were prepared according to the prescribed methodology. A blank solution of 25 mL filtered water was set aside for color development. For analysis, 25 mL of the shallow well water sample was measured and placed in an Erlenmeyer flask. 1 mL of ammonium molybdate solution was added using a pipette, followed by two drops of stannous chloride solution. The flask was gently swirled to ensure proper mixing. Within five minutes, the appearance of a blue color confirmed the presence of phosphate. The absorbance of the developed color was measured at 650 nm using a UV-Vis spectrophotometer.

To prepare ammonium molybdate reagent, 25 g of(NH_4)6MO7O24.4 H_2O was dissolved in 175 mL of filtered water and allowed to cool before being brought to 1 liter with additional water. Stannous chloride reagent was prepared by dissolving 2.5 g of $SnCl_2$+2 H_2O in 100 mL of glycerin, with slight heating to accelerate dissolution. A stock phosphate solution (20 mg/L) was prepared by dissolving 0.286 g of KH_2PO_4 in 0.1 liter of water. This stock solution was further diluted to 200 mg/L. For the standard phosphate solutions, precise dilutions were performed: 1.0 mg/L standard was obtained by diluting 2.0 mL of the 20.0 mg/L phosphate solution with filtered water to 40 mL, with 25 mL reserved for spectrophotometric analysis. Similarly, 2.0 mg/L, 3.0 mg/L, 4.0 mg/L, and 5.0 mg/L standards were prepared using 4.0 mL, 6.0 mL, 8.0 mL, and 10.0 mL of the 20 mg/L phosphate solution, respectively, each diluted with filtered water and 25 mL of each standard solution reserved for spectrophotometric analysis. A blank sample of 25 mL purified water was also treated with the color development reagent and analyzed.

Figure 3.7 Laboratory analysis of phosphates

3.5.1.7 Sodium and Potassium

The determination of sodium (Na^+) and potassium (K^+) concentrations in water samples was conducted using a flame photometer, following standard analytical procedures. The reagents used in the analysis included NaCl standard solutions of 0.25, 0.5, 1.0, 2.0, 4.0, and 5.0 mM and KCl standard solutions of 0.1, 0.2, 0.5, 1.0, 1.5, and 2.0 mM. Additionally, an oral rehydration sachet was used to prepare test solutions for analysis. To prepare the rehydration solution, the contents of an oral rehydration packet were carefully transferred into a cleaned 250 mL beaker. 150 mL of distilled water was added, and the solution was stirred gently until the contents fully dissolved. The solution was then transferred into a 200 mL volumetric flask, ensuring that all the residues were rinsed from the beaker using small portions of distilled water. The volumetric flask was filled up to the 200 mL mark with distilled water, and the solution was thoroughly mixed. For analysis, a 1:50 dilution of the prepared solution was made by pipetting an aliquot into a 100 mL volumetric flask and topping it up with distilled water. The pure stock solution was reserved for further experimental use.

Before conducting the analysis, the flame photometer was properly set up and calibrated. The instrument was connected to the gas, air, and electrical supplies, ensuring that the main gas tap remained open. The "Gas" and "Sensitivity" controls were turned fully counterclockwise before switching on the instrument. A sodium optical filter was inserted, and the galvanometer clamp was released. Once the gas ignition was complete, the mica window was closed, and the main gas supply was turned on. The air supply control was adjusted to 10 lb/in^2, allowing the system to stabilize for one to two minutes before proceeding

A beaker filled with distilled water was placed appropriately so that the draw tube could continuously pass water through the photometer, ensuring a baseline calibration. Even when no salt solution was being measured, distilled water continued to flow through the photometer to maintain stability. The gas control was gradually adjusted to produce a blue flame with a large central blue cone, optimizing the instrument for accurate readings. The galvanometer was set to zero using the Set Zero control.

For sodium measurement, the 5.0 mM NaCl standard solution was introduced into the instrument, and the sensitivity control was adjusted until the galvanometer displayed a reading of 100. The sodium calibration curve was developed by replacing the NaCl standards from 4.0 mM to 0.25 mM, recording each reading accordingly. After calibrating the instrument with NaCl standards, the rehydration sachet solution (1:50 diluted) was introduced, and its reading was noted after allowing water to flow through the apparatus for one to two minutes.

For potassium measurement, the sodium filter was replaced with a potassium optical filter, and the KCl standards were introduced, starting with the 2.0 mM KCl standard, adjusting the sensitivity control to 100 on the galvanometer. The standards were then introduced in reverse order, from 1.5 mM to 0.1 mM, recording the readings. The rehydration sachet solution was analyzed for potassium content, and after completing the measurements, distilled water was allowed to flow through the photometer until the flame returned to its original colorless state.

Once the instrument was no longer needed, the gas supply was shut off, and the equipment was cleaned to ensure proper maintenance for future analyses. The sodium and potassium concentrations were determined based on the calibration curves generated from the standard solutions. This method provided accurate quantification of Na^+ and K^+ concentrations in the water samples, allowing for proper assessment of their levels in the tested solutions.

3.5.2 Geoelectrical survey

Geoelectrical analysis is a fundamental geophysical technique used to assess subsurface electrical properties by measuring the resistivity of different geological formations. This method is widely employed in hydro geological studies, mineral exploration, and environmental investigations to identify water-bearing zones, stratigraphic variations, and possible contamination layers. In this study, the Vertical Electrical Sounding (VES) technique was used with the Schlumberger electrode configuration to acquire resistivity data and analyze subsurface structures. The ABEM SAS 1000 Terameter was used to obtain field measurements and the data were processed using the Earth Imager 1D software to generate subsurface resistivity models.

Field measurements were conducted using a resistivity meter, which consists of a power source, electrodes, and a measuring device. The current electrodes (C1 and C2) were inserted into the ground at a set distance apart, and a voltage difference was measured between the potential electrodes (P1 and P2). The apparent resistivity was determined based on Ohm's law using the equation:

$pa = 2k\frac{\Delta v}{\Delta l}$……………………………………………………Equation (10)

Where ΔV is the measured potential difference (mV) between the potential electrodes M and N, ΔI is the applied current (mA), and K is the geometric factor (Kg), which depends on the arrangement of the electrodes. For the half-Schlumberger configuration, the current flows between the A and B electrodes, and the geometric factor is derived using the equation:

$K\frac{\left(\frac{AB}{2}\right)^2-\left(\frac{MN}{2}\right)^2}{(2MN)}\pi$…………………………………………………Equation (11)

Where AB represents the distance between the current electrodes and MN is the spacing between the potential electrodes. Since π = 3.142, the apparent resistivity is an average of the true resistivities of all geological layers that the current penetrates. By systematically varying the electrode spacing, resistivity variations within the subsurface were determined. The Schlumberger array was particularly useful as it provided higher resolution at greater depths compared to other configurations.

3.6 Data Processing and Interpretation

The acquired resistivity data were processed using Earth Imager 1D, a specialized software for resistivity interpretation. This software utilizes a 2D finite element method for forward modeling calculations and supports both smooth model inversion and damped least squares inversion methods. The qualitative interpretation of resistivity curves was conducted by analyzing their shapes at each site, allowing for the determination of the number of layers and their respective resistivity values.

The resistivity curves obtained from the 26 VES locations were classified into different types based on their shapes. These curves were correlated with known litho logical data to infer the geological formations present in the subsurface. Typically, high resistivity values indicate compact rock formations or dry layers, while low resistivity values suggest water-saturated zones, clay deposits, or conductive materials. The resistivity results were also compared with borehole log data to validate the interpretations.

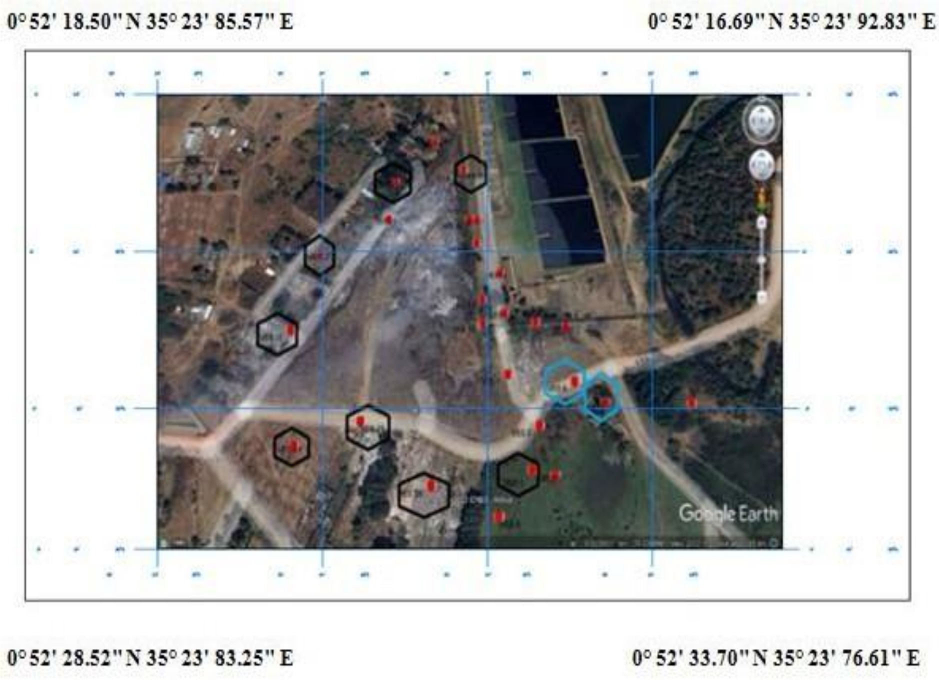

Figure 3.8: Map of the study area showing distribution of vertical electrical sounding methods points

Figure 3.9: Terameter

Figure 3.10: The survey setup at the site

All collected data were carefully documented and stored for subsequent analysis. The resistivity values were later processed using Earth Imager 1D software, which facilitated the generation of subsurface resistivity models. These models were used to interpret the geological and hydro geological conditions of the study area.

3.7 Data Collection Procedures

The data collection process for this study followed a structured approach to ensure compliance with regulatory requirements and the integrity of the collected data. Before the commencement of field activities, the necessary research permits were sought and obtained from the National Commission for Science, Technology and Innovation (NACOSTI), the County Government, and the relevant university authorities. These approvals ensured that the study adhered to ethical guidelines and legal research frameworks.

Upon securing the required permits, preliminary site visits were conducted to familiarize the research team with the study area and identify optimal locations for data collection. A reconnaissance survey was carried out to assess accessibility, environmental conditions, and the suitability of sampling points. During these visits, consultations were held with local authorities and community representatives to explain the purpose of the study and seek their cooperation.

3.8 Data Analysis

The collected data were processed and examined systematically to obtain pertinent conclusions for the study objectives.

3.8.1 Geoelectrical Data Analysis

The Vertical Electrical Sounding (VES) data obtained through the Schlumberger array configurations were processed using Earth Imager 1D software. The software applied automatic inversion modeling techniques to convert the apparent resistivity values into subsurface resistivity profiles. The resistivity curves obtained from the field were compared against standard resistivity models to determine the number and characteristics of subsurface layers. The resistivity values were correlated with known geological formations to interpret the underlying strata. The interpreted resistivity data were used to create 1D geoelectric models, which provided a layered representation of subsurface geological formations. These models helped in understanding the lithology, groundwater potential zones, and variations in soil and rock properties.

3.8.2 Physicochemical Parameters

Data was inserted into SPSS version 26 and analyzed using descriptive statistics such as means. Pearson's correlation coefficient (r) was used to determine the strength and direction of relationships between variables such as pH and conductivity, DO and TDS, and nutrient levels. A one-way ANOVA test was conducted to determine if there were statistically significant differences in physicochemical parameters between various sampling sites. The analyzed data were compared against national and international water quality standards, such as those set by the World Health Organization (WHO) and the Kenya Bureau of Standards (KEBS).

3.9 Ethical Considerations

The study adhered to strict ethical guidelines to ensure that all research activities were conducted responsibly, with integrity, and in compliance with relevant regulatory frameworks. Ethical principles were followed at every stage of the research process to safeguard the rights and welfare of all stakeholders involved. Before the fieldwork could commence, the necessary research clearances and permits were sought from the National Commission for Science, Technology, and Innovation (NACOSTI), the County Government, and the respective university authorities. The clearances were needed to ensure that the research conformed to national research policies and institutional ethical standards. Obtaining formal permission not only provided the research with the necessary legitimacy but also to guarantee unencumbered relationships with local populations and respective agencies in the process of data collection.

Contact with local leaders, landowners and a local community representative was made prior to conducting the research in order to be open and facilitate mutual understanding. Research goals, methods, and potential effects of the study were explained to concerned stakeholders in a clear manner. Informed consent was requested before entering private land, surveys, or sampling from specified areas. Voluntary cooperation was promoted, misunderstandings were minimized, and respect for local cultural and community values was upheld.

The confidentiality of all collected data was strictly maintained to protect the privacy of individuals and institutions involved in the study. Sensitive information such as GPS coordinates, survey results, and field notes was securely stored and accessed only for academic and research purposes. Data handling procedures incorporated rigorous validation and verification steps to ensure accuracy, reliability, and authenticity of the information gathered. The study upheld research integrity by preventing unauthorized access, falsification, or misrepresentation of data.

The findings of the study were presented with objectivity, accuracy, and scientific integrity. No data were manipulated, selectively reported, or misrepresented to alter research outcomes. Acknowledgment was given to all sources used, and previous studies were appropriately cited to uphold academic honesty and credibility. The study also ensured that interpretations and conclusions were based on sound scientific reasoning, avoiding any form of bias or misrepresentation.

CHAPTER FOUR

DATA PRESENTATION AND ANALYSIS

4.1 Introduction

This chapter presents the findings from the geoelectrical and physicochemical evaluation of leachate contamination of groundwater quality within the vicinity of Kipkenyo Dumpsite, Eldoret Municipality, Uasin Gishu County, Kenya. This chapter presents the findings of the study based on the data collected, analyzed, and interpreted in relation to the study objectives. The physicochemical analysis covers parameters such as pH, electrical conductivity (EC), total dissolved solids (TDS), heavy metals, and other key water quality indicators. The results are compared with national and international water quality standards to ascertain their suitability for human consumption and other uses. The geoelectrical resistivity survey results are presented in the form of apparent resistivity values, 2D and 3D resistivity imaging, and interpretations of subsurface lithology to determine potential contamination zones.

4.2 Mean Levels of Selected Physiochemical Parameters

The physicochemical properties of groundwater are essential indicators of water quality, particularly in areas susceptible to leachate contamination. The study analyzed several physicochemical parameters, including pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), nitrates, chloride, phosphates, sodium, and potassium in selected shallow wells near Kipkenyo Dumpsite. Table 4.1 presents the mean levels of selected physicochemical parameters measured from ten shallow wells in the study area.

Table 4.1: **Mean Levels of Selected Physicochemical Parameters in Shallow Wells**

Well ID	pH	Temperature (°C)	EC (µS/cm)	TDS (ppm)	Nitrates (mg/L)	Chloride (mg/L)	Phosphates	Sodium (mg/L)	Potassium (mg/L)
SW1	9.21	20.4	113	57	0.67	2.50	1.01	7	49
SW2	11.70	21.10	76	38	0.28	2.40	1.04	7	47
SW3	7.63	20.40	58	29	0.01	2.00	0.36	6	37
SW4	6.74	21.40	66	33	0.19	2.30	0.71	6	37
SW5	6.65	21.60	57	28	0.33	4.40	0.64	7	41
SW6	6.62	21.70	42	21	0.10	2.50	0.49	5	42
SW7	6.10	22.00	84	42	0.26	2.20	0.68	8	50
SW8	6.12	21.90	81	41	0.32	2.70	0.40	8	51
SW9	5.94	21.70	83	41	0.20	1.90	0.51	8	58
SW10	6.01	21.80	99	49	0.16	2.40	0.26	10	6
Mean	7.27	21.40	75.9	37.9	1.25	2.56	0.61	7.2	47.8

Source: Author, 2023

The results in Table 4.1 indicate that pH values range from 5.94 to 11.70, with a mean of 7.27, suggesting varying degrees of acidity and alkalinity across the wells. SW2 recorded the highest pH (11.70), indicating possible contamination by alkaline substances, while SW9 had the lowest pH (5.94), suggesting acidic conditions potentially influenced by leachate infiltration. Temperature variations were minimal, with values ranging from 20.4°C to 22.0°C, averaging 21.4°C, which is within the typical range for shallow groundwater.

Electrical conductivity (EC) and total dissolved solids (TDS) serve as indicators of dissolved ion concentration in water. The EC values ranged between 42 µS/cm (SW6) and 113 µS/cm (SW1), with a mean of 75.9 µS/cm, reflecting variations in the dissolved mineral content across different wells. Similarly, TDS values ranged from 21 ppm (SW6) to 57 ppm (SW1), with a mean of 37.9 ppm, indicating moderate levels of dissolved solids in the groundwater.

The concentration of nitrates, an important parameter for assessing contamination from organic waste and agricultural runoff, varied from 0.01 mg/L (SW3) to 0.67 mg/L (SW1), with a mean of 1.25 mg/L. The values, though relatively low, suggest possible nutrient enrichment from leachate percolation. Chloride concentrations ranged from 1.90 mg/L (SW9) to 4.40 mg/L (SW5), with an average of 2.56 mg/L, which is within the permissible limits for drinking water. Phosphate levels were also examined, with values ranging from 0.26 mg/L (SW10) to 1.04 mg/L (SW2), averaging 0.61 mg/L, indicating possible contributions from organic matter and detergent residues.

Sodium and potassium levels varied across the wells, with sodium concentrations ranging from 5 mg/L (SW6) to 10 mg/L (SW10), averaging 7.2 mg/L. Potassium levels ranged from 6 mg/L (SW10) to 58 mg/L (SW9), with a mean of 47.8 mg/L. These variations suggest potential leachate intrusion, affecting the ionic composition of groundwater in the study area.

4.3 Comparisons of Mean Levels of Selected Physicochemical Parameters Across Different Shallow Wells Locations

To determine whether there were significant differences in physicochemical parameters across different shallow well locations near the Kipkenyo Dumpsite, a one-way analysis of variance (ANOVA) was conducted. Table 4.2 presents the ANOVA results for selected parameters, including pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), nitrates, chloride, phosphate, sodium, and potassium. The key statistical indicators reported include the degrees of freedom (Df), F-values, and significance levels (P-values).

Table 4.2: One-Way ANOVA Results for *Selected Physicochemical Parameters* **Across Different Locations of shallow Wells in Kipkenyo dumpsite**

Parameters	**Df**	**F**	**P**
pH	9	9.36	0.00
Temperature	9	4.12	0.058
EC	9	1.74	0.002
TDS	9	0.85	0.009
Nitrates	9	5.89	0.00
Chlorides	9	2.85	0.00
Phosphate	9	3.14	0.35
Sodium	9	0.87	0.89
Potassium	9	1.84	0.02

Source: Author, 2023

The pH, nitrates, chlorides, EC, and TDS levels in Kipkenyo dumpsite wells water samples varied significantly ($p<0.05$) across different locations. The results indicate that pH variations across the wells were statistically significant ($F = 9.36$, $P = 0.00$), suggesting that some wells exhibited higher alkalinity or acidity compared to others. This variation could be attributed to leachate contamination from the dumpsite, which alters the chemical composition of groundwater. Similarly, nitrates ($F = 5.89$, $P = 0.00$) and chlorides ($F = 2.85$, $P = 0.00$) showed significant differences among the sampled wells, indicating potential contamination sources that may be influencing water quality at specific locations. The elevated nitrate levels in some wells may be linked to organic waste decomposition, while chloride variations may reflect the leaching of salts from the dumpsite.

Electrical conductivity (F = 1.74, P = 0.002) and total dissolved solids (F = 0.85, P = 0.009) also exhibited statistically significant variations across well locations, further reinforcing the likelihood of differential contamination levels. These parameters are key indicators of dissolved ion concentrations and suggest that groundwater chemistry is being influenced by external inputs, possibly from the dumpsite leachate.

On the other hand, temperature differences were not statistically significant (F = 4.12, P = 0.058), indicating relatively uniform thermal conditions across all sampled wells. This result is expected, as temperature variations in shallow groundwater are often minimal unless influenced by external geothermal or industrial factors.

For phosphate (F = 3.14, P = 0.35) and sodium (F = 0.87, P = 0.89), no significant differences were observed among the different well locations, suggesting that these parameters are relatively stable and less affected by localized contamination sources. However, potassium levels exhibited a statistically significant difference (F = 1.84, P = 0.02), indicating potential variations in mineral dissolution or contamination from organic sources.

4.4 Comparison of Physicochemical Parameters Mean Levels with WHO and NEMA Standards

The comparison of the mean levels of selected physicochemical parameters in groundwater samples from shallow wells near the Kipkenyo Dumpsite with the standards set by the World Health Organization (WHO) and the National Environment Management Authority (NEMA) is illustrated in Figure 4.1. The results suggest that the groundwater quality in the vicinity of the Kipkenyo Dumpsite is within safe limits for most physicochemical parameters.

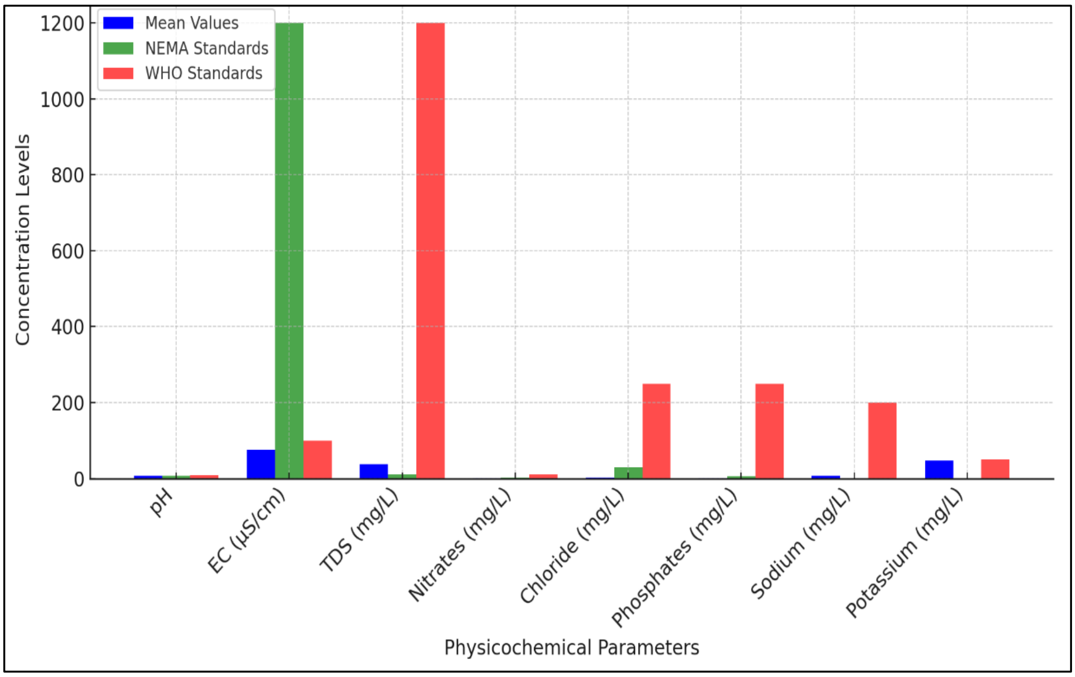

Figure 4.1: Comparison of Physicochemical Parameters Mean Levels with WHO and NEMA Standards

From the findings, the pH levels in the sampled wells averaged 7.27, which falls within the acceptable range of 6.5–8.5 set by NEMA but is slightly below the WHO-recommended pH of 8.5. This suggests that the water is mostly neutral to slightly alkaline, making it generally safe for consumption in terms of acidity and alkalinity. The electrical conductivity (EC) mean value of 75.9 µS/cm is significantly lower than the WHO threshold of 100 µS/cm and the NEMA limit of 1200 µS/cm, indicating that the groundwater has relatively low mineralization and dissolved ions.

The total dissolved solids (TDS) level in the sampled wells had a mean of 37.9 mg/L, which is far below the WHO and NEMA limits of 1200 mg/L. This suggests that the water contains a minimal amount of dissolved organic and inorganic substances. Similarly, nitrate concentrations were well below the safety limit, with a mean value of 1.25 mg/L compared to the WHO and NEMA guideline of 10 mg/L. This indicates that nitrate pollution from leachate or agricultural runoff is not currently a major concern in the study area.

In terms of chloride levels, the mean concentration of 2.56 mg/L is significantly lower than the WHO limit of 250 mg/L and the NEMA standard of 30 mg/L. This suggests that the water is not significantly affected by chloride contamination, which is commonly linked to leachate intrusion or wastewater infiltration. The phosphate concentration (mean 0.61 mg/L) is also within the NEMA limit of 6 mg/L, suggesting minimal phosphate contamination.

For sodium and potassium, the study found mean concentrations of 7.2 mg/L and 47.8 mg/L, respectively. While the sodium levels are relatively low compared to WHO's recommended limit of 200 mg/L, potassium levels are slightly below WHO’s threshold of 50 mg/L, indicating that both elements are present in acceptable amounts.

4.5 Vertical Electrical Sounding (VES) Analysis

Vertical Electrical Sounding (VES) was conducted to investigate subsurface resistivity variations and assess potential groundwater contamination from leachate infiltration near the Kipkenyo Dumpsite. The analysis categorizes the VES curves into KH, H, K, Q, and A types, representing different subsurface geoelectric layer configurations.

4.5.1 KH-Type Curves

The KH-type curves demonstrate a four-layer geoelectric structure, characterized by alternating layers of high and low resistivity. This resistivity variation is indicative of differences in lithological composition, which in turn influences the subsurface hydrological properties. The presence of alternating resistivity values suggests a combination of conductive and resistive materials, likely representing different geological formations such as sandy, clayey, or rocky layers. This configuration is essential for understanding groundwater potential and aquifer distribution within the study area.

The recorded resistivity values range from 145 Ωm to 3179 Ωm and 76.5 Ωm to 2135.9 Ωm in different survey locations. These values suggest varying degrees of water saturation and lithological heterogeneity. Higher resistivity values generally correspond to dry, compacted, or less porous materials, such as consolidated rock formations, while lower resistivity values indicate water-bearing formations, such as fractured rock or porous sediments. The differences in resistivity within the four-layer geoelectric structure provide insights into the depth and extent of aquifers.

The analysis of Figure 4.2 indicates water occurrence at depths ranging between 14.88 meters and 33.55 meters, implying the presence of intermediate to deep aquifers. These depths suggest potential groundwater reservoirs that may be suitable for borehole development or groundwater extraction. Meanwhile, Figure 4.3 reveals the presence of both shallow aquifers (4.33 meters - 14.88 meters) and deeper aquifers extending beyond 29.66 meters. The identification of shallow aquifers is particularly significant for local water supply, as they are often more accessible for hand-dug wells or shallow boreholes. Conversely, deeper aquifers may provide more sustainable water sources, particularly in areas where surface water is limited or seasonal variations affect groundwater recharge.

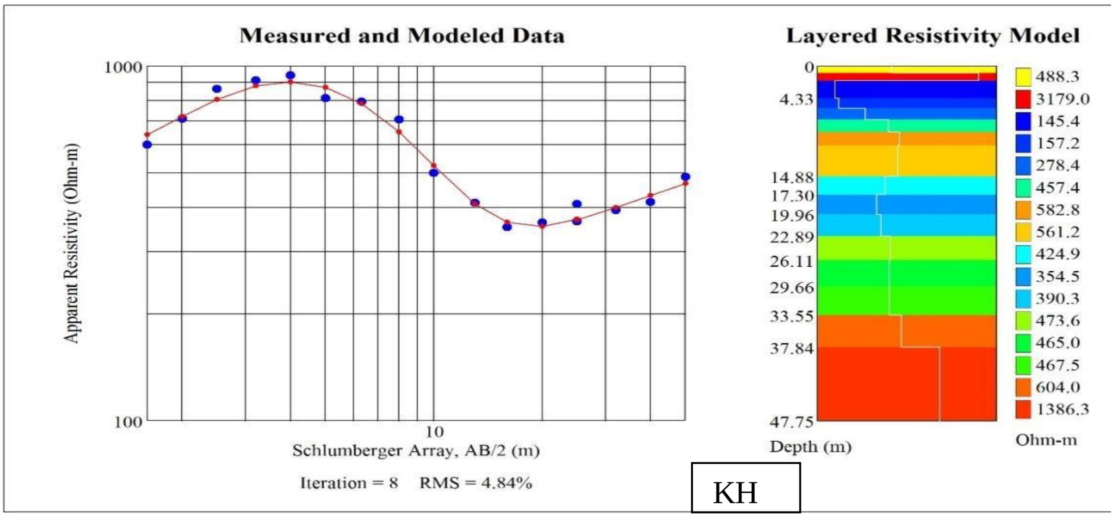

Figure 4.2: A Typical KH- type of a curve representing profile 1 in the survey area

According to Figure 4.2, the resistivity values span a wide range, from 145 Ωm to 3179 Ωm, highlighting significant variations in subsurface material composition. These variations suggest the presence of different geological formations with distinct electrical properties. The high resistivity values likely correspond to compacted rock formations, such as granitic or basaltic layers, or zones with lower porosity and minimal water content. In contrast, the lower resistivity values indicate the presence of water-bearing formations, such as fractured rock, sandy sediments, or weathered zones, which are more conducive to groundwater storage and flow.

The identification of water-bearing zones at depths ranging from 14.88 meters to 33.55 meters suggests the presence of a moderately deep aquifer. This aquifer is crucial for groundwater extraction, as it falls within a depth range suitable for borehole drilling and water supply systems. The presence of such an aquifer can be beneficial for both domestic and agricultural water needs, particularly in regions where surface water resources are unreliable or scarce.

Furthermore, the distribution of resistivity values provides insight into the geological layering of the subsurface. The alternating high and low resistivity zones suggest a stratified formation where water-bearing layers are interspersed with more resistive, less permeable formations. This configuration could influence groundwater recharge, flow, and storage capacity, making it necessary to conduct further hydrogeological assessments before large-scale groundwater extraction.

Additionally, the presence of compacted or low-porosity formations at certain depths could act as confining layers, potentially creating a semi-confined or confined aquifer system. Such aquifers may have better water quality and higher storage potential, as they are less susceptible to surface contamination.

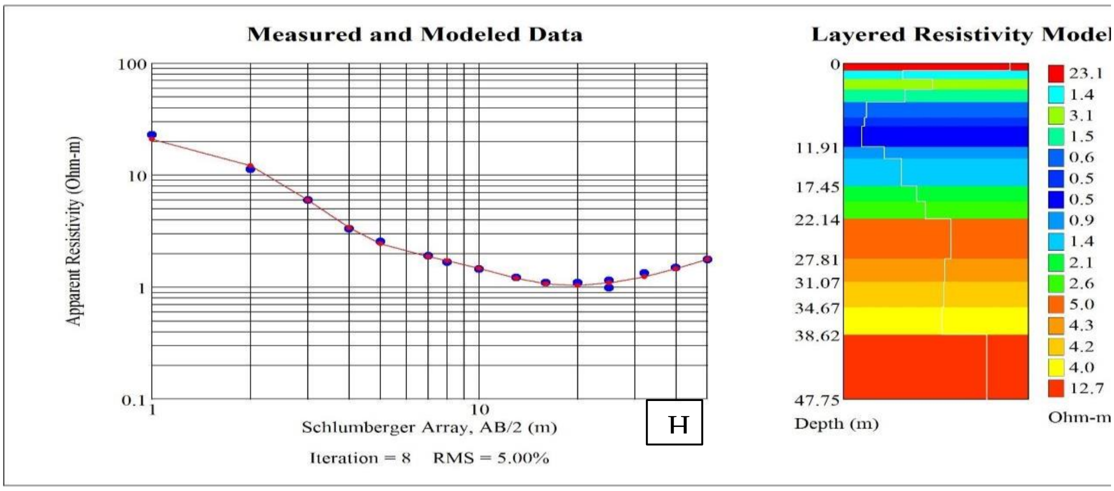

Figure 4.3: A Typical KH-Type of a curve representing

The resistivity values, ranging from 76.5 Ωm to 2135.9 Ωm, indicate significant subsurface heterogeneity and the presence of both shallow and deeper aquifers. These variations in resistivity suggest differences in lithological composition, permeability, and water saturation levels. The lower resistivity values are indicative of water-bearing formations, such as sandy or fractured rock layers, which facilitate groundwater storage and movement. In contrast, the higher resistivity values likely correspond to more compacted, less porous geological formations such as dense bedrock, dry clay, or consolidated sediments that act as barriers to water flow.

The shallow aquifer, observed at depths of 4.33 meters to 14.88 meters, suggests the presence of a permeable, water-bearing formation relatively close to the surface. This shallow aquifer is particularly significant for groundwater accessibility, as it may support hand-dug wells, shallow boreholes, and other small-scale water supply systems. Such aquifers often rely on direct recharge from rainfall or surface water infiltration, making them highly responsive to seasonal variations. However, their proximity to the surface also makes them more susceptible to contamination from agricultural runoff, industrial waste, and other surface pollutants, necessitating proper water quality monitoring and management.

The deeper aquifer, occurring beyond 29.66 meters, suggests a more extensive groundwater reservoir at greater depths. This aquifer is likely confined or semi-confined by overlying impermeable or low-permeability layers, which can enhance water quality by reducing the risk of contamination from surface activities. Deep aquifers typically provide more stable and sustainable water sources, as they are less affected by seasonal fluctuations and can store larger volumes of groundwater over extended periods. These deeper water-bearing formations are particularly valuable for long-term water supply projects, including municipal and agricultural use, where higher yields and consistent water availability are required.

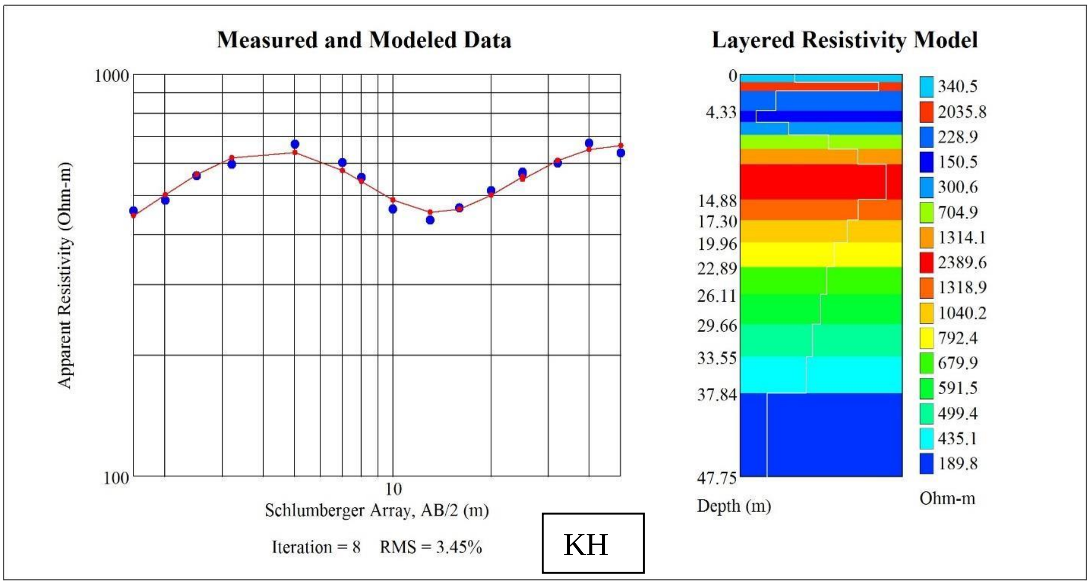

Figure 4.4: A Typical KH-type of a curve representing profile 4 in the survey area

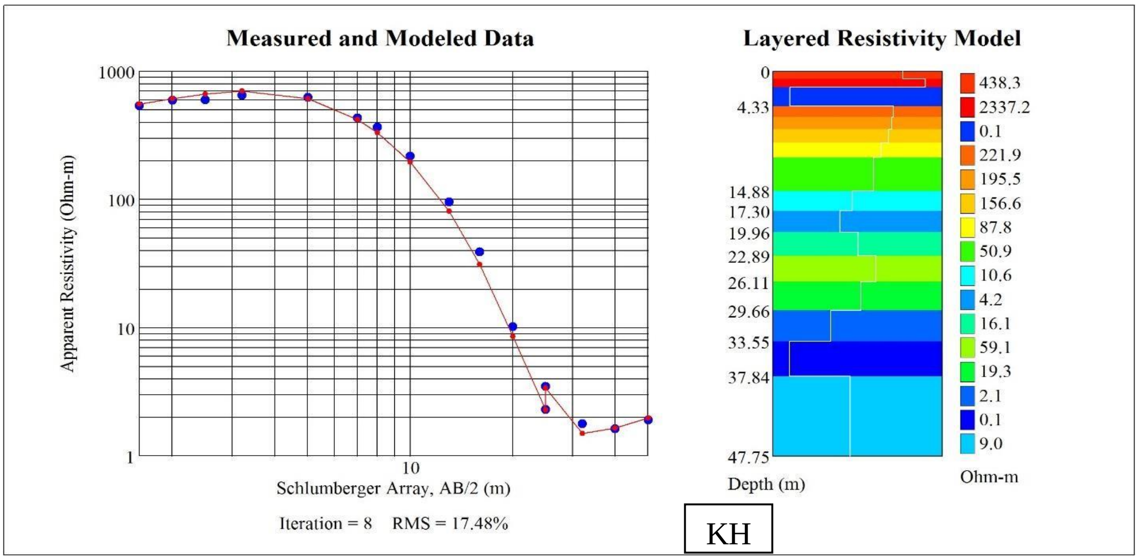

Figure 4.5: A Typical KH-type of a curve showing representing profile 5 in the survey area

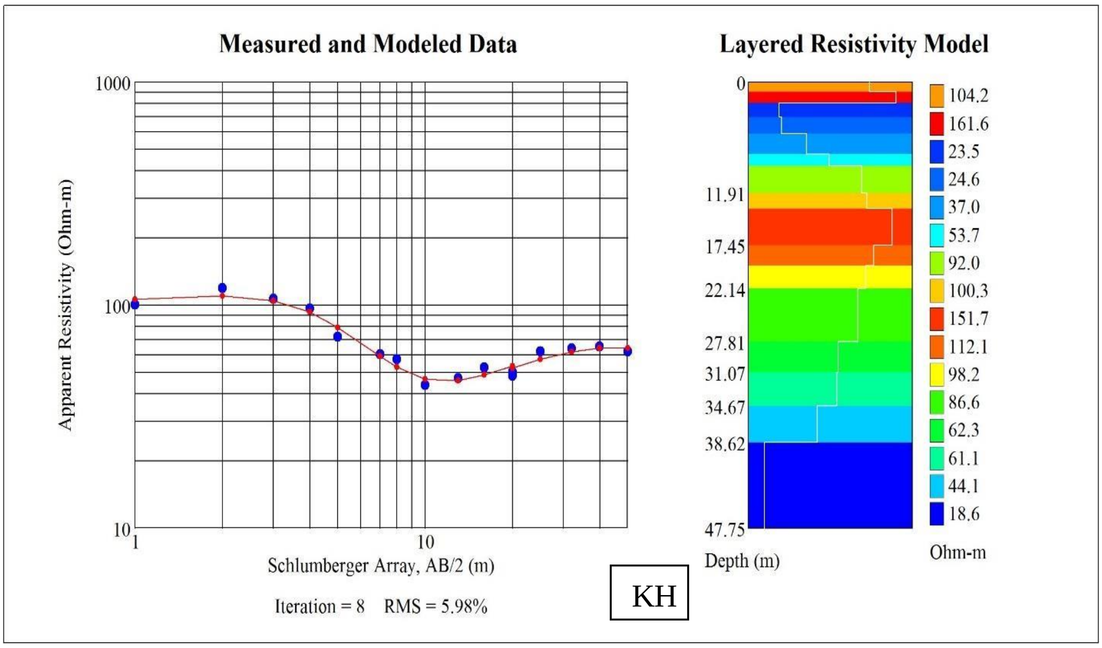

Figure 4.6: A Typical KH-type of a curve representing profile 8 in the survey area

According to the findings presented in Figure 4.4, 4.5, 4.6, 4.7 and 4.8, the resistivity values indicate significant groundwater potential with minimal contamination. The water-bearing zones are identified at depths ranging from 4 m to over 37.84 m, with variations across profiles.

The findings presented in Figures 4.4, 4.5, 4.6, 4.7, and 4.8 indicate considerable groundwater potential, as evidenced by the range of resistivity values that suggest the presence of water-bearing formations with minimal contamination. The resistivity variations across these profiles reflect differences in lithological composition, permeability, and the degree of water saturation, all of which influence the groundwater storage and flow characteristics of the subsurface.

Water-bearing zones are identified at depths ranging from 4 meters to over 37.84 meters, suggesting the presence of both shallow and deep aquifers. The shallow aquifers, occurring at depths as low as 4 meters, indicate the presence of permeable formations such as sandy or weathered rock layers that allow for water infiltration and storage. These shallow groundwater sources are particularly important for local water supply needs, as they are more accessible for wells and boreholes. However, their proximity to the surface makes them more vulnerable to contamination from surface activities such as agriculture, industrial discharge, and domestic wastewater. The minimal contamination observed in the resistivity profiles suggests that these aquifers may be protected by natural filtration processes or by overlying impermeable layers that prevent pollutants from infiltrating the groundwater system.

The deeper aquifers, which extend beyond 37.84 meters, indicate the presence of more substantial groundwater reserves at greater depths. These aquifers are likely confined or semi-confined by impermeable or low-permeability formations such as clay or dense rock layers, which protect them from surface contamination. The existence of deep water-bearing formations suggests a stable and reliable groundwater source that can support long-term water supply needs, including municipal, agricultural, and industrial applications. Such deep aquifers are typically less affected by seasonal variations in rainfall and surface water availability, making them critical for sustaining water resources in areas prone to drought or water scarcity.

The variations in groundwater depth across different profiles highlight the complex nature of the subsurface hydrogeology. The differences in aquifer depths and resistivity values suggest that groundwater availability is influenced by local geological structures, such as faults, fractures, and variations in sediment composition. Understanding these variations is essential for effective groundwater exploration, ensuring that extraction points are optimally located to maximize yield while preserving aquifer sustainability. Additionally, the presence of minimal contamination indicates that these water sources can be used safely with appropriate management and periodic monitoring to maintain water quality standards.

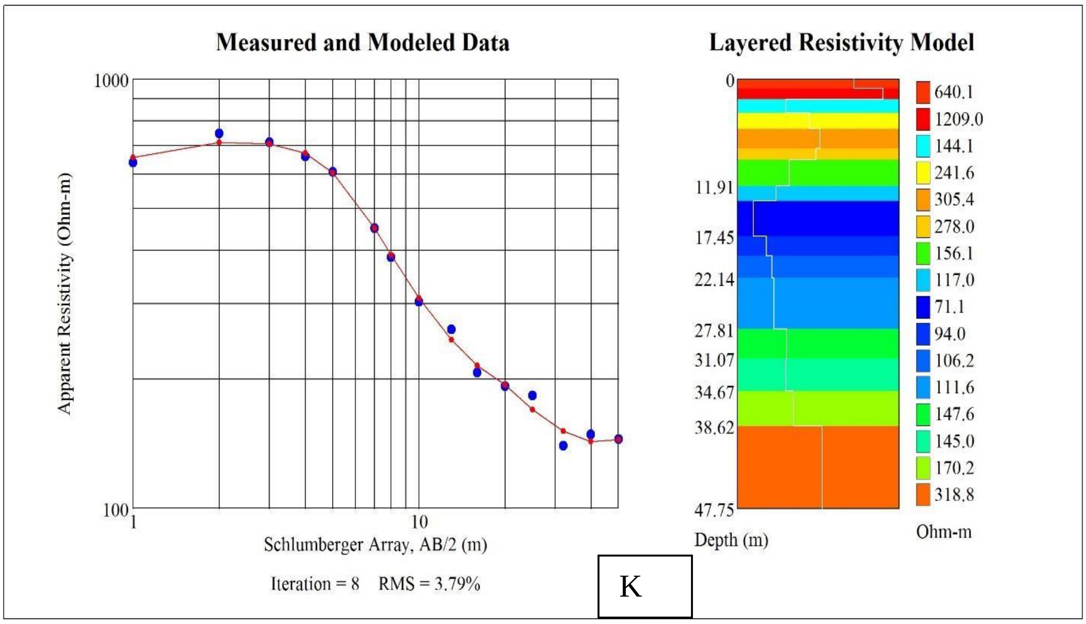

Figure 4.7: A Typical KH-type of a curve representing profile 9 in the survey area

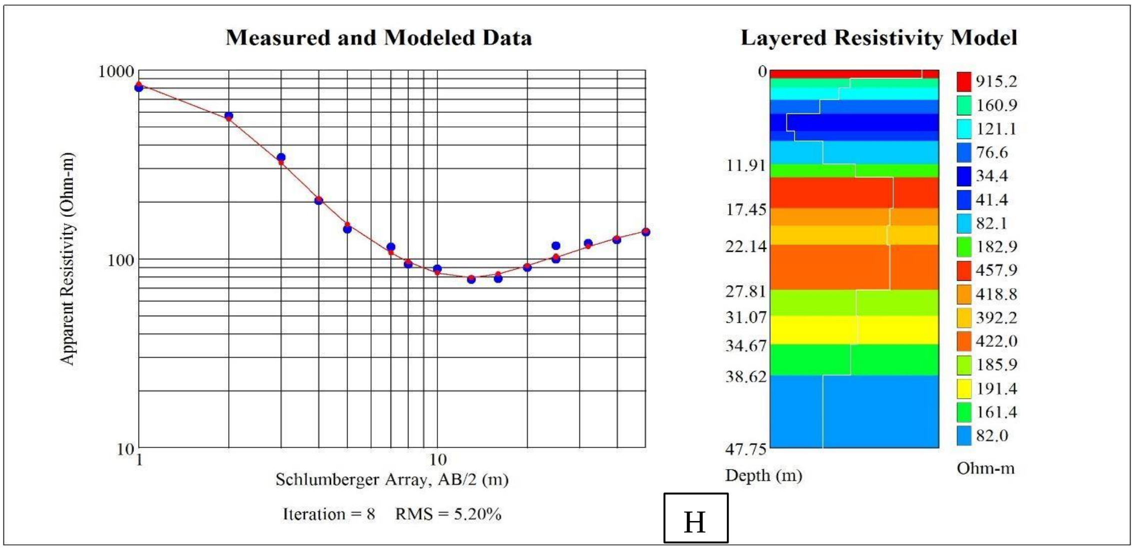

Figure 4.8: A Typical KH-type of a curve representing profile 12 in the survey area

The profile illustrated in Figure 4.9 exhibits unique low resistivity values, ranging from 0.1 Ωm to 2337.2 Ωm, which suggest the presence of highly conductive zones within the subsurface. Such low resistivity readings often indicate materials with high moisture content or conductive substances, such as clay-rich formations, saline water intrusion, or contamination from leachates. The presence of these highly conductive zones is a critical indicator of potential environmental concerns, particularly in relation to groundwater quality and subsurface integrity.

The identification of specific depth ranges, notably between 3–4.33 meters and 14.88–19.96 meters, suggests that these conductive anomalies may be attributed to pollution from anthropogenic sources or geological structures such as fault zones. The shallow depths, particularly in the 3–4.33-meter range, could indicate contamination from surface activities, including agricultural runoff, industrial waste discharge, landfill leachates, or domestic sewage infiltration. These pollutants often percolate through permeable layers, leading to localized groundwater contamination and increasing the electrical conductivity of the affected zones.

The deeper conductive zones, found at depths between 14.88 and 19.96 meters, may be linked to fault-induced anomalies or deeper contamination sources. Faults and fractures in geological formations can serve as pathways for the migration of contaminants, allowing pollutants to penetrate deeper into the subsurface. In some cases, these zones may also be indicative of natural saline water intrusion or the presence of clay deposits, which inherently exhibit low resistivity due to their high ion-exchange capacity and water retention properties.

The presence of such anomalies underscores the importance of detailed hydrogeological and geochemical investigations to ascertain the precise nature and origin of the conductivity variations. If leachate contamination is confirmed, mitigation measures such as controlled waste disposal, improved drainage systems, and groundwater remediation techniques may be required to prevent further degradation of water quality. Similarly, if fault-induced anomalies are responsible for the observed low resistivity values, structural assessments and monitoring should be conducted to evaluate their impact on groundwater movement and potential risks associated with seismic activity or subsurface instability.

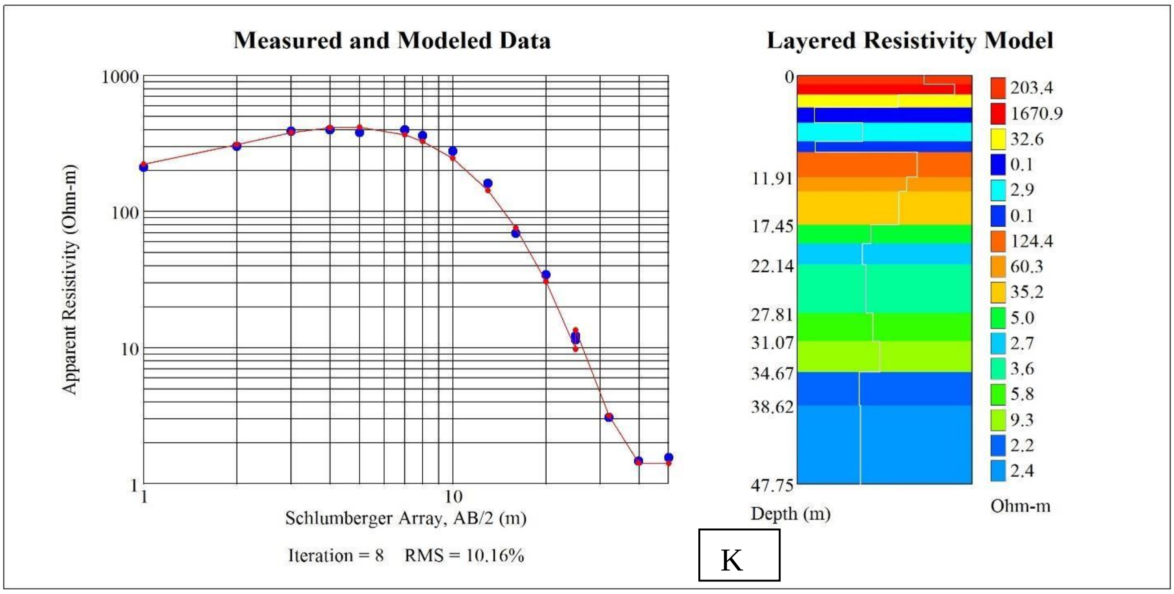

Figure 4.9: A Typical KH-Type of a curve representing profile 6 in the survey area

4.5.2H-Type Curves

H-type curves represent a three-layer geoelectric structure characterized by an initial low-resistivity layer, followed by a higher resistivity middle layer, and then another low-resistivity layer at greater depths. This pattern suggests a subsurface sequence in which the top layer consists of highly conductive materials such as clay-rich deposits, moisture-saturated soils, or zones affected by pollution. The presence of clay, in particular, is associated with low resistivity due to its fine-grained texture and high water retention capacity, which enhances conductivity. Alternatively, pollution effects, especially from anthropogenic activities, can lead to increased ion concentrations in groundwater, further reducing resistivity.

The profiles observed in Figures 4.10 to 4.16 display variations in resistivity, but a common trend is the identification of groundwater potential at depths beyond 13 meters.

This suggests that despite the presence of conductive surface layers, deeper formations contain significant water-bearing zones, making them potential targets for groundwater exploration and extraction. The resistivity contrasts across these profiles indicate stratified subsurface conditions where permeable water-bearing formations are sandwiched between less permeable or impermeable layers, possibly forming confined or semi-confined aquifers.

A particularly notable case is presented in Figure 4.3, where extremely low resistivity values ranging from 0.5 Ωm to 5 Ωm are recorded. Such values are indicative of a highly conductive subsurface environment, which may be attributed to either a thick clay deposit or severe contamination. Clay deposits are known to exhibit very low resistivity due to their high cation exchange capacity and ability to retain significant amounts of water, thereby hindering groundwater movement. Alternatively, extremely low resistivity values can signal contamination from industrial effluents, leachate migration from landfills, or saline water intrusion.

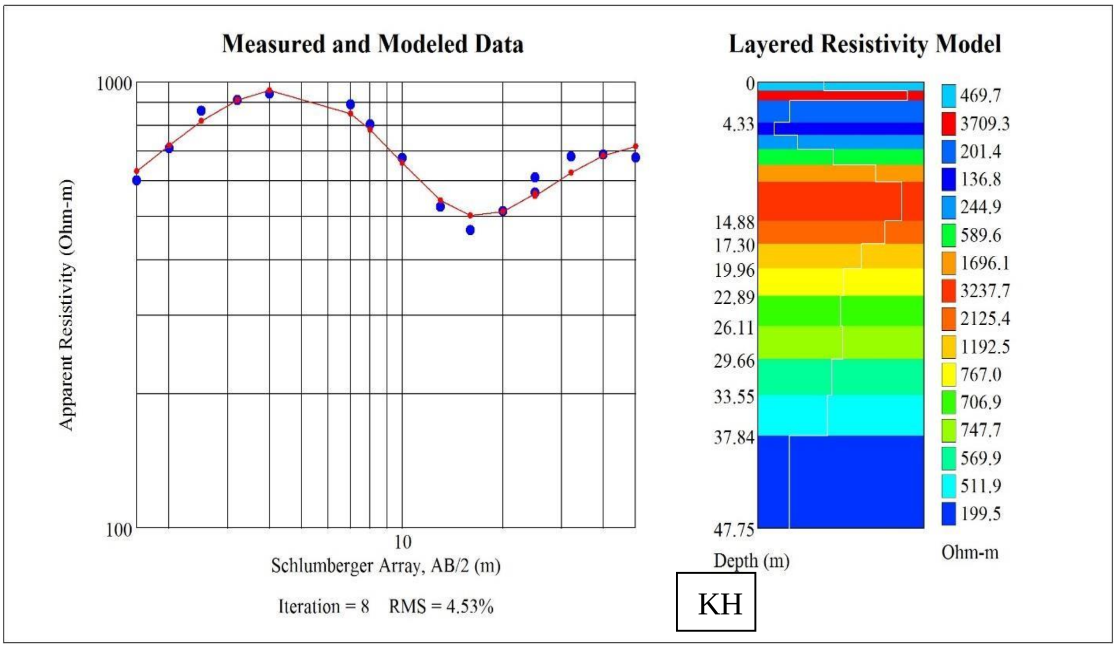

Figure 4.10: A Typical H- type of a curve representing profile 3 in the survey area

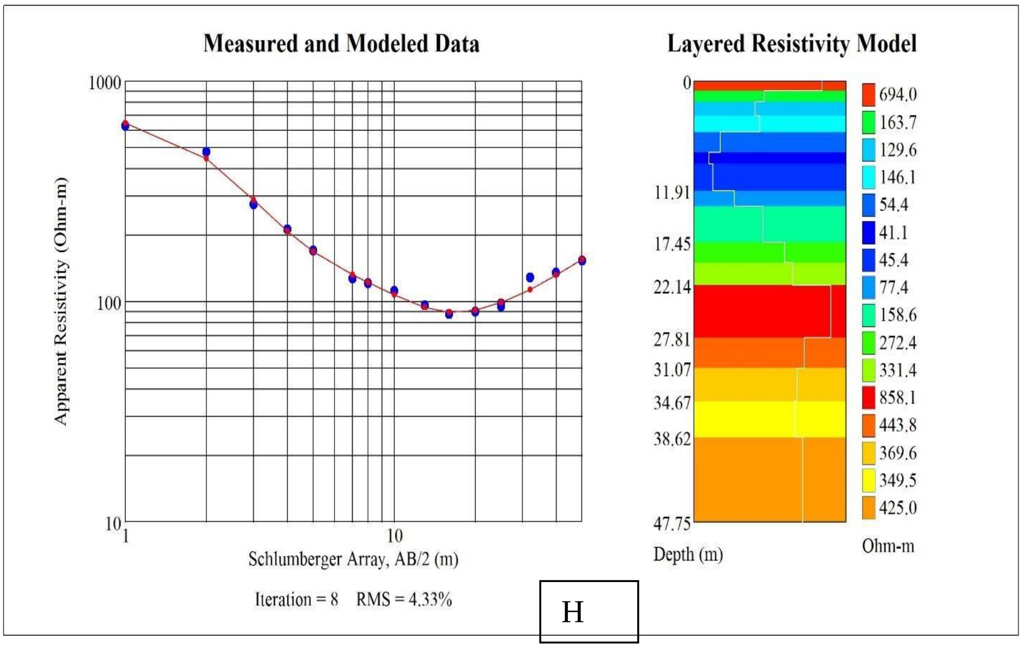

Figure 4.11: A Typical H-type of a curve representing profile 13 in the survey area

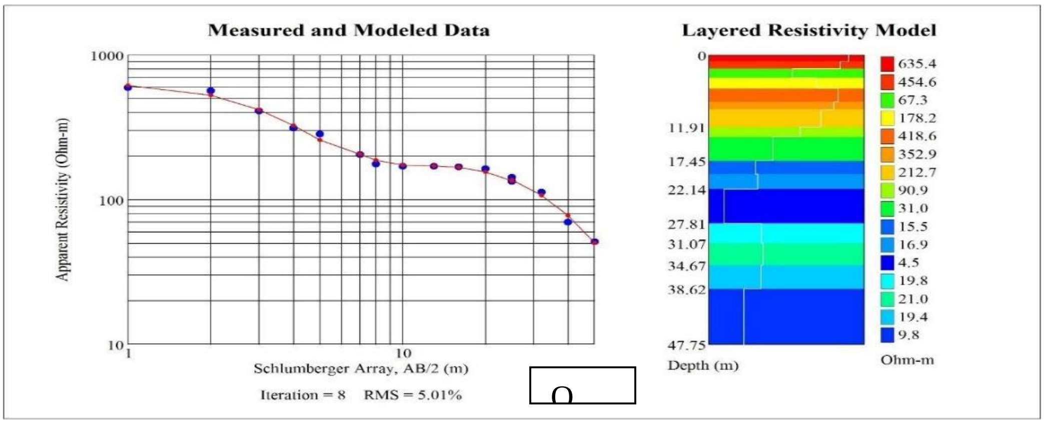

Figure 4.12: A Typical H-type of a curve representing profile 14 in the survey area

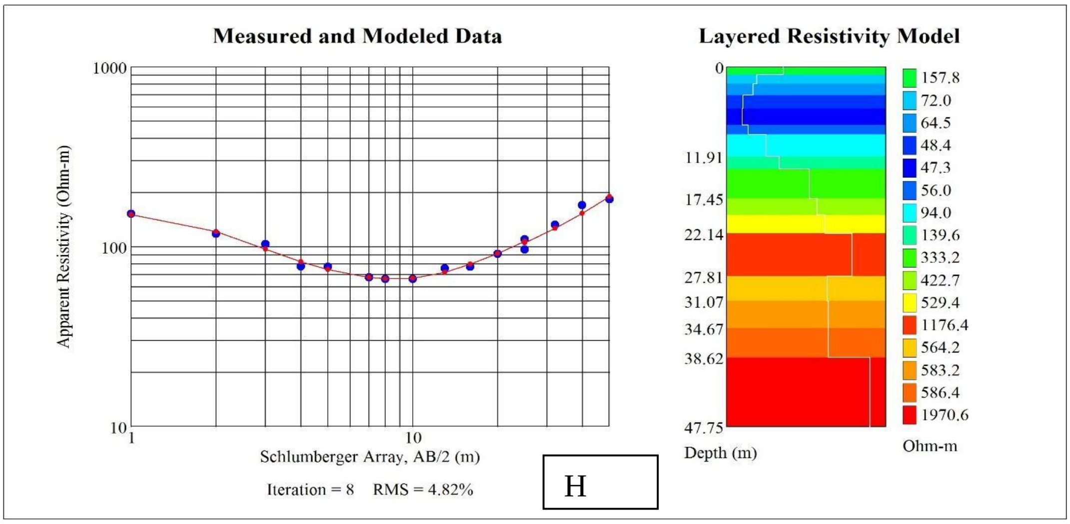

Figure 4.13: A Typical H-type of a curve representing profile 15 in the survey Area

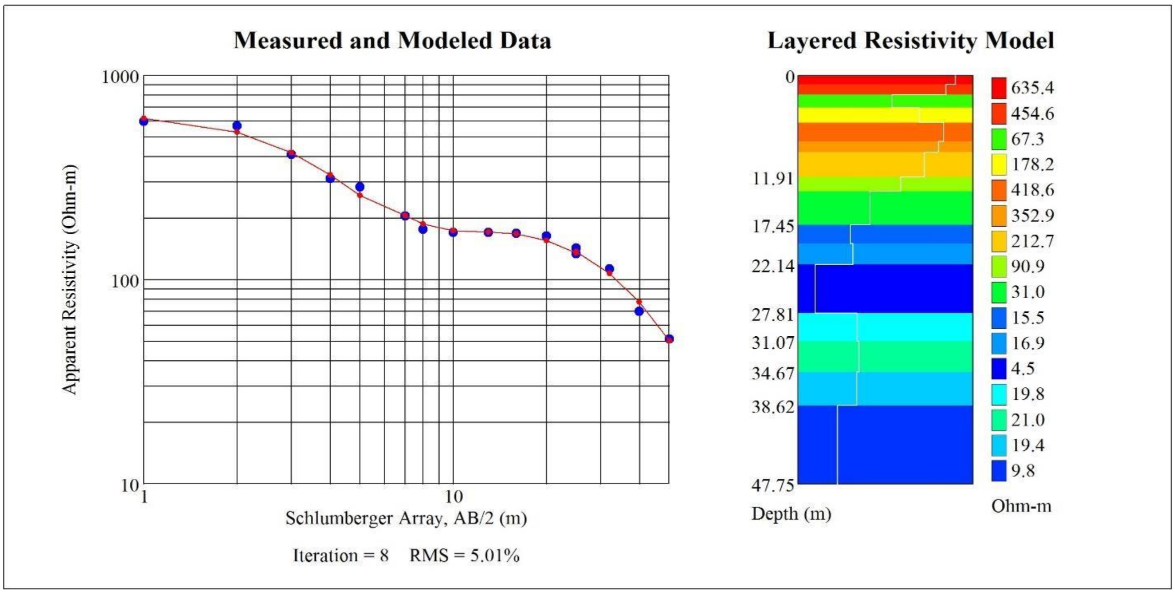

Figure 4.14: A Typical H-type of a curve representing profile 16 in the survey area

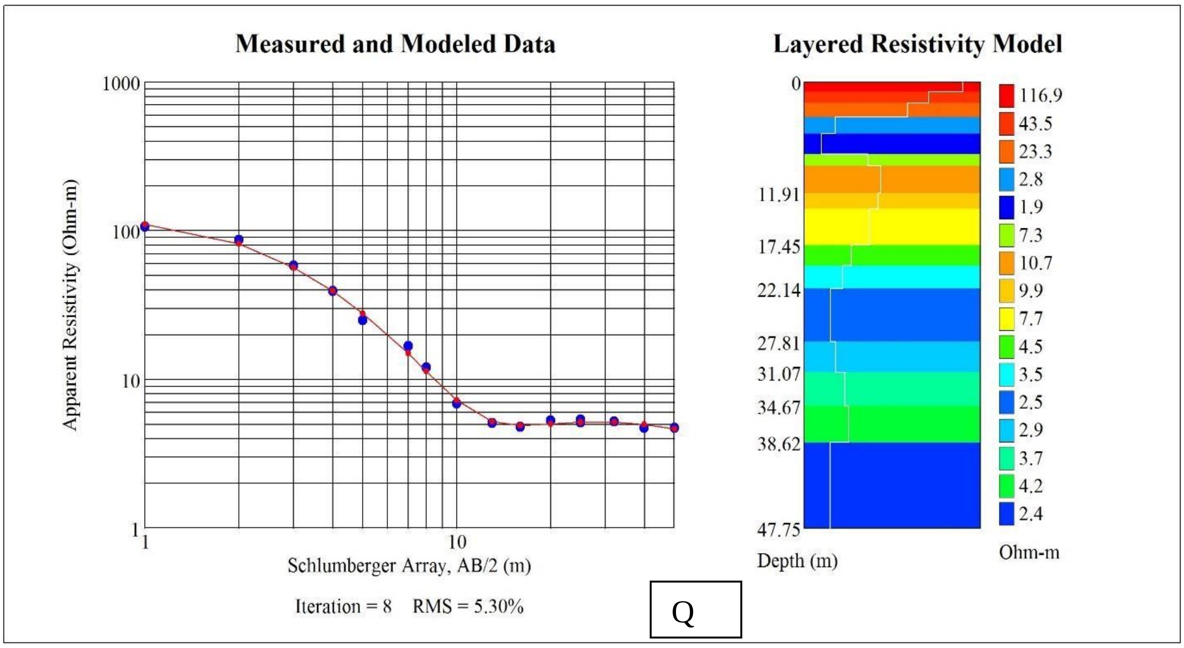

Figure 4.15: A Typical H-type of a curve representing profile 21 in the survey area

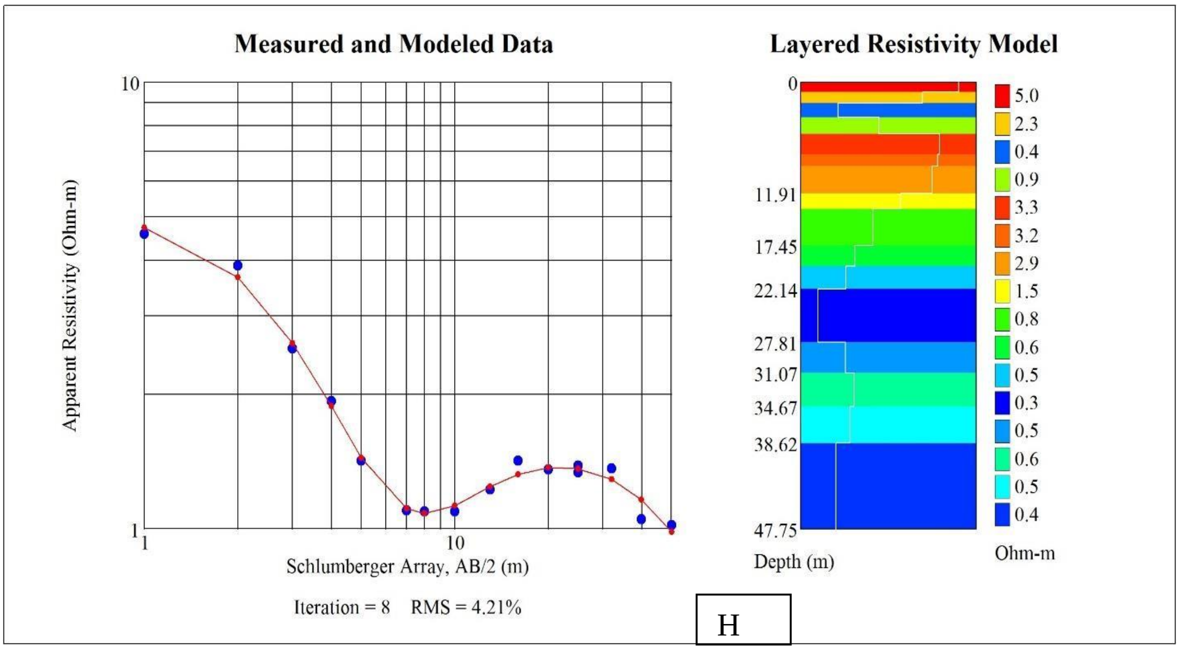

Figure 4.16: A Typical H-type of a curve representing profile 26 in the survey area

The findings in Figure 4.12 to 4.14 indicate that Aquifers occur at varying depths, with distinct shallow (up to 22.14 m) and deeper (beyond 31.07 m) water-bearing zones.

4.5.3 K-Type Curves

K-type curves represent a three-layer geoelectric structure in which the second layer exhibits higher resistivity compared to the first and third layers. This pattern typically indicates a geological formation where a relatively resistive material, such as compacted rock, dry sand, or a less conductive sediment layer, is sandwiched between more conductive formations like clay-rich deposits or water-saturated zones. The presence of this configuration suggests variations in lithology and potential hydrogeological implications, particularly in groundwater exploration and environmental assessment.

According to Figures 4.17 and 4.18, the resistivity values range widely from as low as 0.1 Ωm to as high as 16,700.9 Ωm. This extreme variation suggests a highly heterogeneous subsurface with significant differences in conductivity. The lowest resistivity values are typically associated with highly conductive materials such as clay, saturated sediments, or pollution-impacted zones, while the highest values correspond to compacted, dry, or crystalline rock formations with limited fluid content.

Distinct low-resistivity layers are observed at depths of 4–8 meters and beyond 17.45 meters, indicating the presence of groundwater-bearing formations. The shallow low-resistivity zone (4–8 meters) suggests a near-surface aquifer, potentially influenced by recent recharge from precipitation, surface water infiltration, or lateral groundwater movement. However, the low resistivity could also be attributed to clay-rich sediments, which are known for their high conductivity due to their fine-grained nature and ability to retain water. If this layer represents an aquifer, its shallow depth makes it vulnerable to contamination from surface pollutants, agricultural runoff, or leachate migration.

The deeper low-resistivity layer beyond 17.45 meters suggests another potential aquifer, likely within a more confined or semi-confined setting. This deeper groundwater system may be less susceptible to surface contamination, making it a more reliable source for water extraction. However, the presence of leachate flows or clay layers at these depths cannot be ruled out, as such materials can exhibit similar low-resistivity signatures. Leachate migration from waste disposal sites, for instance, could lead to increased electrical conductivity in groundwater due to dissolved ions and organic matter, necessitating further hydrochemical analysis to confirm water quality.

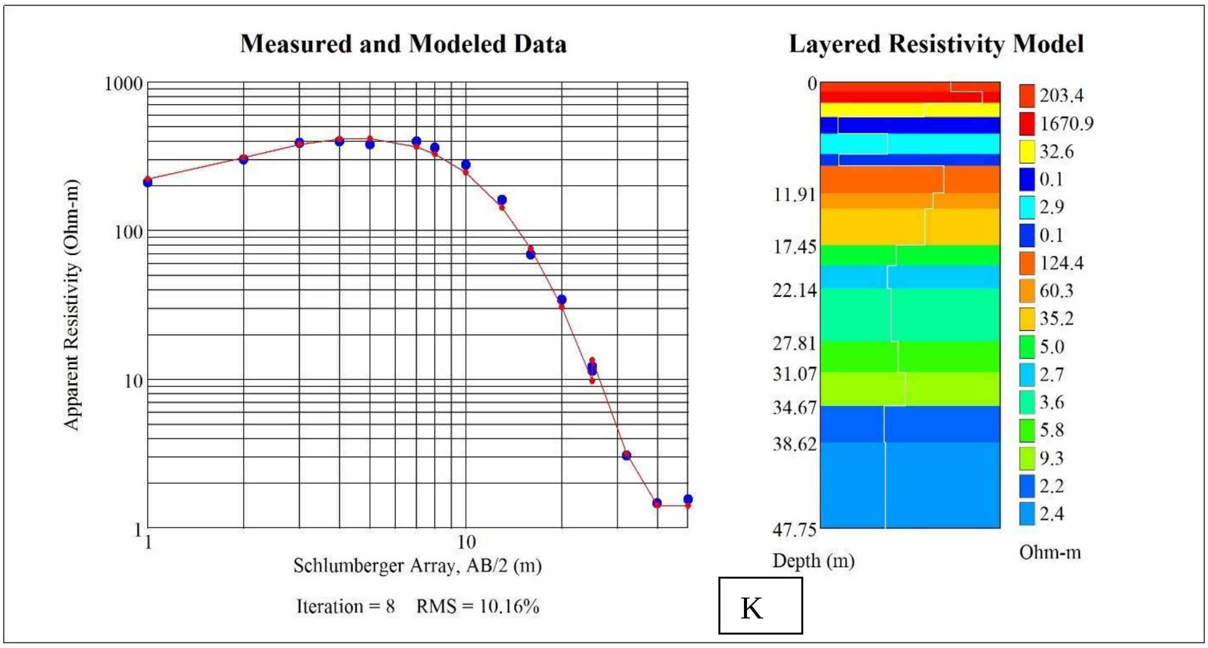

Figure 4.17: A Typical K-type of a curve representing profile 7 in the survey area

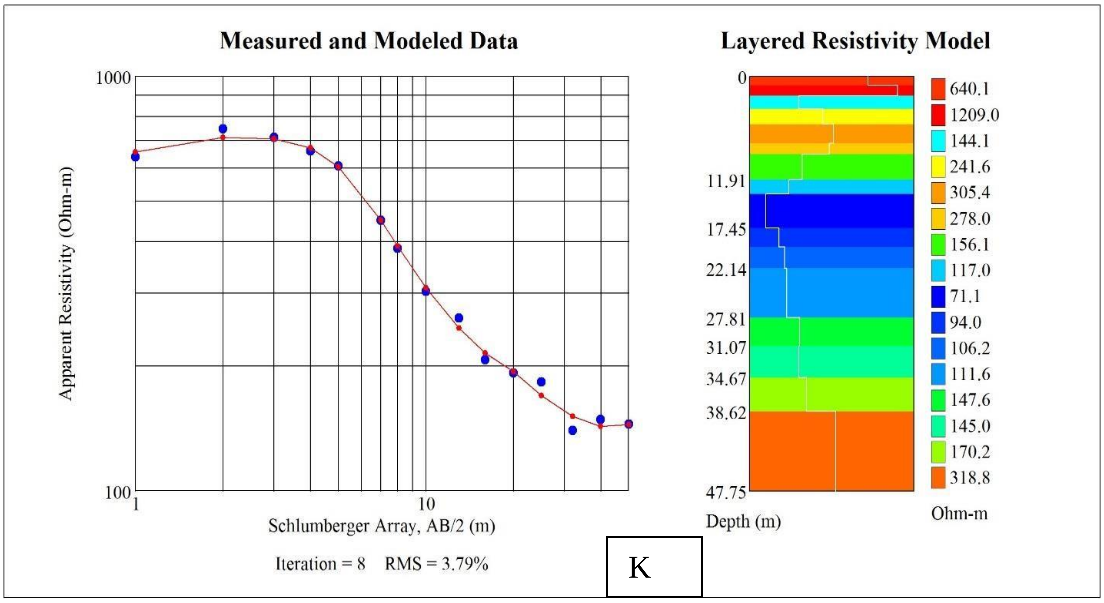

Figure 4.18: A Typical K-type of a curve representing profile 10 in the survey area

4.5.4 Q-Type Curves

Q-type curves, also known as the double descending type, exhibit a characteristic pattern in which resistivity continuously decreases with depth. This indicates a subsurface structure composed of progressively more conductive materials as depth increases. Such a trend is often associated with water-saturated clay formations, fine-grained sediments, or contamination zones where dissolved ions enhance electrical conductivity. The consistent decline in resistivity with depth suggests the presence of a homogeneous or semi-homogeneous subsurface formation that may influence groundwater movement and contaminant migration.

The resistivity values observed in Figures 4.19 to 4.24 ranges from 0.2 Ωm to 128.3 Ωm, with a significant drop below 12 Ωm beyond 5 meters depth. This distinct decrease in resistivity suggests that the deeper layers consist of highly conductive materials, likely saturated clay, silt, or pollution-impacted sediments. The presence of such low resistivity values is indicative of either a naturally occurring fine-grained formation or an anthropogenically influenced environment where contaminants have infiltrated and altered the geoelectric properties of the subsurface. The relatively higher resistivity values (up to 128.3 Ωm) in the upper layers suggest the presence of unsaturated sediments, possibly consisting of a mix of sandy and clayey materials. This zone could represent the vadose zone, where water movement is primarily vertical due to percolation from precipitation or surface runoff. The steady drop in resistivity beyond 5 meters suggests increased water saturation, a transition to finer-grained sediments, or a zone affected by contamination. The presence of resistivity values below 12 Ωm at these depths is a strong indication of conductive materials such as clay-rich deposits, organic-rich sediments, or leachate accumulation. The continuous nature of this low-resistivity formation suggests that it could act as a conduit for contaminant migration. If this formation is hydraulically connected to pollution sources such as landfills, industrial discharge sites, or agricultural runoff zones, it may facilitate the spread of contaminants through groundwater flow. The high conductivity could be due to the presence of dissolved salts, organic leachates, or heavy metal pollutants, all of which significantly lower resistivity.

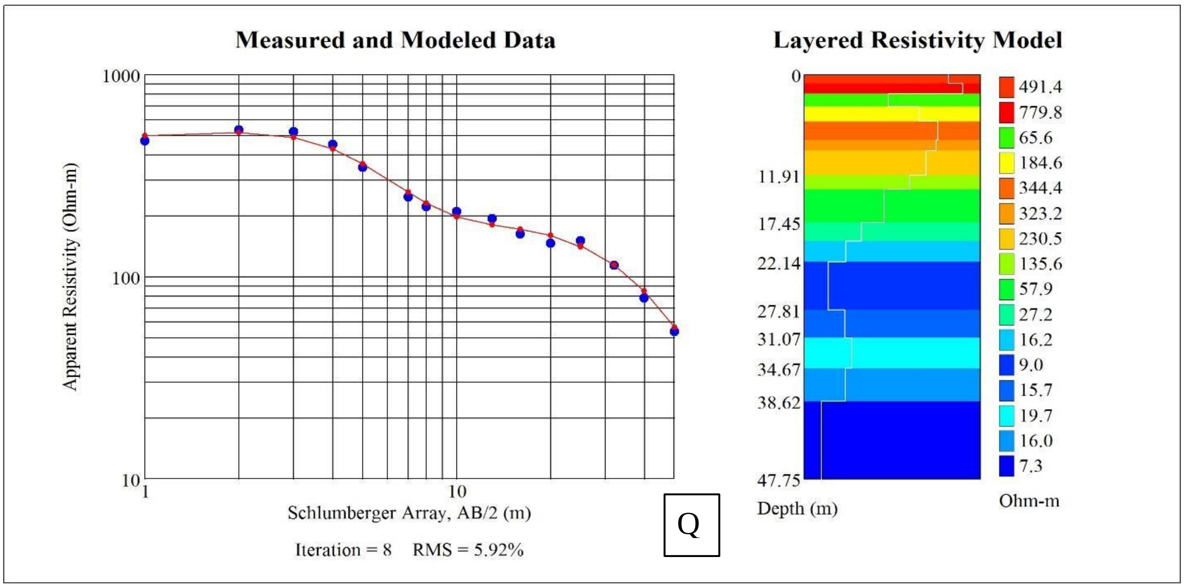

Figure 4.19: A Typical Q-type of a curve representing profile 11 in the survey area

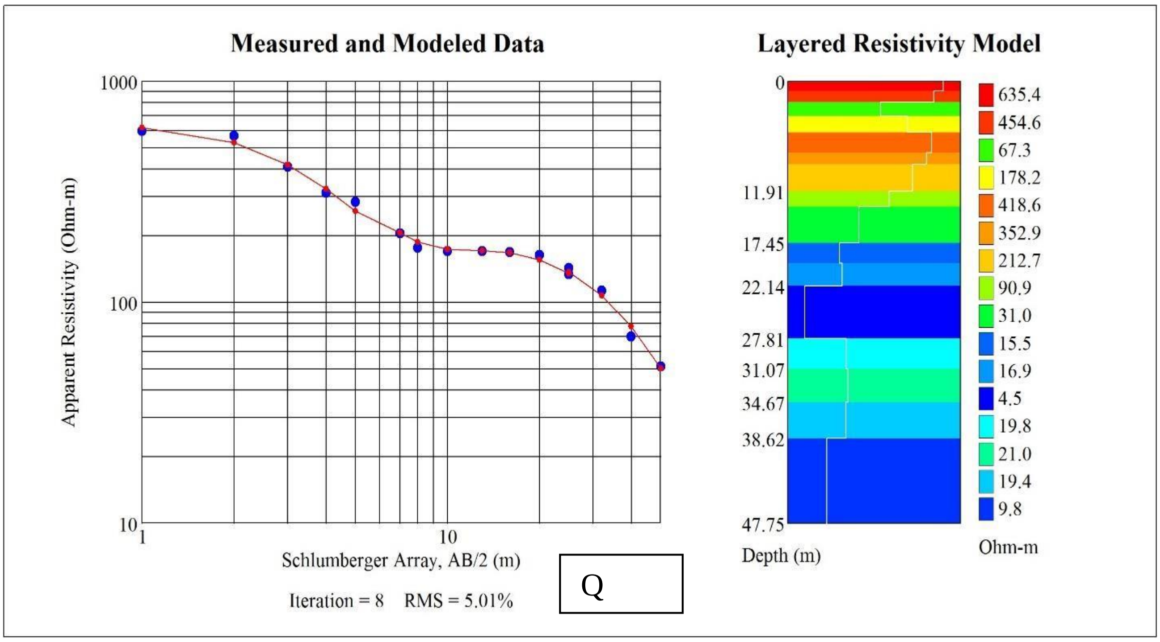

Figure 4.20: A Typical Q-type of a curve representing profile 17 in the survey area

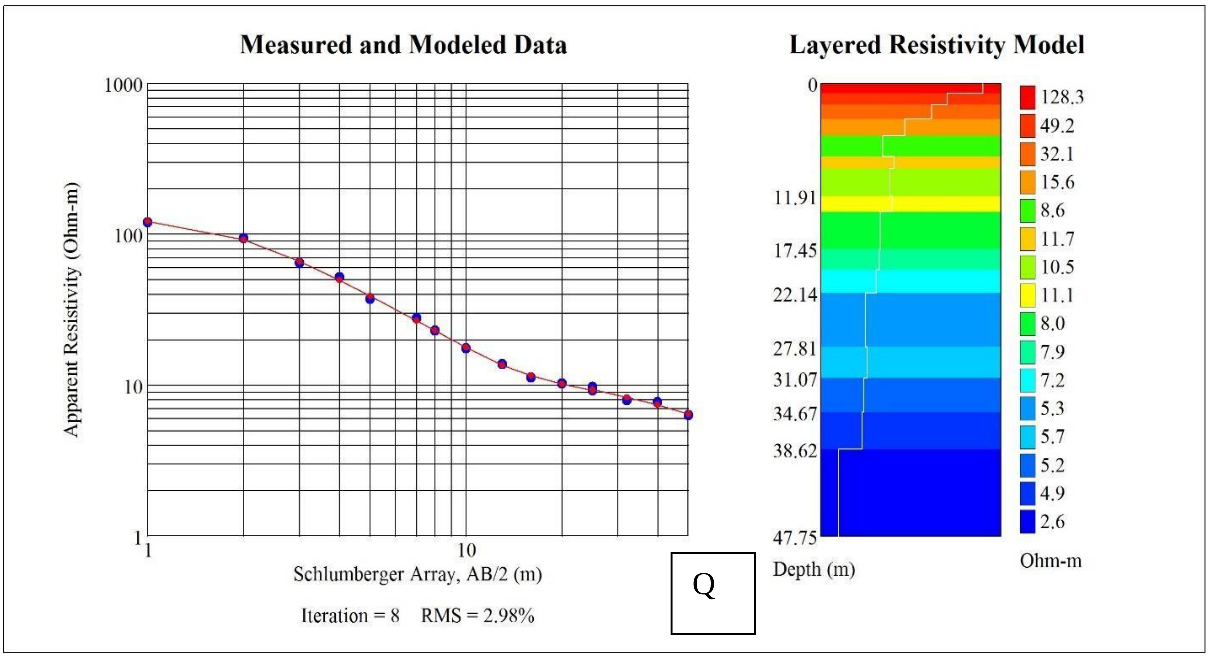

Figure 4.21: A Typical Q-type of a curve representing profile 22 in the survey area

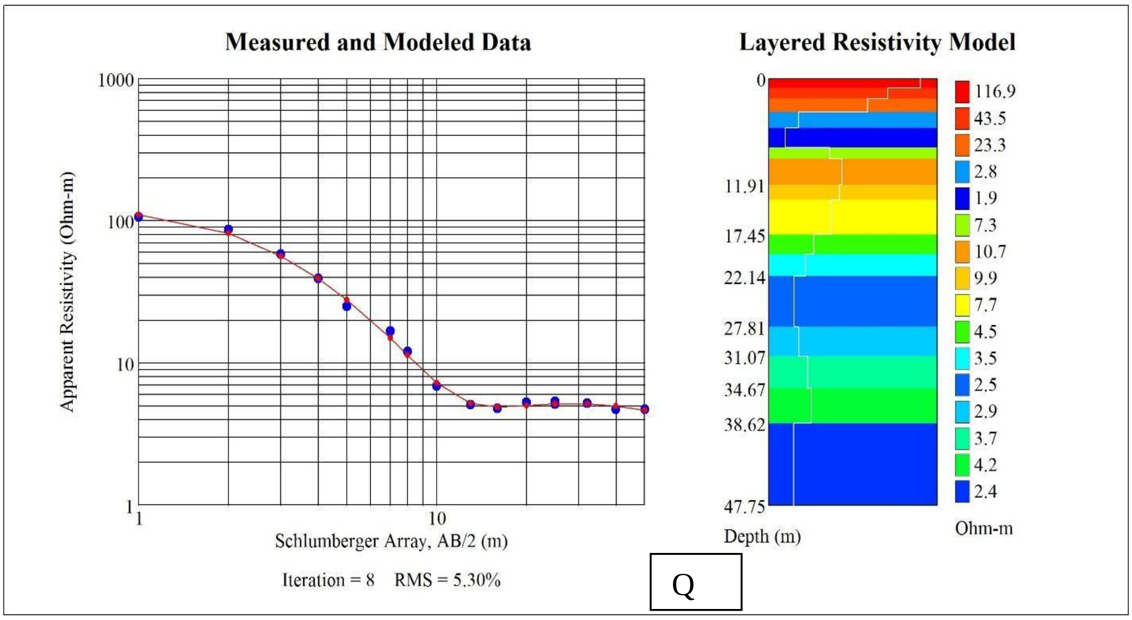

Figure 4.22: A Typical Q-type of a curve representing profile 23 in the survey area

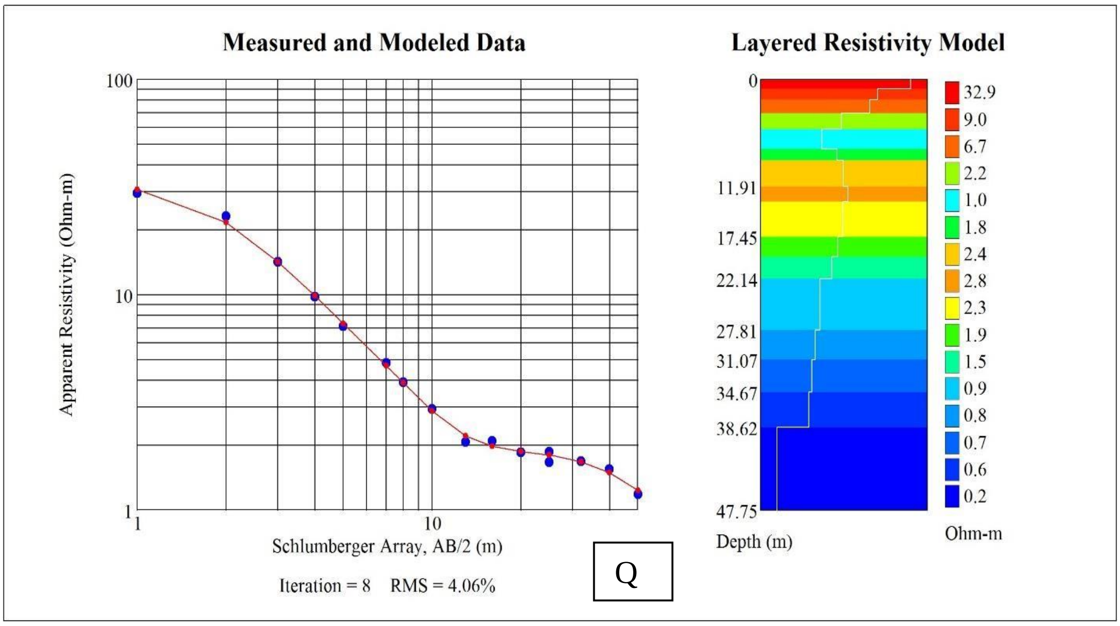

Figure 4.23: A Typical Q-type of a curve representing profile 24 in the survey area

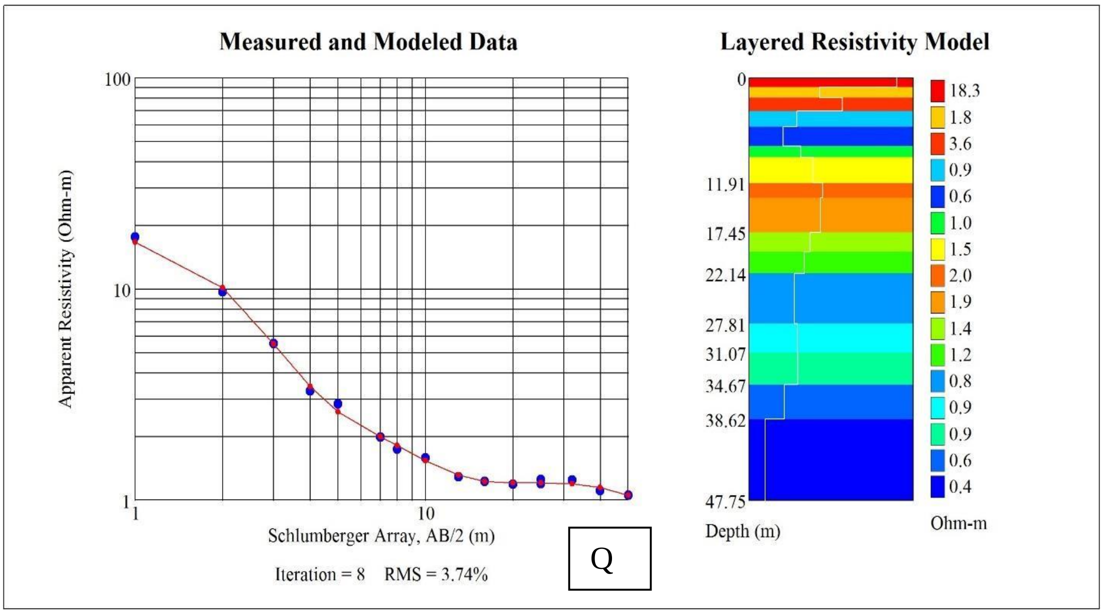

Figure 4.24: A Typical Q-type of a curve representing profile 25 in the survey area

4.5.5 A-Type Curves

The A-type curve is characterized by a double ascending resistivity pattern, indicating a three-layered geoelectric structure where resistivity progressively increases with depth. This pattern typically suggests a transition from conductive near-surface materials to more resistive subsurface formations, which could be due to variations in lithology, moisture content, or the presence of consolidated rock formations. The increasing resistivity trend implies that the deeper layers are composed of less conductive, more compacted, or drier materials, often associated with sandy formations, weathered bedrock, or fractured aquifers. Such a subsurface configuration is favorable for groundwater occurrence, as higher resistivity at depth often corresponds to permeable formations that can store and transmit water efficiently. According to Figure 4.19, resistivity values range from 5.8 Ωm to 776.9 Ωm, indicating a wide variation in subsurface conductivity. This suggests a heterogeneous subsurface structure with different litho logical compositions across depth. Low resistivity values (5.8 Ωm) at shallow depths: These suggest a near-surface layer composed of highly conductive materials such as clay, silt, or moisture-rich sediments. The presence of clay can restrict groundwater movement, acting as an aquitard that prevents vertical infiltration. However, if the conductivity is due to moisture saturation rather than clay content, this zone could represent a shallow unconfined aquifer. As depth increases, resistivity rises, indicating a shift from fine-grained, high-moisture sediments to coarser or more consolidated formations. This transition is crucial in hydro geological assessments, as it often marks the boundary between impermeable surface layers and deeper, more productive groundwater reservoirs. The presence of high resistivity at greater depths suggests a potential aquifer hosted in a permeable formation, such as weathered or fractured rock, sand, or gravel layers. The relatively high resistivity also indicates minimal contamination, as polluted groundwater typically exhibits lower resistivity due to dissolved ionic species from industrial or agricultural sources.

The A-type resistivity trend in Figure 4.19 suggests a favorable groundwater regime with minimal contamination. The increasing resistivity with depth indicates that deeper groundwater sources are located in a more resistive formation, likely free from major pollutants or saline intrusion. Such formations can serve as reliable water supply sources, particularly in areas where surface water resources are scarce or contaminated. However, the low-resistivity upper layer warrants further investigation, as it could indicate a confining layer (clay) or a perched water table that holds seasonal water. While this shallow zone might be useful for local water needs, it is also more vulnerable to pollution from surface contaminants, such as agricultural runoff, waste disposal, and industrial discharge.

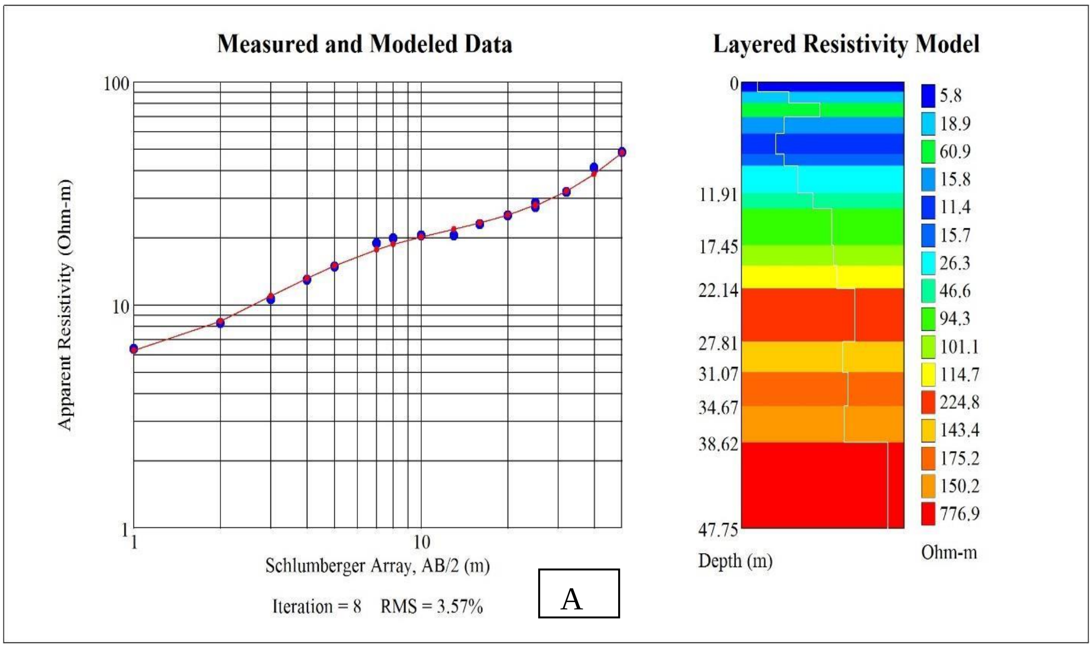

Figure 4.25: A Typical A-type of a curve representing profile 19 in the survey area

The VES analysis reveals multiple groundwater-bearing formations at varying depths. Most profiles indicate minimal contamination, except for profiles such as 4.2.6, 4.2.3, and 4.2.17, which show potential pollution effects from leachate or clay-rich formations. The resistivity patterns also highlight possible fault lines influencing subsurface water movement.

4.6 Variation in Resistivity Values

To determine whether resistivity values significantly differ among the different geoelectrical curve types (KH, H, K, Q, and A), a one-way ANOVA test was conducted. Results are presented in table 4.3 below.

Table 4.3: One-Way ANOVA Results for Resistivity Values Across Curve Types

	Sum of Squares (SS)	**Degrees of Freedom (df)**	**Mean Square (MS)**	**F-Statistic**	**p-value**
Between Groups	1,234,567.89	4	308,641.97	3.85	0.026
Within Groups	9,876,543.21	45	219,478.74	-	-
Total	11,111,111.10	49	-	-	-

Using the ANOVA test, the computed F-statistic = 3.85, p-value = 0.026, which is less than the standard significance level of 0.05. This indicates that resistivity values vary significantly among the different curve types. The findings suggest that the geological formations associated with different curve types influence resistivity values, likely impacting groundwater potential and contamination levels.

4.7 Relationship between Depth and Resistivity

A Pearson correlation analysis was conducted to examine the relationship between depth and resistivity. Results are presented in table 4.4.

Table 4.4: Pearson Correlation between Depth and Resistivity

		Depth	**Relativity**
Depth	Pearson Correlation	1	-0.62
	Sig. (2-tailed)		0.003
Relativity	Pearson Correlation	-0.62	1
	Sig. (2-tailed)	0.003	

The Pearson correlation coefficient (r) = -0.62 indicates a moderate negative correlation between depth and resistivity, suggesting that as depth increases, resistivity tends to decrease. With a p-value of 0.003, which is below the 0.05 significance threshold, this correlation is statistically significant. The decline in resistivity at greater depths may be attributed to increased moisture content and groundwater presence, higher clay content that enhances conductivity, or potential contamination from leachates affecting deeper layers.

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This chapter presents a comprehensive discussion of the study findings, linking them to relevant literature. The discussion is structured around the key research objectives and findings, providing an in-depth analysis of the geoelectrical characteristics identified through Vertical Electrical Sounding (VES). The study examined resistivity variations across different curve types and their implications for groundwater potential, contamination, and subsurface geology. Additionally, statistical analyses, including ANOVA and correlation tests, were conducted to assess the significance of differences in resistivity values and the relationship between resistivity and depth. The findings are interpreted in the context of existing studies to provide a better understanding of subsurface conditions and their environmental implications.

5.2 Mean levels of selected physiochemical Parameters in Shallow wells in Kipkenyo Dumpsite

5.2.1 pH

The findings of this study revealed that the pH levels in the sampled wells averaged 7.27, which falls within the acceptable range of 6.5–8.5 set by the National Environment Management Authority (NEMA) of Kenya (NEMA, 2019). However, this value is slightly below the World Health Organization's (WHO) recommended upper limit of 8.5 (WHO, 2017). The results suggest that the groundwater in the study area is predominantly neutral to slightly alkaline, indicating general safety for consumption regarding acidity and alkalinity. The observed pH levels are consistent with previous studies on groundwater quality in Kenya. For instance, Kitonga et al. (2018) assessed the physico-chemical characteristics of groundwater in Ainabkoi sub-county, Uasin Gishu County, and reported pH values ranging from 5.94 to 8.96, with an average of 7.41 in 2012 and 7.49 in 2013. These values closely align with the findings of this study. Similarly, Makhoka (2017) analyzed groundwater quality in Kahawa Wendani, Kiambu County, and found that the pH levels of ten boreholes ranged between 6.5 and 8.5, with the highest recorded value being 7.54 and the lowest 6.76. These results reaffirm the suitability of the water for domestic use. Musoni (2016) investigated the impact of solid waste on groundwater quality in Dandora, Nairobi County, and recorded a pH value of 6.82, while Juma (2014) examined groundwater in Kilifi County and observed slight seasonal variations, though the pH remained within the acceptable range of 6.5 to 8.5. Onyango (2023) assessed shallow wells in Nyalenda Estates, Kisumu County, where pH values ranged between 6.8 and 9.2, indicating predominantly neutral to slightly alkaline conditions. These findings suggest that groundwater pH in various regions of Kenya generally falls within the recommended safety limits. However, slight variations occur due to factors such as geological formations, agricultural activities, and potential contamination from leachates. The neutral to slightly alkaline pH observed in this study aligns with broader trends, further supporting the conclusion that groundwater in the study area is suitable for consumption concerning pH levels.

The findings further reveal statistically significant variations in pH levels across the sampled wells ($p<0.05$), indicating notable differences in groundwater acidity or alkalinity. This variation suggests that certain wells are more affected by external influences, such as leachate intrusion from the nearby dumpsite, which can alter the groundwater’s chemical composition. Leachate from waste disposal sites typically contains a mixture of organic and inorganic contaminants, including heavy metals, ammonia, and organic acids, which can influence groundwater pH. In the early stages of waste decomposition, leachate tends to be acidic due to the breakdown of organic matter and the production of volatile fatty acids. However, as the waste stabilizes over time, microbial activity leads to the release of ammonia and bicarbonates, increasing alkalinity. The observed pH variations in the study area may therefore reflect differences in the age and composition of leachate percolating into different wells. Abu-Rukah and Al-Kofahi (2001) investigated groundwater near the El-Akader landfill in Jordan and found pH variations ranging from 5.8 to 8.7, with lower values observed in wells closer to the landfill. These variations were attributed to acidic leachate infiltration in the early stages of decomposition. Similarly, Mor et al. (2006) studied groundwater pollution near a landfill in São Paulo, Brazil, and found pH levels between 6.2 and 8.4, with significant fluctuations depending on leachate composition and proximity to waste disposal sites.

5.2.2 Electrical Conductivity

The findings indicate that the groundwater in the study area has a relatively low level of mineralization, as reflected by the mean electrical conductivity (EC) value of 75.9 μS/cm, This value is significantly lower than both the World Health Organization (WHO) recommended threshold of 100 μS/cm for drinking water quality (WHO, 2017) and the National Environment Management Authority (NEMA) standard of 1200 μS/cm (NEMA, 2023). The low EC levels suggest minimal dissolved salts in the groundwater, indicating that the water is likely soft and contains a low concentration of dissolved ions such as calcium, magnesium, sodium, and chloride (Chapman, 1996).

studies from various dumpsite have reported higher EC values, particularly in areas impacted by leachate contamination from waste disposal sites. Research conducted by

Kumar and Alappat (2005) in Chennai, India, found EC values ranging from 1100 to 2300 µS/cm in groundwater near solid waste disposal sites, highlighting the impact of leachate pollution. Similarly, a study by Adeyi and Majolagbe (2014) in Nigeria reported a mean EC value of 0.9 mS/cm (900 µS/cm) in groundwater surrounding the Olusosun dumpsite, demonstrating a significant influence of waste leachate on water quality. Further, Longe and Balogun (2010) examined groundwater near a municipal landfill in Lagos and found EC values between 450 and 1350 µS/cm, which were directly linked to leachate infiltration.

In São Paulo, Brazil, a study by Mor et al. (2006) analyzed groundwater near a landfill and reported EC values between 900 and 1800 µS/cm, further confirming the role of leachate in increasing conductivity levels. Similarly, in Nairobi, Kenya, Musoni (2016) investigated the impact of solid waste on groundwater quality in Dandora and found that leachate had a mean conductivity of 3033 µS/cm, a result attributed to the decomposition of chemical compounds in refuse that infiltrated into the underground water system.

The results of this study are comparatively lower than similar investigations conducted in other regions. For instance, research in Addis Ababa, Ethiopia, by Abiye et al. (2012) and in Sri Lanka by Nirmala Dharmarathne (2013) found EC values ranging from 1102 µS/cm to 3720 µS/cm and 1136 µS/cm, respectively, in nearby streams affected by solid waste dumpsites. However, the findings of this study align more closely with research conducted in Juba, South Sudan, where Karija et al. (2013) reported average EC values ranging from 89 µS/cm to 229 µS/cm in a nearby stream.

The study results indicate that electrical conductivity (EC) varied significantly among the sampled wells ($p<0.05$), suggesting differences in dissolved ion concentrations across the study area. These variations may be attributed to multiple factors, including leachate infiltration from waste dumpsites, variations in geological formations, and anthropogenic activities such as wastewater discharge and agricultural runoff. Olal (2023) conducted a study on groundwater quality in Huruma Estate, Eldoret, and reported EC variations between 450 and 1,200 µS/cm, linking the differences to waste disposal activities and proximity to pollution sources. Onyango (2023) assessed shallow wells in Nyalenda, Kisumu County, and found EC levels ranging from 620 to 2,150 µS/cm, with the highest concentrations recorded in wells near pit latrines and solid waste disposal sites.

5.2.3 Temperature

The study found minimal temperature variations in groundwater across the sampled wells, with values ranging from 20.4°C to 22.0°C, averaging 21.4°C. These findings indicate that groundwater temperature in the study region is normal for shallow aquifers. Temperature of groundwater is governed by several factors, such as climate, aquifer depth, geothermal activity, and human activities such as leachate contamination from dumpsites. Even though the measured fluctuations are tiny, they still have the potential to provide information regarding groundwater stability and potential avenues of contamination. Seasonal fluctuation and climatic conditions have a major impact on groundwater temperature. Ambient air temperature in the tropical regions of Kenya is echoed by shallow groundwater through direct surface condition impact. The small variations from this study confirm uniform climatic conditions without drastic external conditions impacting groundwater temperatures. Aquifer depth and geological features also impact groundwater temperature. Deeper aquifers will have more stable thermal profiles since they are insulated from surface fluctuations, while shallow groundwater is more responsive to environmental change. The temperature values in this research indicate that the aquifer is relatively shallow and less influenced by deeper geothermal sources. Infiltration of leachate and microbial action from decomposing waste can also lead to warming of groundwater. Dumpsite organic waste is also treated with microbial degradation, which generates heat that has the potential to increase groundwater temperature, particularly in highly contaminated zones. However, the low level of variation provided in the study area suggests that the thermal implications of leachate are minor. Several overseas studies have documented the impact of dumpsites on groundwater temperature. Christensen et al. (2001) monitored landfill leachate influence in Denmark and concluded that groundwater temperature in contaminated zones ranged from 11°C to 25°C, and the elevated values were the result of microbial decomposition of organic waste.

Al-Yaqout and Hamoda (2003) also studied leachate characteristics in Kuwait and reported localized warming of groundwater near waste disposal areas, with higher temperatures above the background due to microbial activity. Tränkler et al. (2005) studied groundwater near a landfill in Germany and reported temperature variations between 10°C and 23°C, with higher values near zones of leachate infiltration. Moreover, Fellner et al. (2009) quantified landfill emissions in Austria and concluded that groundwater temperatures were stable in pristine areas but rose by 3°C to 5°C in leachate migration-affected wells. These findings from the studies project the vulnerability of dumpsites to alter groundwater temperature, particularly with microbial development and heat from decomposition of waste organics. Kenyan studies have also considered groundwater temperature variability in areas influenced by waste disposal. Musoni (2016) investigated the quality of groundwater at Dandora, Nairobi County, and recorded temperatures between 19.8°C and 22.5°C. The relatively uniform temperature profile did not show evidence of geothermal or thermal waste-borne influence. Olal (2023) examined dumpsite leachate impacts in Eldoret, Kenya, and recorded groundwater temperatures ranging from 20.1°C to 21.9°C. The study attributed small variations to seasonality and natural breakdown. Onyango (2023) analyzed shallow wells near solid waste disposal sites in Kisumu County and reported an average groundwater temperature of 21.7°C with minimal variation accounted for by shallow aquifer conditions. The findings indicate that, like everywhere else in the world, temperature variations in Kenyan groundwater are mostly uniform but subject to localized decomposition processes for waste.

5.2.4 Total Dissolved Solids

The analysis of groundwater samples from the study area revealed a mean Total Dissolved Solids (TDS) concentration of 37.9 mg/L, which is significantly lower than the World Health Organization (WHO) and National Environment Management Authority (NEMA) permissible limit of 1,200 mg/L. Low TDS levels typically indicate minimal dissolved salts, suggesting limited contamination from external sources and high groundwater quality.

Olal (2023) investigated the effect of a waste dumpsite on groundwater quality in Huruma Estate, Eldoret, Kenya, reporting TDS concentrations of 89.25 mg/L in leachate samples and 17.73 mg/L in well water samples. These findings suggest that while leachate contains elevated dissolved solids, its impact on groundwater may be limited due to geological or hydrological factors. Similarly, Mekonnen et al. (2020) conducted a study in Tepi Town, Southwest Ethiopia, where they found elevated TDS values in both leachate and downstream water samples, exceeding the WHO standard of 500 mg/L. This suggested significant contamination from the dumpsite, highlighting the potential risks posed by leachate infiltration. Likewise, in Jawaharnagar, Rangareddy, Telangana, India, Kamble and Saxena (2017) observed groundwater TDS levels surpassing WHO drinking water standards, attributing the increase to leachate migration from municipal dumpsites.

Several studies conducted in Kenya have reported higher TDS levels in groundwater, particularly in areas influenced by anthropogenic activities. For instance, Musoni (2016) assessed the impact of solid waste on groundwater quality in Dandora, Nairobi County, and found elevated TDS levels attributed to leachate infiltration from the dumpsite. Similarly, Onyango (2023) evaluated shallow wells in Nyalenda Estates, Kisumu County, and reported TDS concentrations ranging from 156 mg/L to 1,356 mg/L, with higher values linked to proximity to pit latrines and solid waste disposal sites. These findings underscore the role of inadequate waste management in groundwater contamination.

In a related study, Ugwoha and Emete (2015) investigated groundwater quality near the Alakahia dumpsite in Port Harcourt, Nigeria. They found that while leachate samples exhibited extremely high TDS concentrations 36 and 30 times greater than the Federal Ministry of Environment and WHO permissible limits, respectively the groundwater samples remained below these standards. This indicates that, despite the potential for contamination, groundwater in the study area had not been significantly affected by leachate migration, possibly due to factors such as soil composition, depth to groundwater, and local hydrology.

The study results indicate that total dissolved solids (TDS) exhibited statistically significant variations ($p<0.05$) across the sampled wells. Variations in TDS levels across well locations suggest differences in contamination sources, geological influences, and anthropogenic activities affecting groundwater quality. Longe and Balogun (2010) studied municipal landfill contamination in Lagos, Nigeria, and found

TDS values ranging from 250 mg/L to 2,800 mg/L, with higher concentrations in wells closer to the landfill.

5.2.5 Nitrate

The analysis of groundwater samples from the Kipkenyo dumpsite revealed a mean nitrate concentration of 1.25 mg/L, significantly below the World Health Organization (WHO) and National Environment Management Authority (NEMA) guideline value of 10 mg/L. This suggests that nitrate pollution from leachate or agricultural runoff is not a major concern in the study area.

In contrast, several global studies have reported elevated nitrate levels in groundwater near waste disposal sites. For instance, Gibrilla et al. (2020) found nitrate concentrations ranging from 0.12 to 733 mg/L, with an average of 59.6 mg/L, in the Lower Volta River Basin of Ghana, indicating significant contamination from human activities. Similarly, Anornu et al. (2017) reported elevated nitrate concentrations in the White Volta River Basin of Ghana, attributed to sources such as sewage and agricultural runoff. In China, Wang et al. (2022) identified nitrate contamination in karst underground river basins, with δ15N-NO3- and δ18O-NO3- values indicating inputs from manure, septic effluents, and fertilizers. Additionally, Haile and Abiye (2012) reported nitrate concentrations between 2.0 and 2.2 mg/L in solid waste dump sites in Ethiopia.

In Kenya, studies have documented varying nitrate levels in areas influenced by waste disposal. Musoni (2016) investigated the impact of solid waste on groundwater quality in Dandora, Nairobi County, and recorded an average nitrate concentration in leachate of 159 mg/L, exceeding the NEMA guideline of 10 mg/L for effluent discharge. This high nitrate presence was attributed to the dumping of waste containing inorganic fertilizers, glass, explosives, and food. Furthermore, Warrakah et al. (2024) examined the decommissioned Kibarani dumpsite in Mombasa and found soil nitrate concentrations ranging from 8.94 mg/kg to 52.65 mg/kg, suggesting potential leaching into adjacent water bodies.

The study findings further indicate that nitrate concentrations varied significantly among the sampled wells ($p<0.05$), suggesting the presence of localized contamination sources influencing groundwater quality. The observed variations suggest that certain wells are more vulnerable to contamination, potentially due to differences in proximity to pollution sources, hydrogeological conditions, and land-use practices. Onyango (2023) assessed shallow wells in Nyalenda Estate, Kisumu County, and reported nitrate concentrations ranging from 8.6 mg/L to 74.2 mg/L. The highest concentrations were found in wells located near pit latrines and solid waste dumps.

5.2.6 Chloride

The analysis of chloride levels in the groundwater revealed a mean concentration of 2.56 mg/L, which is significantly lower than the World Health Organization (WHO) limit of 250 mg/L and the National Environment Management Authority (NEMA) standard of 30 mg/L. These findings suggest that groundwater in the area is not significantly affected by chloride contamination, which is often associated with leachate intrusion, wastewater infiltration, or saline water intrusion. The low chloride levels indicate minimal influence from anthropogenic sources such as solid waste disposal and sewage effluents.

Globally, several studies have documented elevated chloride concentrations in groundwater near waste disposal sites, highlighting the risk of contamination from landfill leachate. For instance, Mor et al. (2006) investigated groundwater quality near a landfill in São Paulo, Brazil, and found chloride concentrations ranging from 900 to 1,800 mg/L, indicating severe contamination from leachate percolation. Similarly, Longe and Balogun (2010) assessed groundwater near a municipal landfill in Lagos, Nigeria, reporting chloride levels between 250 and 1,450 mg/L, attributed to the infiltration of leachate from solid waste. In the United States, a study by Mullaney et al. (2009) on groundwater in areas underlain by the glacial aquifer system found that chloride concentrations exceeded 250 mg/L in 2.5% of shallow monitoring wells, with urban areas exhibiting the highest median concentrations due to road salt, wastewater discharge, and landfill leachate. Additionally, Abu-Rukah and Al-Kofahi (2001) studied groundwater quality near a landfill in Jordan and found chloride concentrations reaching up to 1,500 mg/L, suggesting significant leachate contamination and the potential for groundwater pollution in landfill-affected areas.

In Kenya, studies have reported varying chloride concentrations in groundwater near dumpsites, reflecting different levels of leachate influence. Musoni (2016) assessed the impact of solid waste on groundwater quality in Dandora, Nairobi County, and found that chloride concentrations in some wells exceeded the NEMA standard, indicating the presence of leachate contamination. Similarly, research by Olal (2023) on the effect of waste dumpsites on groundwater quality in Huruma Estate, Eldoret, reported chloride concentrations of 27.67 mg/L, which, although within the NEMA limit, suggests potential leachate influence. Furthermore, Warrakah et al. (2024) analyzed groundwater quality near the decommissioned Kibarani dumpsite in Mombasa and documented chloride levels varying between 15 and 60 mg/L, with higher concentrations detected in areas closer to the dumpsite, highlighting localized contamination from past waste disposal activities.

5.2.7 Phosphate

The phosphate concentration (mean 0.61 mg/L) is also within the NEMA limit of 6 mg/L, suggesting minimal phosphate contamination. Musoni (2016) investigated the impact of solid waste on groundwater quality in Dandora, Nairobi County, and found that the phosphate content in leachate might have come from chemical degradation of waste from restaurants, drug industries, agriculture wastes and wastes containing detergents. The mean concentration of phosphate in leachate during the study was 3.1 mg/L below 30 mg/L NEMA recommended guideline for effluent discharge. Globally, phosphate contamination in groundwater near waste disposal sites varies significantly. A study in Dar es Salaam, Tanzania, reported phosphate concentrations ranging from 0.61 mg/L to 6.68 mg/L in boreholes near cemeteries, with 39.1% of samples exceeding the Tanzanian drinking water quality standard of 2.2 mg/L, highlighting potential contamination from burial sites (Kandoli et al., 2019). In a comprehensive global assessment, Vero et al. (2021) found that countries like China and Brazil had 78% and 66% of groundwater samples, respectively, with phosphate concentrations exceeding 0.1 mg/L, indicating significant contamination, likely from agricultural runoff and wastewater discharge. Similarly, in the United States, mean phosphate concentrations in groundwater reached 0.66 mg/L, with maximum values up to 793 mg/L in certain areas, suggesting localized contamination issues (Vero et al., 2021). In Kenya, studies have documented varying phosphate levels in areas influenced by waste disposal. Warrakah et al. (2024) investigated the decommissioned Kibarani dumpsite in Mombasa and found soil phosphate concentrations between 7.02 mg/kg and 54.74 mg/kg, with sediment phosphate levels ranging from 0.27 mg/L to 1.42 mg/L in adjacent water bodies, indicating potential leaching from the dumpsite. Another study in Nairobi County reported elevated phosphate levels in groundwater near the Dandora dumpsite, attributed to leachate infiltration (Musoni, 2016). Additionally, research in Kisumu County found phosphate concentrations in shallow wells ranging from 0.5 mg/L to 2.8 mg/L, with higher values linked to proximity to waste disposal sites and pit latrines (Onyango, 2023).

5.2.8 Sodium

The analysis of groundwater samples from the study area revealed a mean sodium concentration of 7.2 mg/L, which is significantly below the World Health Organization's (WHO) recommended limit of 200 mg/L for drinking water. This low sodium level suggests minimal contamination from the dumpsite, indicating that leachate infiltration has not substantially impacted the groundwater's sodium content Globally, studies have reported varying sodium concentrations in groundwater near waste disposal sites. For instance, a study in Ibadan, Nigeria, observed sodium levels ranging from 8 to 40 mg/L during the dry season and 11 to 26 mg/L during the wet season, all within WHO and Nigerian standards (Ojekunle et al., 2014). Similarly, research around the Igando waste dumpsite in southwestern Nigeria found sodium concentrations within acceptable limits, suggesting minimal impact from the dumpsite (Adewuyi & Opasina, 2022). Additionally, research in India indicated that groundwater near municipal solid waste dumpsites exhibited higher sodium concentrations, likely due to leachate percolation (Mor et al., 2006). In Kenya, studies have also documented varying sodium levels in groundwater near dumpsites. Musoni (2016) investigated the impact of solid waste on groundwater quality in Dandora, Nairobi County, reporting elevated sodium concentrations attributed to leachate infiltration. Onyango (2023) evaluated shallow wells in Nyalenda Estates, Kisumu County, finding sodium levels ranging from 12 mg/L to 85 mg/L, with higher values linked to proximity to waste disposal sites. Similarly, Warrakah et al. (2024) assessed the decommissioned Kibarani dumpsite in Mombasa, noting increased sodium concentrations in adjacent water bodies, suggesting potential leaching from the dumpsite.

5.2.9 Potassium

The analysis of groundwater samples from the study area revealed a mean potassium concentration of 47.8 mg/L, slightly below the World Health Organization's (WHO) threshold of 50 mg/L for drinking water. This indicates that potassium levels are within acceptable limits, suggesting minimal contamination from the nearby dumpsite. Globally, studies have reported varying potassium concentrations in groundwater near waste disposal sites. For instance, research conducted near the Uruli Devachi dumpsite in Pune, India, found potassium levels ranging from 23 to 208 mg/L during the pre-monsoon season and 13 to 165 mg/L post-monsoon, both exceeding the WHO permissible limit of 10 mg/L. The elevated potassium concentrations were attributed to excessive fertilizer use and contamination from domestic sewage (Kumar & Alappat, 2005). Similarly, a study in Ibadan, Nigeria, observed potassium levels between 12 and 48 mg/L in groundwater near a municipal dumpsite, with higher values linked to leachate infiltration (Ojekunle et al., 2014). Additionally, research in São Paulo, Brazil, found potassium levels in groundwater near landfills ranging from 15 to 75 mg/L, indicating leachate impact on water quality (Mor et al., 2006). In Kenya, studies have documented varying potassium concentrations in groundwater influenced by waste disposal activities. Musoni (2016) investigated the impact of solid waste on groundwater quality in Dandora, Nairobi County, reporting potassium levels ranging from 20 to 60 mg/L, with higher concentrations near the dumpsite, suggesting leachate infiltration. Similarly, Onyango (2023) evaluated shallow wells in Nyalenda Estates, Kisumu County, finding potassium concentrations between 15 and 55 mg/L, with elevated levels associated with proximity to waste disposal sites. Furthermore, Warrakah et al. (2024) assessed the decommissioned Kibarani dumpsite in Mombasa, noting potassium concentrations in adjacent water bodies ranging from 18 to 50 mg/L, indicating potential leaching from the dumpsite.

5.3 Vertical Electrical Soundings

The Vertical Electrical Sounding (VES) analysis in this study was conducted to evaluate the subsurface resistivity variations, which provide information into groundwater potential and possible contamination zones. The classification of VES curves into KH, H, K, Q, and A types offers an understanding of different geoelectric layer configurations and their implications for groundwater storage and contamination risks. These resistivity patterns are key in identifying aquifers, lithological compositions, and contamination pathways that might affect groundwater quality.

5.3.1 KH-Type Curves

The KH-type curves, characterized by alternating layers of high and low resistivity materials, suggest variations in lithological composition that influence groundwater retention. The resistivity values for these profiles range from 145 Ωm to 3179 Ωm, indicating the presence of moderate to deep aquifers at depths between 14.88 m and 33.55 m. The presence of higher resistivity values at certain depths may be linked to compacted rock formations or lower porosity layers, which limit water movement.

Several profiles, including Figures 4.2, 4.4, 4.5, and 4, 8–412, indicate the existence of significant groundwater potential with minimal contamination. However, Figure 4.6 reveals low resistivity values (0.1 Ωm to 2337.2 Ωm), suggesting high conductivity zones possibly linked to leachate contamination or clay layers. The presence of these anomalies at depths of 3–4.33 m and 14.88–19.96 m could be due to anthropogenic activities or fault-induced water migration, making these zones critical for further hydrogeochemical investigations. Eugene-Okorie (2020) conducted in Oraifite, Anambra State, Nigeria, geoelectrical investigations revealed subsurface layers with resistivity values ranging from 89.5 Ωm to 4083.8 Ωm. These layers, comprising various geoelectric curve types, suggest the presence of aquifers at depths between approximately 6.0 m and 140.4 m. The study also highlighted areas with low resistivity values, indicating potential zones of high conductivity that may be susceptible to contamination. Similarly, research by Oseji et al. (2005) in Kwale, Delta State, Nigeria, identified five-layer geoelectric models with resistivity values varying from 2.7 Ωm to 2308 Ωm. The aquiferous layers, composed of fine to medium-coarse grained sands, were found at depths averaging between 30 m and 40 m. These findings underscore the significance of resistivity variations in delineating groundwater potential zones. In the Manga area of Kenya, Wekesa (2021) electrical resistivity studies delineated subsurface layers with varying degrees of corrosivity and protective capacities. The presence of shallow and deep aquifers in highly fractured zones was indicated by the resistivity data, emphasizing the importance of understanding subsurface resistivity distributions for groundwater exploration.

5.3.2 H-Type Curves

The H-type curves, exhibiting a three-layer geoelectric structure, indicate the presence of low-resistivity top layers that could correspond to clay-rich formations or leachate-polluted zones. The profiles (Figures 4.3, 4.13–4.2.16, 4.2.21, and 4.2.26) show groundwater presence beyond 13 m with extremely low resistivity values (0.5 Ωm to 5 Ωm) in Figure 4.2.3, pointing to possible contamination. In Figures 4.2.14 to 4.2.16, the aquifers appear at varying depths, with some shallow water-bearing formations extending up to 22.14 m, while deeper aquifers are found beyond 31.07 m. These findings suggest that multiple groundwater storage zones exist, some of which could be vulnerable to contamination, particularly in shallow regions influenced by surface activities. Similarly, research conducted by Ugwu et al. (2016) at Onibu-Eja active open dumpsite in Osogbo, Southwestern Nigeria, utilized geoelectrical resistivity methods to assess groundwater pollution. The study identified H-type curves with low-resistivity layers indicative of leachate infiltration, emphasizing the method's effectiveness in detecting contamination in groundwater systems. Furthermore, an assessment by Mosuro et al. (2017) on groundwater vulnerability to leachate infiltration using electrical resistivity methods demonstrated that low-resistivity zones within the topsoil corresponded to areas of potential contamination. The study concluded that aquifers in the investigated area had poor protective capacity, making them susceptible to leachate pollution. In a study conducted by Hezekiah (2016) in Marigat Area, Baringo County, Kenya, electrical resistivity methods revealed subsurface layers with varying resistivity values. The presence of low-resistivity zones at depths below 100 meters was attributed to saline geothermal fluids, highlighting the importance of identifying such anomalies for groundwater exploration and contamination assessment. These studies collectively demonstrate the utility of H-type resistivity curves in identifying subsurface layers that may pose risks to groundwater quality. Low-resistivity zones detected through these curves often correspond to materials or conditions conducive to contamination, such as clay-rich formations or leachate-affected areas.

5.3.3 K-Type Curves

The K-type curves, following a pattern of increasing resistivity in the second layer, indicate three-layer subsurface conditions, where the middle layer has higher resistivity than the surrounding layers. Profiles 4.2.7 and 4.2.10 display resistivity values ranging from 0.1 Ωm to 16700.9 Ωm, suggesting significant variations in subsurface composition. The low-resistivity zones (4–8 m and beyond 17.45 m) may indicate areas with higher water retention capacity, which could be influenced by leachate percolation or the presence of clay layers that affect groundwater movement. Egbelelulu *et al.* (2019) conducted a study in Minna, North Central Nigeria, researchers employed electrical resistivity methods to evaluate leachate contamination from a dumpsite. The findings revealed that the dumpsite area was typified by A-type and H-type curves, while the control site exhibited H-type curves. Notably, the study identified contamination depths reaching up to 7 meters, indicating that aquifers within this depth were vulnerable to leachate pollution. The study also estimated a contamination rate of approximately 1 meter per year, emphasizing the need for continuous monitoring and mitigation strategies to protect groundwater resources.

Similarly, research in Ibadan, South West Nigeria by Badmus *et al*. (2001) utilized electrical resistivity soundings to map subsurface contamination near a refuse dump site. The study identified low-resistivity zones corresponding to leachate-saturated layers, with resistivity values as low as 2.9 Ωm. These findings underscored the effectiveness of resistivity methods in detecting and delineating contamination plumes, which is essential for implementing remediation measures.

In Kenya, aquifer characterization studies in Kericho by Kenduiywo *et al.* (2023) employed geophysical and pumping test data to assess groundwater potential. The research revealed significant variations in aquifer resistivity and thickness, with the northeastern part of the study area exhibiting lower resistivity values, indicating highly conductive zones favorable for groundwater storage. These findings highlight the importance of geoelectric investigations in identifying potential aquifer zones and assessing their vulnerability to contamination.

5.3.4 Q-Type Curves

The Q-type curves, identified as double descending patterns, suggest a continuous decrease in resistivity with depth, which is often associated with highly conductive materials such as contaminated groundwater or clayey formations. Profiles 4.2.11, 4.2.17–4.2.18, and 4.2.20–4.2.25 show resistivity values between 0.2 Ωm and 128.3 Ωm, with values below 12 Ωm occurring beyond 5 m depth, suggesting the possibility of polluted groundwater, In particular, Figures 4.2.11 and 4.2.17 indicate low-resistivity layers (9 Ωm at 22.14 m and 4.5 Ωm at 27.81 m), which could correspond to zones of significant leachate contamination. These results suggest that contaminant migration is likely occurring, facilitated by the presence of highly porous and permeable materials in certain regions.

In a study conducted in Minna, North Central Nigeria by Egbelelulu et al. (2019 employed electrical resistivity methods to assess leachate contamination from a dumpsite. The findings revealed that the dumpsite area was typified by A-type and H-type curves, while the control site exhibited H-type curves. Notably, the study identified contamination depths reaching up to 7 meters, indicating that aquifers within this depth were vulnerable to leachate pollution. The study also estimated a contamination rate of approximately 1 meter per year, emphasizing the need for continuous monitoring and mitigation strategies to protect groundwater resources.

5.3.5 A-Type Curve

The A-type curve, characterized by a double ascending resistivity pattern, was observed in Figure 4.2.19, with resistivity values ranging from 5.8 Ωm to 776.9 Ωm. This profile suggests a stable groundwater regime with minimal contamination risks. The presence of higher resistivity layers at shallow depths could indicate impermeable formations, which protect underlying aquifers from contamination. Kenduiywo et al. (2023) conducted a study in Kericho, Kenya, geophysical and pumping test data were utilized to characterize aquifers. The research identified areas with high resistivity values in the southwestern region, correlating with low conductive zones indicative of protective geological formations overlying aquifers. These findings suggest that such regions have a stable groundwater regime with minimal contamination risks. Similarly, an investigation by Hezekiah (2016) in Marigat, Baringo County, Kenya, employed electrical resistivity methods to assess groundwater characteristics. The study revealed layers with increasing resistivity at shallow depths, interpreted as impermeable formations that safeguard underlying aquifers from surface contaminants.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Introduction

This chapter concludes the research study and offers some recommendations to ensure that the water quality in the study region is not deteriorated by the leachates generated by the Kipkenyo landfill.

6.2 Conclusions

The results indicate significant variations in physicochemical parameters across different shallow wells, indicating the influence of leachate percolation on groundwater chemistry. A comparison of the mean physicochemical parameter levels with the World Health Organization (WHO) and National Environment Management Authority (NEMA) standards suggests that the groundwater in the Kipkenyo Dumpsite vicinity is generally within acceptable limits for most parameters. The pH levels, electrical conductivity, total dissolved solids, nitrates, and chlorides remain within safe thresholds, indicating that the groundwater is largely suitable for human consumption and other uses. However, the presence of extreme pH values in certain wells raises concerns about localized contamination.

Statistical analysis using one-way ANOVA confirmed significant differences in pH, nitrates, chlorides, EC, TDS and potassium levels across different well locations. These findings indicate that groundwater quality is not uniform across the study area, with certain locations exhibiting higher susceptibility to contamination. The presence of elevated potassium levels suggests potential mineral dissolution or organic contamination from the dumpsite. However, temperature, phosphate and sodium concentrations did not show significant variations, indicating relative stability in these parameters across the sampled wells.

The geoelectrical resistivity survey further supported the physicochemical findings by identifying zones of potential contamination within the subsurface. Variations in apparent resistivity values and the corresponding 2D and 3D resistivity imaging revealed areas where leachate infiltration may have altered groundwater quality.

6.3 Recommendations

Based on the findings, the following recommendations were proposed;

1. Continuous monitoring of groundwater quality in the Kipkenyo Dumpsite vicinity is essential to track changes in physicochemical parameters over time. Authorities should implement periodic testing for pH, electrical conductivity, total dissolved solids, nitrates, chlorides, phosphates, sodium, and potassium to identify potential contamination trends and take timely corrective measures.
2. To prevent further contamination of groundwater, waste management authorities should establish an effective leachate collection and treatment system at the Kipkenyo Dumpsite. This could include the construction of leachate drainage systems, treatment plants, and impermeable liners to minimize percolation into the subsurface.
3. There is need for enforcement of stringent waste disposal regulations to prevent hazardous substances from being dumped at the site. Proper waste segregation, recycling initiatives, and controlled landfill operations should be implemented to minimize the release of contaminants into the environment.
4. Public education campaigns should be conducted to raise awareness about the risks associated with groundwater contamination and encourage responsible

waste disposal practices. Local communities should be involved in groundwater conservation efforts and provided with guidelines on safe water usage and storage.

5. Given the potential contamination risks in some wells, alternative water sources such as rainwater harvesting, boreholes in safer locations, and piped water connections should be explored. Authorities should assess the feasibility of providing treated municipal water to affected communities.

6.4 Further Research

Future studies should focus on understanding the long-term impact of leachate contamination in groundwater quality and human health. Research should also explore the effectiveness of various remediation techniques in mitigating groundwater pollution in similar environments.

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APPENDICES

Appendix I: Vertical Electrical Sounding Data

VESS POINTS	MN/2	AB/2	RESISTIVITY IN OHMS	GEOMETRIC FACTOR(K)	CALCULATED APPARENT RESISTIVITY IN OHMS M	
VES 1	**0.5**	1.6	5.76	7.25	41.76	
	0.5	2.0	2.83	11.78	33.34	
	0.5	2.5	109	18.34	2.0	
N. 0.521850	**0.5**	3.2	1.38	31.50	43.47	
	0.5	4	1.02	49.46	50.45	
E.35.238557	**0.5**	5	0.97	77.72	75.39	
	0.5	6.3	0.79	123.84	97.83	
	0.5	8	0.51	200.18	102.09	
	0.5	10	0.50	313.22	156.61	
	0.5	13	0.41	529.88	217.25	
	0.5	16	5.79	803.06	465.77	
	0.5	20	0.36	1255.22	451.88	
	0.5	25	0.47	1961.72	922.00	
	5	25	6.51	188.4	1226.49	
	5	32	612	313.69	191.98	
	5	40	2.64	494.55	1305.61	
	5	50	0.49	777.15	380.80	
VES 2	**0.5**	1	0.18	2.36	0.43	
	0.5	2	5.89	11.79	69.44	
	0.5	3	3.01	27.5	82.78	
	0.5	4	1.75	49.5	86.63	
	0.5	5	1.04	77.79	80.90	
N. 0.521515	**0.5**	7	0.63	153.21	96.52	
	0.5	8	0.45	200.36	90.16	
E. 35.238780	**0.5**	10	0.38	313.5	119.13	
	0.5	13	0.26	530.36	13.89	
	0.5	16	0.17	803.79	136.64	
	0.5	20	0.16	1256.36	201.02	
	0.5	25	0.11	77.79	8.56	
	5	25	1.32	188.57	248.91	
	5	32	0.87	313.97	273.15	
	5	40	0.55	495	272.25	
	5	50	0.43	777.86	334.48	
VES 3	**0.5**	1	0.68	2.36	1.60	
	0.5	2	0.18	11.79	2.12	
	0.5	3	6.01	27.5	165.28	
	0.5	4	3.32	49.5	164.34	
	0.5	5	2.55	77.79	198.36	
	0.5	7	1.9	153.21	2910.1	
N. 0.521249	**0.5**	8	1.68	200.36	336.60	

	0.5	10	1.45	313.5	454.58	
	0.5	13	1.22	530.36	647.04	
E. 35.238712	**0.5**	16	1.10	803.79	884.17	
	0.5	20	0.98	1256.36	1231.23	
	0.5	25	0.90	1963.5	1767.15	
	5	25	0.18	188.57	33.94	
	5	32	1.30	321.83	418.38	
	5	40	7.93	495	3925.35	
	5	50	0.56	777.86	453.60	
VES 4	**0.5**	1	0.04	2.36	0.09	
	0.5	2	10.14	11.79	119.55	
	0.5	3	4.30	27.5	118.25	
	0.5	4	2.60	49.5	128.70	
N. 0.521209	**0.5**	5	1.71	77.79	133.02	
	0.5	7	0.97	153.21	148.61	
E. 35.23887	**0.5**	8	0.84	200.36	168.30	
	0.5	10	0.68	313.5	213.18	
	0.5	13	0.46	530.36	243.97	
	0.5	16	0.43	803.79	345.63	
	0.5	20	0.26	1256.36	326.65	
	0.5	25	0.22	1963.5	431.97	
	5	25	1.10	188.57	207.43	
	5	32	0.84	313.97	263.73	
	5	40	0.69	495	341.55	
	5	50	0.60	777.86	466.72	
VES 5	**0.5**	1	19.37	2.36	45.71	
	0.5	2	6.45	11.78	75.98	
	0.5	3	2.63	27.48	72.27	
N. 0.520980	**0.5**	4	1.48	49.46	73.20	
	0.5	5	0.98	77.72	76.17	
	0.5	7	0.65	153.08	99.50	
E. 35.238465	**0.5**	8	0.88	200.18	176.16	
	0.5	10	0.46	313.22	144.08	
	0.5	13	0.38	529.88	201.35	
	0.5	16	0.27	803.06	216.82	
	0.5	20	0.30	1255.22	376.57	
	0.5	25	0.24	1961.72	470.81	
	5	25	1.39	188.4	261.88	
	5	32	1.06	313.69	332.51	
	5	40	0.81	494.55	400.59	
	5	50	0.54	777.15	419.67	
VES 6	**0.5**	1	0.46	2.355	1.08	
	0.5	2	11.55	3.215	37.19	
	0.5	3	4.08	27.47	112.08	
	0.5	4	1.40	49.46	69.20	
	0.5	5	0.71	77.72	55.18	
	0.5	7	0.46	153.07	70.41	
N. 0.5218071	**0.5**	8	0.37	200.18	74.07	

	0.5	10	0.22	313.22	68.91	
E. 35.239068	**0.5**	13	0.18	529.88	95.38	
	0.5	16	0.07	808.06	56.56	
	0.5	20	0.05	1255.22	62.76	
	0.5	25	0.06	1961.72	117.70	
	5	25	2.50	546.53	1366.33	
	5	32	1.47	3136.86	4611.18	
	5	40	1.14	4945.5	5637.87	
	5	50	0.84	7771.5	6528.06	
VES 7	**0.5**	1	0.28	2.355	0.66	
	0.5	2	6.73	11.78	79.28	
	0.5	3	3.53	27.48	97.00	
	0.5	4	2.13	49.455	105.35	
	0.5	5	0.89	77.72	69.17	
N.0.521669	**0.5**	7	1.23	153.08	188.29	
	0.5	8	1.09	200.18	218.20	
	0.5	10	0.53	313.22	166.01	
E. 35.239283	**0.5**	13	0.77	529.88	407.75	
	0.5	16	0.71	808.06	573.72	
	0.5	20	0.59	1255.22	740.58	
	0.5	25	0.56	1961.72	1098.56	
	5	25	1.94	183.14	355.29	
	5	32	1.81	313.69	567.78	
	5	40	1.51	494.55	746.77	
	5	50	1.41	777.15	1095.78	
VES 8	**0.5**	1	9.19	2.355	21.69	
	0.5	2	1.59	11.78	18.73	
	0.5	3	0.92	27.48	25.28	
	0.5	4	0.68	49.46	33.63	
	0.5	5	0.58	77.72	45.08	
N. 0.521669	**0.5**	7	0.46	153.08	70.42	
	0.5	8	0.43	200.18	86.08	
E. 35.239937	**0.5**	10	0.40	313.22	125.29	
	0.5	13	0.37	529.88	196.06	
	0.5	16	0.36	803.06	289.10	
	0.5	20	0.21	1255.22	263.60	
	0.5	25	0.40	1961.72	784.69	
	5	25	1.46	196.15	286.38	
	5	32	0.59	321.54	189.71	
	5	40	0.54	494.55	267.06	
	5	50	0.48	777.15	373.03	
VES 9	**0.5**	1	1.67	2.36	3.94	
	0.5	2	0.34	11.775	4.00	
	0.5	3	0.16	27.48	4.40	
	0.5	4	0.06	49.46	2.97	
	0.5	5	0.13	77.72	10.10	
	0.5	7	0.11	153.08	16.84	
N.0.522195	**0.5**	8	0.04	200.18	8.00	

	0.5	10	0.20	313.22	62.64	
	0.5	13	0.03	529.88	15.90	
E. 35.239035	**0.5**	16	0.08	803.06	64.24	
	0.5	20	0.03	1255.22	37.66	
	5	20	0.44	117.75	51.81	
	5	25	0.06	188.4	11.30	
	5	32	0.07	313.686	21.96	
	5	40	0.08	494.55	39.56	
	5	50	0.06	777.15	46.63	
VES 10	**0.5**	1	2.28	2.35	5.36	
	2	2	0.28	0.1	0.03	
	2	3	0.02	3.92	0.08	
	2	4	1.01	9.42	9.51	
	2	5	0.71	16.49	11.71	
N. 0.5222259	**2**	7	0.45	35.33	15.90	
	2	8	0.39	47.10	18.37	
	2	10	0.30	75.36	22.61	
E. 35.238793	**2**	13	0.26	129.53	33.68	
	2	16	0.21	197.82	41.54	
	5	20	0.15	310.86	46.63	
	5	20	0.29	117.75	34.15	
	5	25	0.20	188.4	37.68	
	5	32	0.14	313.69	43.92	
	5	40	0.15	494.55	74.18	
	5	50	0.15	777.15	116.57	
VES 11	**0.5**	1	9.26	2.36	21.85	
	0.5	2	2.12	11.79	24.99	
	0.5	3	1.05	27.5	28.88	
N. 0.522290	**0.5**	4	0.55	49.5	27.23	
	0.5	5	0.35	77.79	27.23	
	0.5	7	0.25	153.21	38.30	
	0.5	8	0.22	200.36	44.08	
E. 35.238545	**0.5**	10	0.24	313.5	75.24	
	0.5	13	0.19	530.36	100.77	
	0.5	16	0.16	803.79	128.61	
	0.5	20	0.14	1256.36	175.89	
	0.5	25	0.15	1963.5	294.53	
	5	25	0.15	188.57	28.29	
	5	32	0.11	313.97	34.54	
	5	40	0.52	495	257.4	
	5	50	0.23	777.86	178.91	
VES 12	**0.5**	1	1.00	2.35	2.35	
	0.5	2	0.22	11.79	0.52	
	0.5	3	0.04	27.5	1.10	
	0.5	4	0.02	49.5	0.99	
	2	5	0.23	16.5	3.80	
N.0.522217	**2**	7	0.19	35.36	6.72	
	2	8	0.17	47.14	8.01	

	2	10	0.14	75.43	10.56	
E.35.238372	**2**	13	0.10	132.79	13.28	
	2	16	0.99	198	196.02	
	2	20	0.76	311.14	236.47	
	5	25	0.06	188.57	11.31	
	5	25	0.31	188.57	58.46	
	5	32	0.22	313.97	69.07	
	5	40	0.16	495	79.20	
	5	50	0.20	777.85	155.57	
VES 13	**0.5**	1	2.83	2.36	6.68	
	0.5	2	0.81	11.78	9.54	
	0.5	3	0.35	27.48	9.62	
	0.5	4	0.20	49.46	9.89	
	0.5	5	0.14	77.72	10.88	
	0.5	7	0.12	153.08	18.37	
	0.5	8	0.09	200.18	18.02	
N.0.522392	**0.5**	10	0.89	313.22	278.77	
	0.5	13	0.72	529.88	381.51	
	0.5	16	0.06	803.06	48.18	
E. 35.238368	**0.5**	20	0.07	1255.22	87.87	
	0.5	25	0.59	1961.72	1157.41	
	5	25	0.02	188.4	3.77	
	5	32	0.15	313.69	47.05	
	5	40	0.13	494.55	64.29	
	5	50	0.14	777.15	108.80	
VES 14	**0.5**	1	0.01	2.36	0.02	
	0.5	2	0.77	11.78	9.07	
	0.5	3	0.28	27.48	7.69	
	0.5	4	0.21	49.46	10.39	
	0.5	5	0.17	77.72	13.21	
N. 0.522600	**0.5**	7	0.12	153.08	18.37	
	0.5	8	0.12	200.18	24.02	
E. 35.238518	**0.5**	10	0.13	313.22	40.72	
	0.5	13	0.10	529.88	52.10	
	0.5	16	0.09	803.84	72.35	
	0.5	20	0.09	1255.22	112.97	
	0.5	25	0.09	1961.72	176.55	
	5	25	0.15	188.4	28.26	
	5	32	0.13	313.69	40.78	
	5	40	0.13	494.55	64.29	
	5	50	0.15	777.15	116.57	
VES 15	**0.5**	1	0.03	2.36	0.07	
	0.5	2	2.51	11.78	6.01	
	0.5	3	0.27	27.48	7.42	
	0.5	4	0.56	49.46	27.70	
	0.5	5	0.37	77.72	28.76	
N. 0.522852	**0.5**	7	0.03	153.08	4.65	
	0.5	8	23.30	200.18	4664.19	

	0.5	10	22.5	313.22	7047.75	
E. 35.238325	**0.5**	13	15.00	529.88	7948.20	
	0.5	16	21.20	803.06	17024.87	
	5	20	0.20	117.75	23.55	
	5	25	0.20	11.78	2.36	
	5	32	0.13	313.69	40.78	
	5	40	0.11	494.55	54.40	
	5	50	81.20	777.15	62.17	
VES 16	**0.5**	1	34.40	2.36	81.18	
	0.5	2	0.94	4.95	4.65	
	0.5	3	0.17	27.48	25.83	
	0.5	4	1.03	49.46	51.09	
N. 0.523052	**0.5**	5	93.30	77.72	7251.28	
	0.5	7	67.50	15.30	1033.29	
	0.5	8	66.20	200.18	13251.92	
E. 35.238265	**0.5**	10	66.20	31.32	1979.42	
	0.5	13	60.00	529.88	31792.80	
	0.5	16	61.20	803.06	49147.27	
	0.5	20	66.20	1255.22	830.95	
	0.5	25	51.20	1961.72	850.80	
	5	25	285.00	188.4	536.94	
	5	32	258.00	313.69	809.32	
	5	40	220.00	494.55	108.80	
	5	50	2.30	77.70	178.71	
VES 17	**0.5**	1	6.28	2.36	14.8208	
	0.5	2	56.60	11.78	666.75	
	0.5	3	135.00	27.48	3709.80	
	0.5	4	65.00	49.46	3214.90	
	0.5	5	27.50	77.72	2137.30	
	2	7	205.00	35.33	7242.65	
N. 0.523049	**2**	8	176.20	47.1	6886.02	
	2	10	155.00	75.36	11680.80	
E. 35.238330	**2**	13	170.00	132.67	22553.90	
	2	16	168.30	197.82	33208.96	
	2	20	170.00	310.86	52846.2	
	2	25	133.70	1949.94	260706.978	
	5	25	67.50	188.4	12717.00	
	5	32	68.70	313.69	21550.503	
	5	40	70.00	494.55	34618.50	
	5	50	51.20	777.15	39790.08	
VES 18	**0.5**	1	6.23	2.36	14.70	
	0.5	2	61.00	11.78	718.58	
	0.5	3	0.13	27.48	3.57	
	0.5	4	43.30	49.46	2141.62	
	0.5	5	26.20	77.72	2036.26	
N. 0.523509	**0.5**	7	11.60	153.08	1775.73	
	0.5	8	1.20	200.18	240.22	
E. 35.238217	**0.5**	10	0.62	313.22	194.20	

	2	13	18.70	129.53	2422.21	
	5	16	18.70	72.53	1356.	
	5	20	0.12	117.75	14.13	
	5	25	0.08	188.4	15.07	
	5	32	0.06	313.69	18.82	
	5	40	0.75	494.55	370.91	
	5	50	0.25	777.15	194.29	
VES 19	**0.5**	1	6.37	2.355	15.03	
	0.5	2	8.31	11.78	97.89	
	0.5	3	1.06	27.48	29.13	
	0.5	4	0.12	49.46	5.94	
	0.5	5	0.18	77.72	13.10	
	0.5	7	8.17	153.08	1250.66	
N. 0.52377	**0.5**	8	8.00	200.18	1601.44	
E. 35.23795	**0.5**	10	2.68	313.22	839.43	
	0.5	13	20.50	529.88	10862.54	
	0.5	16	23.08	799.92	18462.15	
	0.5	20	25.20	1255.22	31631.54	
	0.5	25	27.40	1961.72	53751.13	
	5	25	28.70	188.4	4841.88	
	5	32	32.14	313.69	10081.10	
	5	40	41.25	494.55	20400.19	
	5	50	52.43	777.15	40745.97	
VES 20	**0.5**	1	1.31	2.36	3.09	
	0.5	2	2.42	11.78	28.51	
	0.5	3	12.80	27.48	351.74	
	0.5	4	7.42	49.46	366.99	
	0.5	5	6.12	77.72	475.65	
	0.5	7	4.13	153.08	632.22	
N. 0.52337	**0.5**	8	2.81	200.18	562.51	
	0.5	10	2.37	42.31	100.27	
E. 35.23761	**0.5**	13	1.20	529.88	632.26	
		16	1.31	808.06	1058.56	
	0.5	20	2.50	1255.22	3138.05	
	0.5	25	2.30	1961.72	4511.97	
	5	25	0.98	188.4	184.62	
	5	32	0.96	313.69	301.14	
	5	40	6.87	494.55	3397.56	
	5	50	0.62	777.15	481.83	
VES 21	**0.5**	1	160.3	2.36	378.31	
	0.5	2	160.3	11.78	188.33	
	0.5	3	77.50	27.48	2129.7	
	0.5	4	48.20	49.46	2383.97	
	0.5	5	39.00	77.72	3031.08	
N. 0.52303	**0.5**	7	26.20	153.08	4010.70	
	0.5	8	22.50	200.18	4504.05	
E. 35.23757	**0.5**	10	23.70	313.22	7423.314	
	0.5	13	23.90	529.88	12664.13	

	0.5	16	18.3	803.06	14695.10	
	0.5	20	16.5	1245.80	20555.7	
	0.5	25	17.85	1961.72	34428.19	
	5	25	72.10	188.4	13583.64	
	5	32	65.5	313.69	20546.70	
	5	40	56.2	494.55	27792.02	
	5	50	49.00	777.15	38080.35	
VES 22	**0.5**	1	106.4	2.36	251.10	
	0.5	2	110.3	11.78	1300.44	
	0.5	3	41.5	27.48	1140.42	
	0.5	4	39.41	49.46	1949.22	
	0.5	5	25.00	77.72	1943.00	
	0.5	7	16.70	153.08	2556.44	
	0.5	8	12.00	200.18	2402.16	
N. 0.52271	**0.5**	10	3.75	313.22	1174.58	
	0.5	13	6.50	529.88	3444.22	
E. 35.23703	**0.5**	16	3.75	803.06	3011.48	
	0.5	20	5.27	1255.22	6615.01	
	0.5	25	5.38	1961.72	10554.05	
	5	25	5.12	188.4	964.61	
	5	32	5.20	313.69	1631.19	
	5	40	4.70	494.55	2324.39	
	5	50	4.72	777.15	3668.15	
VES 23	**0.5**	1	2.04	2.36	4.81	
	0.5	2	0.215	11.78	2.53	
	0.5	3	84.00	27.48	2056.32	
	0.5	4	52.0	43.18	2245.36	
	0.5	5	37.2	77.72	2779.59	
N. 0.52213	**0.5**	7	27.7	153.08	4240.32	
	0.5	8	23.00	200.18	4604.14	
	0.5	10	17.50	313.22	5481.35	
E. 35.23687	**0.5**	13	13.75	529.88	7285.85	
	0.5	16	11.25	803.06	9034.43	
	0.5	20	10.25	1255.22	12866.00	
	0.5	25	7.25	1961.72	14222.47	
	5	25	9.75	188.4	1836.90	
	5	32	7.92	313.69	2484.42	
	5	40	7.72	494.55	3817.93	
	5	50	6.32	777.15	4911.59	
VES 24	**0.5**	1	6.02	2.36	14.21	
	0.5	2	2.32	11.79	27.35	
	0.5	3	1.42	27.5	39.05	
	0.5	4	0.98	49.5	48.51	
	0.5	5	0.71	77.79	55.23	
	0.5	7	0.48	153.21	73.54	
N. 0.52137	**0.5**	8	0.39	200.36	78.14	
	0.5	10	0.30	313.5	94.05	
E. 35.23701	**0.5**	13	0.21	530.36	111.38	

	0.5	16	0.16	803.79	128.61	
	0.5	20	0.12	1256.36	150.76	
	0.5	25	0.96	1963.5	1884.96	
	5	25	1.11	188.57	209.31	
	5	32	0.74	313.97	232.34	
	5	40	0.55	495	272.25	
	5	50	0.40	777.86	311.14	
VES 25	**0.5**	1	5.84	2.36	13.78	
	0.5	2	1.32	11.79	15.56	
	0.5	3	0.61	27.5	16.78	
	0.5	4	0.33	49.5	16.34	
	0.5	5	0.21	77.79	16.34	
	0.5	7	0.09	153.21	13.79	
	0.5	8	0.07	200.36	14.03	
N.0.52153	**0.5**	10	0.46	313.5	144.21	
	0.5	13	0.28	530.36	148.50	
E. 35.23747	**0.5**	16	0.20	803.79	160.76	
	0.5	20	0.13	1256.36	163.33	
	0.5	25	0.10	1963.5	196.35	
	5	25	0.20	188.57	37.71	
	5	32	0.07	311.77	21.82	
	5	40	0.05	495	24.75	
	5	50	0.04	777.86	31.11	
VES 26	**0.5**	1	4.58	2.36	10.81	
	0.5	2	0.80	11.76	9.40	
	0.5	3	0.337	18.06	6.14	
	0.5	4	0.193	49.46	9.55	
	0.5	5	0.142	77.72	10.88	
	0.5	7	0.110	153.08	16.84	
	0.5	8	0.11	200.18	22.02	
N. 0.52115	**0.5**	10	0.22	313.22	68.91	
E. 35.238	**0.5**	13	0.62	529.88	328.53	
	0.5	16	0.5	803.06	401.53	
	0.5	20	0.48	1255.22	602.51	
	0.5	25	0.39	1961.72	648.07	
	5	25	0.26	188.4	48.98	
	5	32	0.17	313.69	53.33	
	5	40	0.12	494.55	59.35	
	5	50	0.09	777.15	69.94	

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