



WALLAGA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

**GROUNDWATER POTENTIAL ASSESSMENT USING INTEGRATED
ELECTRICAL RESISTIVITY AND MAGNETIC METHODS : A CASE
OF ENTO CATCHMENT, BODJI DIRMEJJI DISTRICT, OROMIA,
ETHIOPIA**

MSc Thesis

BY

Bikila Dame

May 2025

Nekemte, Ethiopia



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ELECTRICAL RESISTIVITY AND MAGNETIC METHODS: A CASE
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OROMIA, ETHIOPIA**

**A Thesis Submitted To The College Of Natural Science In Partial
Fulfillment Of The Requirements For The Degree Of Master Of Science in
Exploration Geophysics**

By

Bikila Dame

Major Advisor: Dr. Geremew Lemessa

May 2025

Nekemte, Ethiopia



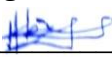
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As members of the Board of Examining of the Final MSc. thesis open defense, we certify that we have read and evaluated the thesis prepared by Bikila Dame Daba under the Title “Groundwater Potential Assessment Using Integrated Electrical Resistivity And Magnetic Methods : A Case Of Ento Catchment, Bodji Dirmejji District, Oromia, Ethiopia” and recommend that the thesis be accepted as fulfilling the thesis requirement for the **Degree of Master of Science in Exploration Geophysics.**

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STATEMENT OF THE AUTHOR

I Mr. Bikila Dame Daba hereby declare and affirm that the thesis entitled “**Groundwater potential assessment using integrated electrical resistivity and magnetic methods: A case of the Ento Catchment, Bodji Dirmejjii District, Oromia, Ethiopia**” is my own work conducted under the supervision of Geremew Lemessa (Ass. Professor). I have followed all the ethical principles of scholarship in the preparation, data collection, data analysis and completion of this thesis. All scholarly matter that is included in the thesis has been given recognition through citation. I have adequately cited and referenced all the original sources. I also declare that I have adhered to all principles of academic honesty and integrity and I have not misrepresented, fabricated, or falsified any idea / data / fact / source in my submission. This thesis is submitted in partial fulfillment of the requirement for a degree from the Post Graduate Studies at Wallaga University. I further declare that this thesis has not been submitted to any other institution anywhere for the award of any academic degree, diploma or certificate.

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Name: Geremew Lemessa (Ass. Professor) sign:  Date: _____

Thesis Advisor

ABBREVIATIONS AND ACRONYMS

ANS: Arabian-Nubian Shield

DC: Direct current

EC: Electrical conductivity

EHAL: Eastern highlands and associated lowlands

GPS : Global Positioning System

MB: Mozambique Belt

nT: Nanotesla

RV: Rift Valley

UTM: Universal Transverse Mercator

VES: Vertical electrical sounding

WHO: World Health Organisation

WHAL: Western highlands and associated lowlands

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DEDICATION

I dedicate this thesis to my father, Dame Daba, who set me on the path of knowledge, and to my mother, whose constant love, support, and understanding throughout the years have always inspired me to reach for the best.

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ABSTRACT

This study was conducted in the Ento watershed region, Bodji Dirmejjii district, Oromia, Ethiopia. Water supply has been a problem in the study area. There is now only one existing borehole. The yield of the water is 200 m³ per day (200,000 liters per day), but the population of the town is 22,000 (twenty-two thousand). To close this gap, assess groundwater potential using integrated electrical resistivity and magnetic methods to find out the location of preferred borehole areas and the depth at which the aquifers are located. Data were acquired from fifteen VES points using the Schlumberger electrode array, with a maximum half-current electrode spacing of $AB/2 = 330$ meters, along with 155 magnetic data points. The VES and magnetic datasets were processed using IP2WIN, IPI2Win-Res3, Surfer 10 (32-bit), and Oasis Montaj 6.4.2 software. The interpretation of VES data was carried out using resistivity curves, geo-electric sections, and pseudo-section maps. Similarly, magnetic data interpretation involved several anomaly maps, including total magnetic field, residual magnetic field, analytical signal, and upward continuation maps. Field results from the VES survey revealed zones of low resistivity, suggesting potential groundwater presence. Along Profile 1, VES 3 and VES 4 show a third layer with a thickness of 35 m, resistivity ranging from 76–98 Ωm , and extending to a depth of 51 m. This continues into a fourth layer at VES 4, which is 38 m thick, has a resistivity of 142 Ωm , and reaches a depth of 89 m—indicating favorable aquifer conditions. At VES 8, the third layer is 31 m thick with a resistivity of 61 Ωm and extends to 49 m, while the fourth layer is 38 m thick, has a resistivity of 119 Ωm , and reaches a depth of 87 m—also suggesting aquifer potential. Similarly, the third layer at VES 15, with a thickness of 48 m, resistivity of 62 Ωm , and depth of 62 m, is identified as a promising aquifer zone. Meanwhile, the magnetic survey results revealed low magnetic anomalies in the southwest to northwest regions of the study area, particularly in the upward continuation maps. These low magnetic responses suggest areas of intense weathering and fracturing, likely due to weakened geological structures. The integrated interpretation of VES and magnetic data, along with geological information, provided a comprehensive understanding of the subsurface conditions.

Key words: Ento watershed, electrical resistivity, magnetic methods, groundwater, Resistivity Curves, geo-electric section, and residual magnetic field map.

1.INTRODUCTION

1.1.Background of the study

Water is essential for life; without it, life cannot exist. It is essential to bringing about significant socioeconomic growth and is one of the basic natural resources needed for all living things to exist on Earth. (Goswami & Bisht, 2017). The need for water is growing rapidly and serves a variety of purposes, making it crucial for both industrial and agricultural growth in addition to home usage. It is the most important resource influencing economic growth. In actuality, water use is connected to all developmental activities, either directly or indirectly.

Both surface and groundwater are currently crucial sources of water for industrial, agricultural, and household use. However, the demand for groundwater is increasingly becoming the primary supply of water for various uses because of the surface water's temporal and spatial unpredictability. Finding commercially viable groundwater that can be used as a sustainable water source is one of the main challenges in using groundwater resources.

In the Ento Watershed region, groundwater is the primary source of water for households. However, the growing demand for groundwater, driven by population growth, has created a significant challenge. In such regions, investigating groundwater is essential to guaranteeing a sustainable supply of water for the expanding population and agricultural operations.

The study area has not yet been investigated using an integrated geophysical approach. In this context, integrated geophysical methods have become a popular substitute for assessing groundwater potential. Among these techniques, magnetic surveys and vertical electrical sounding (VES) are especially important because they can yield vital subsurface data (Getachew & Abdulkadir, 2024).

A particular use of electrical resistivity, vertical electrical sounding (VES), is a geophysical technique that determines the subsurface's resistivity at different depths. VES measures the potential difference by injecting an electrical current into the ground using an array of electrodes. The kind and distribution of subsurface materials, particularly

aquifers, which are frequently characterized by lower resistivity due to their higher water content, are then inferred from the resistivity values acquired. Thus, it is possible to determine the aquifers' depth and size, which is crucial for understanding groundwater potential.

In the magnetic method, the measured anomalous magnetic field is primarily a result of subsurface geological structures or buried targets (Neurologist, 2000). These techniques identify changes in the Earth's magnetic field brought on by magnetic materials found beneath the surface, usually iron-bearing rocks and sediments. The movement and storage of groundwater are greatly influenced by structural elements like faults, fractures, and lithological borders, all of which can be revealed by these magnetic anomalies.

The integration of VES and magnetic data presents a powerful approach to groundwater potential assessment, especially in regions with complex geological settings. Magnetic data aids in determining the structural context that controls groundwater flow, whereas VES offers comprehensive information about the hydrogeological characteristics and water-bearing formations.

1.2.Statement of the Problem

Groundwater is a vital yet limited renewable resource, replenished primarily through the direct infiltration of precipitation. This recharge process is influenced by various natural factors, including climate, topography, soil type, and the geological characteristics of the subsurface. Due to typically low flow rates and limited storage capacity, groundwater reservoirs are susceptible to overuse and spatial distribution challenges.

In the Ento Watershed region, groundwater serves as the main source of water for drinking, personal hygiene, washing clothing, preparing meals, and personal and home sanitation. However, the growing demand for groundwater, driven by population growth, has created a significant challenge. Currently, the area relies on a single borehole with a yield of 200 cubic meters (200,000 liters) per day to serve a population of approximately 22,000 people. This equates to less than 10 liters (9.09 litres) of water per person per day—far below the World Health Organization's (WHO) recommended minimum of 50 to 100 liters per day for basic personal and domestic needs (WHO, 2011). As a result, a substantial portion of the community lacks reliable access to sufficient drinking water.

Moreover, no integrated geophysical study has been conducted in the area to identify potential groundwater sources or understand the subsurface hydrogeological conditions. This lack of detailed geophysical data limits the ability to sustainably manage groundwater resources and plan for future water supply development.

To fill this gap, the present study will employ an integrated geophysical approach using Vertical Electrical Sounding (VES) and magnetic methods. The objective is to identify and characterize water-bearing geological formations, determine their thickness, extent, and physical properties, and locate structural features such as faults and fractures that may facilitate groundwater flow. Additionally, the study aims to assess groundwater flow dynamics and estimate the degree of subsurface water mineralization. The findings will provide essential data to support effective groundwater exploration and sustainable water resource management in the Ento Watershed area.

1.3.Research questions

I What lithological and geological units are present in the study area?

II What are the main geological features affecting the distribution and occurrence of groundwater in the study area?

III Which aquifer systems—deep or shallow aquifers—are the subject of the study?

1.4.Objectives of the study

1.4.1.General Objective

The general objective of this study is to assess groundwater potential using integrated electrical resistivity and magnetic methods in the study area.

1.4.2.Specific Objectives

- ❖ To determine resistivity distribution of the area
- ❖ Mapping subsurface structures of the area.
- ❖ To map the thickness of the water bearing zone
- ❖ Estimate the groundwater potential resources
- ❖ To identify locations that will provide an adequate and long-lasting yield of ground water.

1.5. Significance of the Study

This study provides critical insights into the groundwater potential of the Ento Catchment in the Bodji Dirmeji District using integrated electrical resistivity and magnetic methods. The combined geophysical approach enhances the accuracy of subsurface characterization, enabling effective identification of groundwater-bearing zones. The findings support sustainable groundwater investigation in a region where groundwater is vital for domestic and agricultural use, addressing local water scarcity challenges.

1.6. Scope of the Study

This study focuses on assessing groundwater potential in the Ento Catchment, Bodji Dirmeji District, using integrated electrical resistivity and magnetic geophysical methods. It covers data collection, interpretation, and analysis to identify subsurface structures, aquifer zones, and groundwater-bearing formations, aiming to support sustainable groundwater exploration in the study area.

1.7. Thesis Layout

This paper is structured into five chapters. Chapter One introduces the study, covering the background, problem statement, objectives, research questions, significance, and the paper's organization. Chapter Two reviews relevant literature and includes an overview of the study area's geology. Chapter Three describes the research methodology. Chapter Four presents data interpretation and discussion, while Chapter Five concludes with key findings and recommendations.

2.LITERATURE RIVIEW

2.1.Regional geological setting

2.1.1.Geology of the Gimbi-Nejo Area

The Ethiopian basement is made up of various metavolcanic, sedimentary, and plutonic rocks that have undergone diverse degrees of metamorphism, ranging from greenschist to amphibolite facies and, locally, granulite facies (Kenea et al., 2021).

The lithology of the Gimbi-Nejo area includes a range of rock types such as granite, granitoid orthogneiss, granite-granodiorite, quartz diorite, magmatic biotite, and biotite-hornblende gneiss. Additionally, the area features gabbro, meta-basalt, meta-gabbro amphibolite, chloritoid-quartz-sericite schist, and cordierite-muscovite-quartz schist. Diorite-gabbro and lower basalts are also present, as illustrated in Figure 1 below.

In the western region of the nation, granitic intrusions locally cut metamorphic rocks and ultrabasic masses. The distinct disparities in Ethiopia's basement rocks' lithology led to variations in their hydrogeologic and groundwater characteristics .

Western Ethiopian Precambrian terrain is thought to have lithological elements in common with both the Mozambique Belt (MB) in the south and the Arabian-Nubian Shield (ANS) in the north. Precambrian rocks in Western Ethiopia include high-grade gneiss and migmatites, low-grade metavolcano-sedimentary rocks and related intrusive rocks, and metavolcano-sediments and related mafic to ultramafic rocks of likely ophiolitic origin.

There are four litho-tectonic zones that may be used to categorise the Precambrian rocks in the Nekemte-Gimbi-Nejo region. The Aba Sina Domain, the Tulu Dimtu Belt, the Chochi Domain, and the Katta Domain are listed in order from east to west (Alemu & Corporation, 2019). These units frequently have intrusive rocks that range in composition from granite to gabbro. The Tulu Dimtu mafic-ultramafic belt, which also includes the Katta and Chochi domains, forms the western boundary of the Aba Sina domain. The Sayi Chenga Group's metavolcano-sedimentary rocks, high-grade (amphibolite facies) gneiss, and migmatites make up the domain. The high-grade migmatites and gneiss of the Aba Sina domain are correlative with the Geba and Hamar domains to the south along strike. These rocks were tentatively dated as being from the Archean period and were associated with the Awata and Alghe gneiss of southern Ethiopia.

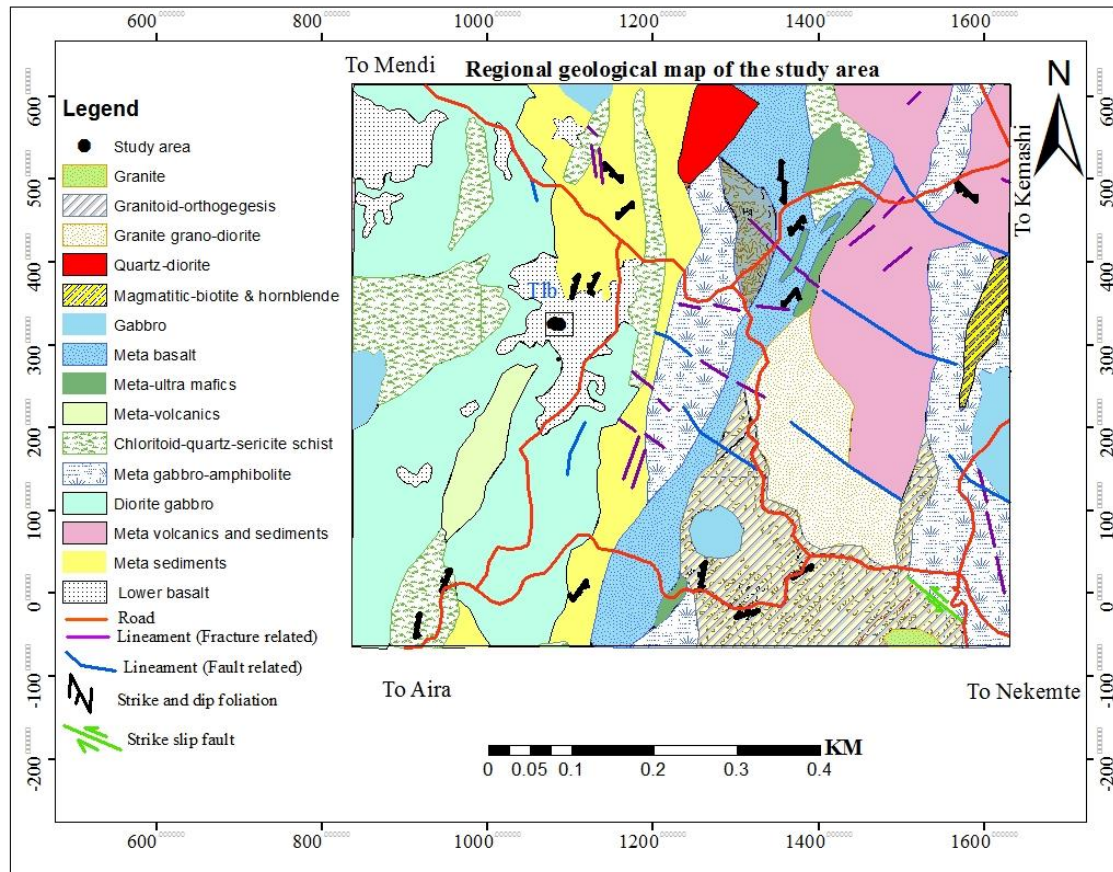


Figure 1.Regional geological map of the study area (modified from gimbi geological map sheet 2001).

2.2.Hydro geology

Groundwater is a component of the hydrological cycle in nature. As raindrops hit the surface of the soil, part of the water penetrates deeper and ultimately builds up above impermeable bedrock, filling any accessible area to create an underground reservoir. The rocks that hold and transfer ground water are known as an aquifer, as is the water itself, which is now known as ground water (Ali & Goshu, 2017).

A significant portion of Ethiopia, roughly 18% of the total surface area, is covered by hard rock topography, making the hydrogeology of metamorphic rocks extremely important. Groundwater extraction in this region has become necessary due to the rising demand for water. (“Groundwater Occurrence in Ethiopia,” 2006).

The degree and depth of weathering and fracture determine the presence of groundwater in crystalline rocks. Basement aquifers can form in the regolith (which has a low permeability but a relatively high storage capacity) or fractured bedrock (which has a low

storage capacity but a relatively high permeability). The groundwater, which is confined in weathered or fractured rocks, is refilled primarily by surface precipitation and secondarily by lateral flow from rivers and tributaries (Badmus & Olatinsu, 2010).

Different geological units within a hydrogeological basin contain groundwater at varying depths. Depending on their pore spaces and other characteristics, rocks of the igneous, sedimentary, and metamorphic groups can all contain groundwater at varying scales. The porosity of rocks, which is correlated with the percentage of voids, determines how much groundwater can be stored and how productive an aquifer is. Rocks are said to be permeable when their pores and features are connected, allowing water to move through them with ease. The two main features of crystalline rocks that are crucial for the presence of groundwater are fractured and weathered zones (regolith).

2.3.Underground Water and Aquifers

Underground water, also known as groundwater or subterranean water, refers to water that exists beneath the Earth's surface. It is typically found in two main zones: the vadose zone (unsaturated zone) and the phreatic zone (saturated zone). In the vadose zone, pores and spaces contain both air and water, whereas in the phreatic zone, all voids are fully saturated with water.

An aquifer is a subsurface layer of water-bearing rock or geological formation capable of storing and transmitting significant quantities of groundwater to wells and springs. According to geological definitions, an aquifer is a body of saturated rock with sufficient permeability to allow water to flow easily through it, making it a vital source for groundwater extraction (*Jira Service Service*, 2023)

2.4.Electrical Resistivity Method of Prospecting

By using the characteristics of electrical current in the rock with relation to earth as a conductor, resistivity may be utilised to determine subsurface geological conditions.(Rahmani et al., 2020). One of the most common approaches and methodologies used for the investigation of geophysical methods and the state of groundwater is called geo-electrical resistivity. The existence of porous structures, the presence of salt, saturation, the quality of ground water, and the presence of aquifers are only a few of the variables that affect a material's resistivity. The key factor that affects an

aquifer's resistivity is the EC (abbreviation for electrical conductivity). When the electrical conductivity of groundwater rises, the aquifer's resistivity falls and reaches a range close to that of clayey media, making the resistivity characteristic no longer relevant for identifying the aquifer.

The resistivity approach has been successfully used to explore groundwater in a correct manner. It is frequently used to establish the limits, nature, thickness of the saturation zones, and water quality of aquifers, as well as the length, depth, and type of alluviums. Delineating water-bearing formations, measuring the distance to basement rocks, and differentiating between different rock types are the major goals of this study (Partial et al., 2021).

Given that a rock's resistivity is extremely sensitive to its water content, the electrical resistivity method is one of the most effective methods for determining groundwater hydrology. The ionic concentration of water, in turn, has a significant impact on its resistivity. This technique is frequently used because electrical resistivity surveys are among the easiest and least expensive geophysical surveys used. Additionally, it may be utilized to look for ground water in porous and fissured material using either horizontal profiling or vertical electrical soundings (TAYE, 2019).

It is possible to separate electrical investigation techniques into two primary categories. The measuring of rocks' conductivity or resistivity is the focus of one group, while their capacitance is the focus of the other. The first category includes the galvanic, induction, magneto-telluric, and telluric methods, while the second group includes the induced polarization techniques.

2.5.Direct-Current, Resistivity Method

The electrical resistivity method offers a rapid and cost-effective way to gather crucial subsurface data for geophysical research projects, including groundwater exploration, mining prospecting, depth to bedrock determinations, etc.

By injecting a current into the ground section, the DC-resistivity approach calculates the potential difference that results from the artificial stimulation. The electrical characteristics in the ground as a function of depth or lateral distance are reflected in the

diagnostic parameter, the electrical resistivity ρ , which is the result of measurements at various electrode placements.

The resistance across a unit cross-section of a material is known as its electrical resistivity, or ρ . It is a property of the material and, in contrast to resistance, is independent of sample dimensions. Conductivity, the reciprocal or inverse of resistivity, is measured in mho/m or S/m, whereas its unit is ohm-m.

2.5.1. Resistivity of Earth Materials

By taking measurements on the ground surface, geoelectrical surveys aim to ascertain the subsurface resistivity distribution. It is possible to estimate the subsurface's true resistivity using these data. Numerous geological factors, including the rock's porosity, degree of water saturation, and mineral and fluid composition, are correlated with ground resistivity.

Electrical resistivity, or simply resistivity, is an inherent feature of all materials, including rocks and soil, that controls the relationship between the gradient of electric potential and the current density. The relationship between the applied current and the potential distribution as measured on the surface changed as a result of variations in the resistivity of the subsurface materials, either laterally or vertically. This variation provides information about the physical characteristics and composition of the subsurface materials. While the majority of minerals that constitute soil and rock are largely nonconductive, the conduction of electric current occurs almost exclusively in the water that occupies the pore spaces or joint holes in most earth materials. The concentration of clays and some other minerals, such as carbon, pyrite, magnetite, specular hematite, and other metallic sulfides, may be high enough to detectably increase the conductivity of the rock or soil.

Pure water is almost nonconductive, but when chemical salts are present in solution, it becomes a conductive electrolyte, and the conductivity increases with salinity. The conductivity of the electrolyte increases as the temperature rises. Depending on the salinity, the resistivity increases when the pore water freezes, maybe by a factor of 104 or 105. This effect is lessened in soil or rock, though, because not all of the pore water freezes at once, and even at temperatures much below freezing, some water is typically

still present. The freezing temperature is lowered by the adsorption of water on grain surfaces and the presence of dissolved salts. Nevertheless, due to the high resistivity of the frozen top layer and the high contact resistance at the electrodes, electrical resistivity investigations conducted on frozen ground are likely to encounter challenges. However, because of the way that freezing affects resistivity, the resistivity method is a great way to find out how deep the frozen layer is. Having comparative data collected when the ground is not frozen is particularly beneficial for interpreting such studies.

The electrical conduction in soil and rock occurs primarily through electrolytes within the pore spaces; resistivity is largely influenced by the material's porosity (or void ratio) and the geometry of the pore network. Intergranular voids, joint or fracture holes, and blind pores like bubbles or vugs are examples of pore space. Conductivity is only efficiently contributed by the interconnected pores, and it is further influenced by the tortuosity of current channels or the shape of the interconnections.

In general, clay or shale bodies are less resistive than rocks or soils made up of large mineral grains. The absorption of exchangeable cations from the surfaces of clay particles increases the conductivity of pore water in clays, despite the fact that the clay particles themselves are nonconductive when dry (TAYE, 2019). The resistivity levels of igneous and metamorphic rocks are generally high. Compared to igneous and metamorphic rocks, sedimentary rocks typically have lower resistivity values because they are more porous and contain more water. Groundwater's resistivity ranges from 10 to 100 ohm.m. At 0.2 ohm.m, seawater has a low resistivity value. Table 1 shows resistivity of common sub surface.

Table 1: Resistivity of common geologic and sub surface materials (Partial et al., 2021).

Materials	Normal Resistivity
Granite	$3 \times 10^2 - 10^6$
Syenite	$10^2 - 10^6$
Diorite	$10^4 - 10^5$
Gabbro	$10^3 - 10^6$
Basalt	$10 - 1.3 \times 10^7$
Schist(Graphite)	$10 - 10^2$
Quartzite	$10 - 2 \times 10^8$
Sandstones	$1 - 7.4 \times 10^8$
Limestones	$50 - 10^7$
Dolomite	$3.5 \times 10^2 - 5 \times 10^3$
Clays	$1 - 10^2$
Gravel (Dry)	1400
Gravel (Saturated)	100
Quaternary (Recent Sands)	50-100
Dry Sandy Soil	80-1050
Sand And Gravel	30-225
Glacier Ice (Temperature)	$2 \times 10^6 - 1.2 \times 10^8$
Glacier Ice (Polar)	$5 \times 10^4 - 3 \times 10^5$
Permafrost	$10^3 - > 10^4$

Source :Partial et al., 2021.

2.5.2.General Principles of Resistivity Survey

In the theory behind the resistivity survey, any subsurface variation in conductivity alters the flow of current within the Earth, which in turn influences how electric potential is distributed when current is applied by conduction into the ground through two electrodes. The extent to which the potential is affected at the surface depends on the position, size, shape, and conductivity of the materials at depth. Therefore, surface measurements of electric potential can reveal information about the subsurface distribution of materials. The resistivity method is based on Ohm's law, which in its generalized form states that

the electric field strength at a point in an electrically isotropic material is proportional to the current density at that point.

The medium is considered electrically isotropic when the current density J points in the same direction as the electrical field vector, E , and the resistivity ρ is a scalar function of the observation point. J is generally not in the direction of E and has a directive property in an anisotropic medium. Ohm's law needs to be modified in this way because:

$$\begin{aligned} J_x &= \sigma_{xx}E_x + \sigma_{xy}E_y + \sigma_{xz}E_z \\ J_y &= \sigma_{yx}E_x + \sigma_{yy}E_y + \sigma_{yz}E_z \\ J_z &= \sigma_{zx}E_x + \sigma_{zy}E_y + \sigma_{zz}E_z \end{aligned} \quad \dots (3.3.1)$$

An electrically homogenous and isotropic half space of resistivity, ρ , is now the subject of a single electrode, as shown in Fig. 2 below.

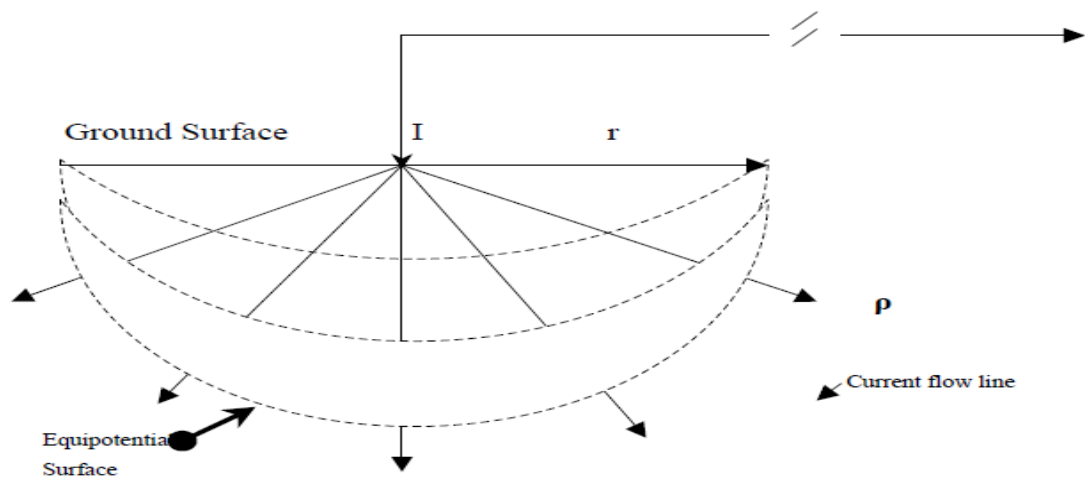


Figure 2. Current Flow in a uniform half space, from a single electrode

Source: (Partial, I N Of, Fulfillment Requirements, T H E The, F O R Sciences, Climate, 2006)

The current density at distance r :

$$J = I/A = I/2\pi r^2 \quad \dots (3.3.2)$$

By Ohm's Law $E = \rho J \Rightarrow$

$$E = \rho I/2\pi r^2 \quad \dots (3.3.3)$$

The potential V at distance r from the electrode for current strength in a hemispherical ground section of resistivity (ρ) is determined by:

$$V = \rho I / 2\pi r, \text{ since } V = E \cdot r \dots (3.3.4)$$

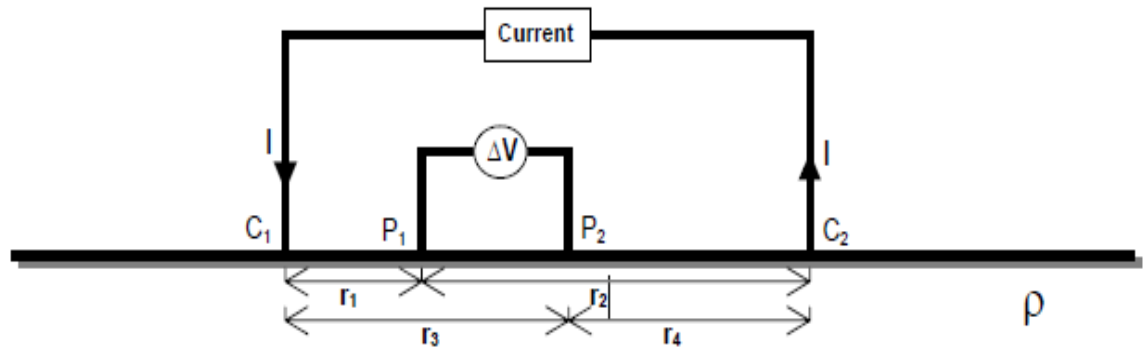


Figure 3.Four-Electrode Layout

Source:(Partial, I N Of, Fulfillment Requirements, T H E The, F O R Sciences, Climate, 2006)

Four-Electrode Layout. C1 and C2 are current electrodes, while P1 and P2 are potential probes.

Typically, two electrodes are used to transfer current to the ground, and a second pair is positioned in line between them to measure the potential difference (figure 3). Because currents enter and escape through C1 and C2, the potential measured at P1 is:

$$VP1 = \frac{I\rho}{2\pi} \left[\frac{1}{r1} - \frac{1}{r2} \right]$$

And, at P2
is:-

$$VP2 = \frac{I\rho}{2\pi} \left[\frac{1}{r3} - \frac{1}{r4} \right]$$

In fact, a measure is a possible difference rather than a possibility. Therefore, the following represents the potential difference between P1 and P2:

$$\Delta V = VP1 - VP2 = \frac{I\rho}{2\pi} \left[\frac{1}{r1} - \frac{1}{r2} - \frac{1}{r3} + \frac{1}{r4} \right] \dots (3.3.5)$$

A half-space's resistivity can be measured using:

$$\rho = \frac{\Delta V}{I} \cdot \left[\frac{2\pi}{\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}} \right] = \frac{K\Delta V}{I} \quad \dots (3.3.6)$$

where K is the measured potential difference, I is the current, and ΔV is

$$K = \left[\frac{2\pi}{\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}} \right] \quad \dots (3.3.7)$$

The positions of the electrodes in a particular array determine K, also known as the geometric factor.

The ratio $\Delta V/I$ will change on homogeneous ground if the electrode arrangement is changed to change K, but the predicted real resistivity ρ , as shown in equation (3.3.6), will always remain the same. The resistivity determined by equation (3.3.6) will change depending on the electrode array's position and/or direction across an anisotropic and/or inhomogeneous earth.

The apparent resistivity, represented by ρ_a , is the resistivity value derived from equation (3.3.6) on inhomogeneous ground. This is the actual ground resistivity in homogeneous ground; however, it typically represents the weighted average of the resistivities of all the formations that the current flows through.

The resistivity calculated using equation (3.3.6) varies with the position and orientation of the electrode array when applied to an anisotropic or inhomogeneous subsurface. This value, known as the apparent resistivity (ρ_a), reflects the result of applying the equation to an inhomogeneous medium. In a homogeneous earth, ρ_a corresponds to the true resistivity; however, in practice, it usually represents a weighted average of the resistivities of all the geological formations encountered by the current path.

A simple average of true resistivities or a single measurement of apparent resistivity at a given location does not necessarily represent the actual resistivity of any specific subsurface material. However, apparent resistivity typically varies in a consistent manner across a geologic section, making it a useful diagnostic tool for identifying layering and detecting resistive or conductive anomalies. Accordingly, the expression for apparent resistivity is given as follows:

$$\rho_a = \frac{K\Delta V}{I} \quad \dots (3.3.8)$$

2.5.3. Electrode Configurations and Apparent Resistivity

The resistivity method essentially consists of injecting current into the ground with two electrodes while measuring the voltage drop with two additional electrodes. Consider a set-up with two current electrode pairs and two potential electrode pairs. The relative sources and sinks are the current electrodes A and B.

2.5.3.1. Electrode Configurations

Four electrodes can be arranged in a variety of ways to create several array types, including Schlumberger, Wenner, dipole-dipole, and pole-dipole arrays. We will only talk about the Schlumberger setup and its geometric factors, though. These arrays were picked because the interpretation tools are well-developed and they are frequently utilized for groundwater studies.

2.5.3.1.1. Schlumberger Array

Vertical electrical sounding (VES) of aggregate materials and groundwater is a common application for the Schlumberger array. The vertical electrical sounding (VES) of the Schlumberger array provides higher resolution and requires less time to deploy the source than the Wenner array. The lateral resistivity changes are also mapped or profiled using the Schlumberger array. Larger fixed AB current electrode pairs and movable MN potential electrode pairs are typically used for profiling. With a set four ABMN electrode spacing, it is likewise carried out similarly to Wenner profiling.

The Schlumberger array operates in a symmetrical configuration when the current moves outward in the electrodes designated A and B as shown in Fig. 4, and the electrodes for voltage are designated M and N and closely spaced to one another in the array's centre.

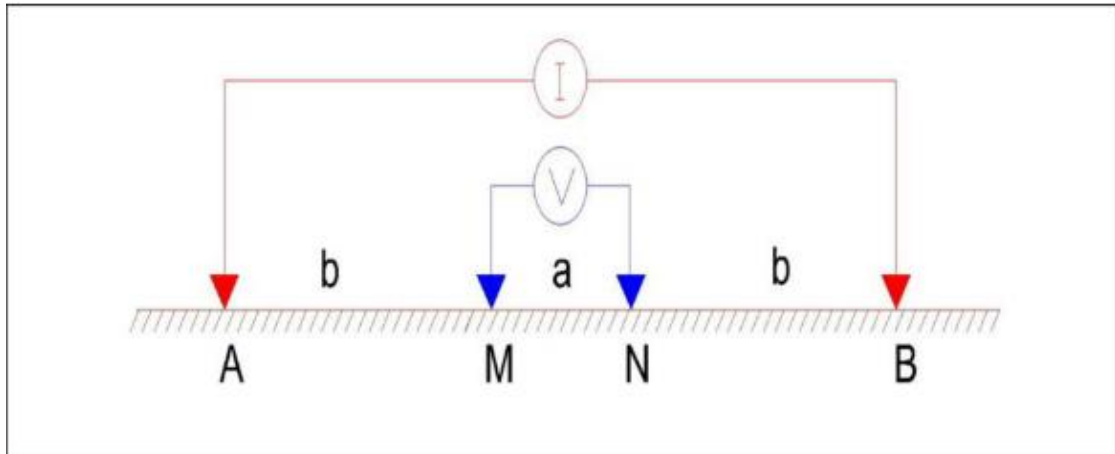
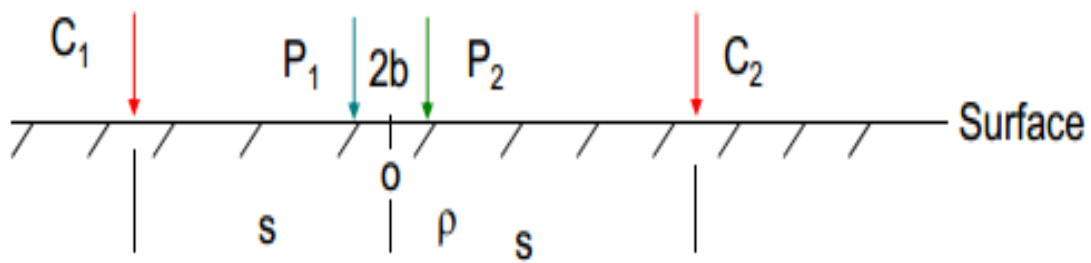


Figure 4.Schlumberger configuration

Source:(Partial et al., 2021).

In this configuration, the electrodes are symmetrically arranged around a central point of the array.



here $r_1 = s - b$; $r_2 = s + b$; $r_3 = s + b$, and $r_4 = s - b$ and therefore

$$\Delta V = \frac{I\rho}{2\pi} \left[\left(\frac{1}{s-b} - \frac{1}{s+b} \right) - \left(\frac{1}{s+b} - \frac{1}{s-b} \right) \right]$$

$$\Delta V = \frac{I\rho}{2\pi} \left(\frac{4b}{s^2 - b^2} \right)$$

$$\rho_{as} = \pi \left(\frac{s^2 - b^2}{2b} \right) \left(\frac{\Delta V}{I} \right)$$

where the **geometrical factor** in this case is $\pi (s^2 - b^2)/2b$.

The most widely used techniques for determining earth resistivity include employing galvanic contact to push current into the ground. Since the impact of material close to the current contacts may be reduced, four-terminal electrode arrays are typically employed.

One set of electrodes (A and B) is used to drive current, while the other set of electrodes (M and N), which is coupled to a sensitive voltmeter, is used to detect the potential that this current creates in the earth. The subsurface's apparent or effective resistivity may then be calculated .

From various locations on the earth's surface, the electrical resistivity technique analyses both lateral and vertical variations in ground resistance (Alisiobi & Ako, 2012). Measurements of electrode placements for current and potential are noted , where $MN/2$ is the potential electrode spacing and $AB/2$ is the current electrode spacing(Ubaidullah et al., 2021).

2.6.Magnetic Method

The earliest geophysical method of prospecting is magnetic, and it is used mostly to explore for minerals, oil, gas, coal, and groundwater as well as to examine geotechnical and archaeological sites (Markos & Gidey, 2022) .The technique is particularly useful for mapping structural features like faults, fractures, and contact zones since these areas frequently serve as possible habitats for various minerals and conduits for groundwater migration.

The magnetic method is among the most versatile geophysical techniques, as it can be applied to both shallow and deep-seated targets. Additionally, it is reasonably priced for regional and local research. The magnetic approach has mostly been employed for regional surveys in mineral and hydrocarbon explorations since the early 1900s. These applications include estimating the thickness of sedimentary basins and mapping igneous intrusions and geological features. The primary objectives of shallow subsurface studies are to characterize the sediments above the bedrock, define the shape of the bedrock, and locate buried metallic objects. The main application of the magnetic method in groundwater investigation had been in defining large-scale basin structures and regional aquifers (Oni et al., 2020) .

The earth's magnetic field is similar to that of a large bar magnet in the center of the planet.A magnetic field is linked to many geological formations because of their magnetic mineral composition, which causes them to behave like giant buried magnets. These local magnetic fields, which deviate from the undisturbed earth's magnetic field, will be overlaid on the magnetic field measured in the vicinity of such geological structures. The

earth's main field may rise or decrease as a result of these modifications or anomalies, which may vary in size. The direction and strength of the inducing earth's field, as well as the body's magnetic characteristics, orientation, depth of burial, and shape, all affect the primary field.

Magnetic techniques are employed to detect and map a variety of targets, including magnetic iron ore deposits, metallic ore bodies containing minerals like pyrrhotite or magnetite, and geological structures such as faults, dykes, and lithological contacts. Because the characteristics of a magnetic anomaly are suggestive of the rock, magnetic surveys are useful in groundwater investigations for mapping the depth of the magnetic basement rock. They also serve as a vital tool for lithological mapping. Additionally, it may be used to map structural elements, which occasionally serve as barriers and frequently serve as a conduit for the buildup of groundwater (Yehualaw et al., 2024)

2.6.1.Principle of Magnetic Method

2.6.1.1.Magnetic force

In the event that the poles are of the same kind, the force will push them apart; in the event that they are not, the force will be attractive and pull the poles in the direction of one another. The force between two magnetic poles of strengths m_1 and m_2 , separated by a distance r , is expressed as:

$$F = \frac{1}{4\pi\mu} \frac{m_1 m_2}{r^2}$$

where m_1 and m_2 are the pole strengths and the distance between them, respectively, and μ is the magnetic permeability of the medium between the poles.

2.6.1.2.The Earth's Magnetic Field

The Earth's magnetic field resembles that of a dipole located at its center, with its magnetic moment oriented toward the geographic South Pole. At any given moment, the components of this field fully define the Earth's magnetic field vector F .

The Earth's total magnetic field, F , forms an angle I — known as the inclination or magnetic dip — with the horizontal plane, as illustrated in Figure 5. This inclination can be measured using a dip needle. The angle D , called declination, represents the deviation of the horizontal component H of the magnetic field from true north, indicating the angle between true north and magnetic north.

In the Southern Hemisphere, the magnetic field is directed upward and away from the south magnetic pole, whereas in the Northern Hemisphere, it is directed downward toward the north magnetic pole. At the magnetic equator, the field is horizontal; at the magnetic poles, it is vertical. The total field F varies more significantly in the north-south direction than in the east-west direction. In Figure 5, Z represents the vertical component of F : it is positive (downward) in the Northern Hemisphere and negative (upward) in the Southern Hemisphere. The horizontal component, H , always points toward magnetic north in both hemispheres.

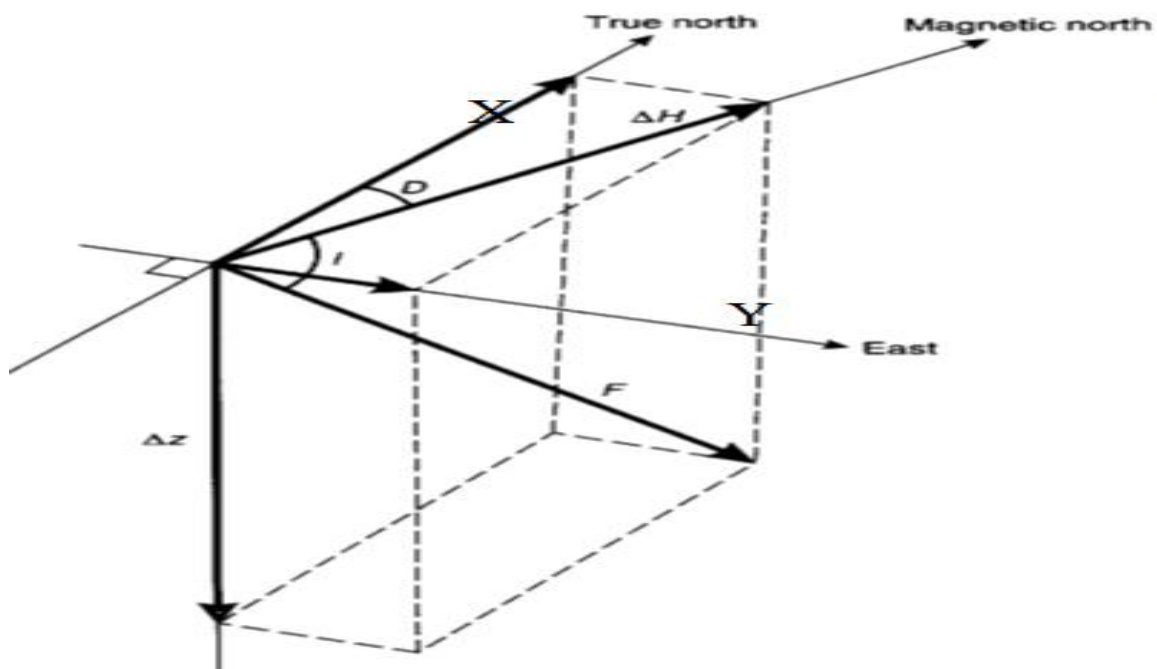


Figure 5.Elements of the earth's magnetic field

Source:(Partial, I N Of, Fulfillment Requirements, T H E The, F O R Sciences, Climate, 2006).

2.6.1.3.Relative permeability, susceptibility and magnetization

For a medium other than a vacuum, we obtain the following from the equation above:

$$\mu = \mu_r \mu_0$$

$$B = \mu H$$

$$= \mu_r \mu_0 H$$

$$\mu_0 H + \mu_0 (\mu_r - 1) H$$

$$\mu_0 H + \mu_0 k H \quad \dots (3.4.3)$$

Where, we have put, $k = \mu_r - 1$, that is $\mu_r = 1 + k$

μ_r is the two permeabilities' ratio: ($\mu_r = \frac{\mu}{\mu_0}$) and thus, is a pure number.

It is referred to as the medium's relative permeability, while k , which is likewise a dimensionless quantity, is known as susceptibility. In a vacuum, $k=0$ and $\mu_r=1$.

Magnetic susceptibility describes how readily a material becomes magnetized in response to an applied magnetic field. The intensity of induced magnetization (M) increases with increasing susceptibility, resulting in a larger anomaly in relation to the earth's field. Rocks' susceptibility varies greatly since it is mostly determined by the concentration of ferrimagnetic minerals, their particle size, and their distribution pattern.

2.6.2. Magnetic properties of rocks and minerals

Rocks can acquire magnetization in various unexpected ways, either as primary or secondary magnetization, and as either induced or remanent forms. When rocks are heated or cooled, their magnetization can be modified and lost; it can also be formed, destroyed, or altered by chemical changes and other processes. The typical carriers of rock magnetism are specific minerals whose distribution can have minimal bearing on bulk lithologic patterns; lateral changes of these minerals result in magnetic anomalies. Because magnetic minerals are unevenly distributed in rocks, magnetic surveys can be used to map magnetic rocks because of the minerals' magnetic susceptibility. A rock's magnetic susceptibility is primarily influenced by its magnetite content. Sedimentary and acidic igneous rocks typically exhibit lower susceptibility compared to more magnetic rocks such as serpentinites, gabbros, dolerites, and basalts. Table 2 below shows the magnetic susceptibilities of common rocks and minerals, expressed in rationalized SI units.

Table 2:The susceptibilities of some common rocks and minerals (Legedadi, 2013).

Common Rocks	
Altered ultrabasic rocks	10^{-4} - 10^{-2}
Andesite	10^{-4}
Granite	10^{-5} - 10^{-3}
Basalt	10^{-4} - 10^{-3}
Rhyolite	10^{-5} - 10^{-4}
Shale	10^{-4} - 10^{-3}
Most sedimentary rocks	10^{-6} - 10^{-4}
Gabbro	10^{-4}
Limestone and chert	10^{-6} - 10^{-5}

Source :(Legedadi, 2013).

3.METHOD AND MATERIALS

3.1.Description of the Study Area

The research area is situated around 490 km from Addis Ababa along the route from Addis Ababa-Nekemte-Gimbi-Bila Area in the west of Ethiopia, in the bodji dirmeji Wereda, west Wollega, Oromia regional state,Ethiopia.

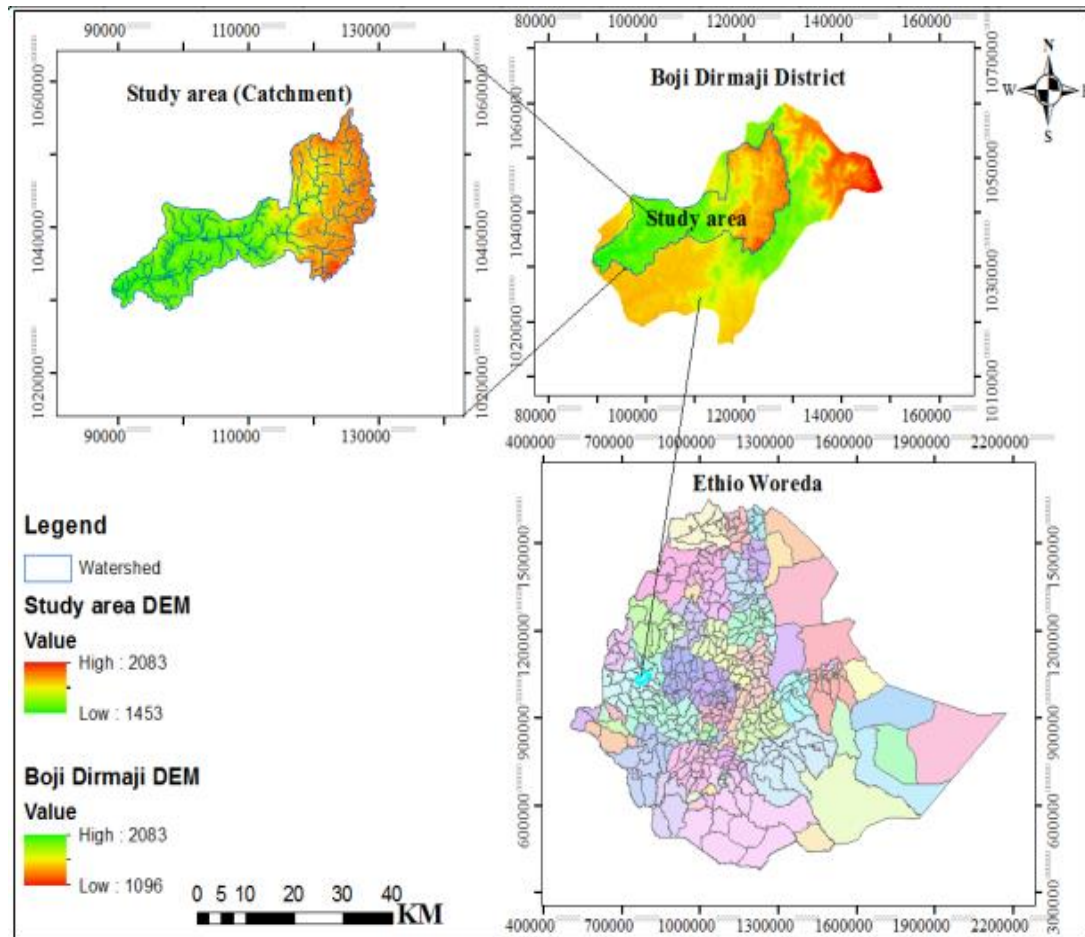


Figure 6.Location Map of the study area

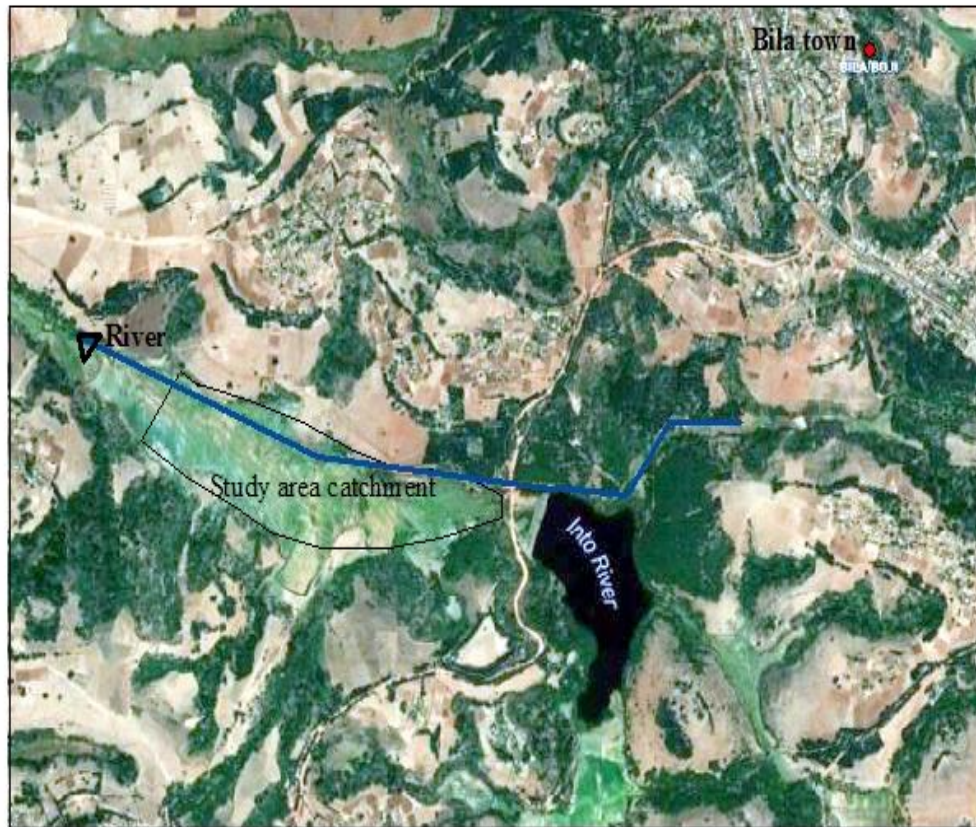


Figure 7. Satellite image of Ento Catchment area

3.1.1. Local Geology of the Study Area

The geology of the Bila region is characterized by a variety of rock types, including metasedimentary, metavolcanic, plutonic, and volcanic formations. The plutonic rocks are primarily composed of diorite-gabbro, while the volcanic rocks, predominantly found in the central part of the study area, are mostly composed of lower basalts. The metasedimentary rocks in the region include chloritoid–quartz schist and cordierite–muscovite–quartz schist.

The lithology of the area consists of diorite-gabbro, lower basalts, meta-gabbro amphibolite, and chloritoid–quartz–sericite schist, along with cordierite–muscovite–quartz schist, as shown in Figure 8 below. Field observations indicate that diorite-gabbro and lower basalts are the most widely distributed rock types within the study area.

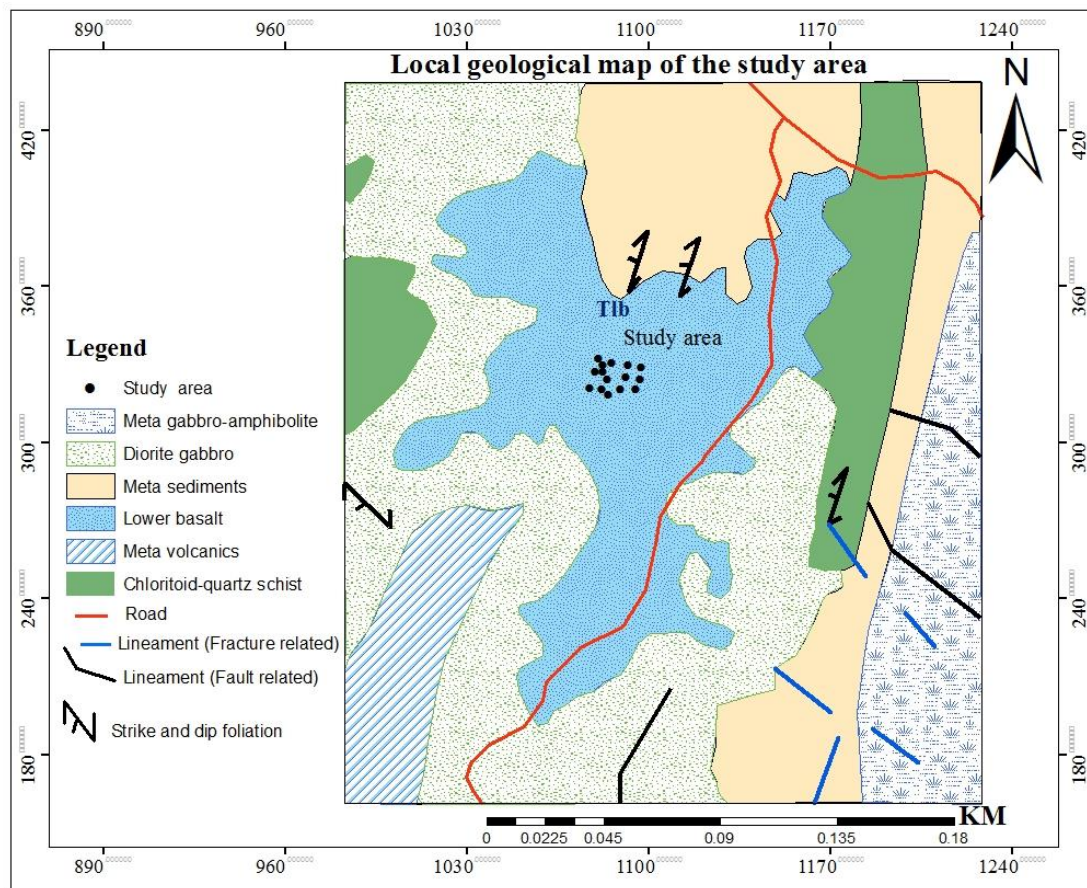


Figure 8. Local geological map of the study area (modified from gimbi geological map sheet 2001).

3.1.2. *physiography*

From a physiographic standpoint, Ethiopia can be broadly divided into three major regions:

I) The Western Highlands and Associated Lowlands (WHAL), which encompass the Ethiopian Plateau and surrounding lowland areas;

II) The Eastern Highlands and Associated Lowlands (EHAL); and

III) The Rift Valley (RV), a north–south trending feature that cuts through the center of the country, separating the western and eastern highlands.

3.1.3.Drainage of the study area

Drainage is a highly sensitive factor that plays a crucial role in delineating groundwater potential zones. They show how much osmotic precipitation there is in relation to outflow. In the study area, highly permeable rocks allow for significant groundwater infiltration, resulting in less surface water reaching the rivers compared to direct runoff. Conversely, if the rocks have low infiltration capacity, surface runoff increases while groundwater recharge decreases. As a result, areas with higher infiltration tend to exhibit greater water accumulation and higher groundwater potential. The Digital Elevation Model (DEM) values within the study area range from 1,876 to 2,096 meters, as illustrated in Figure 9.

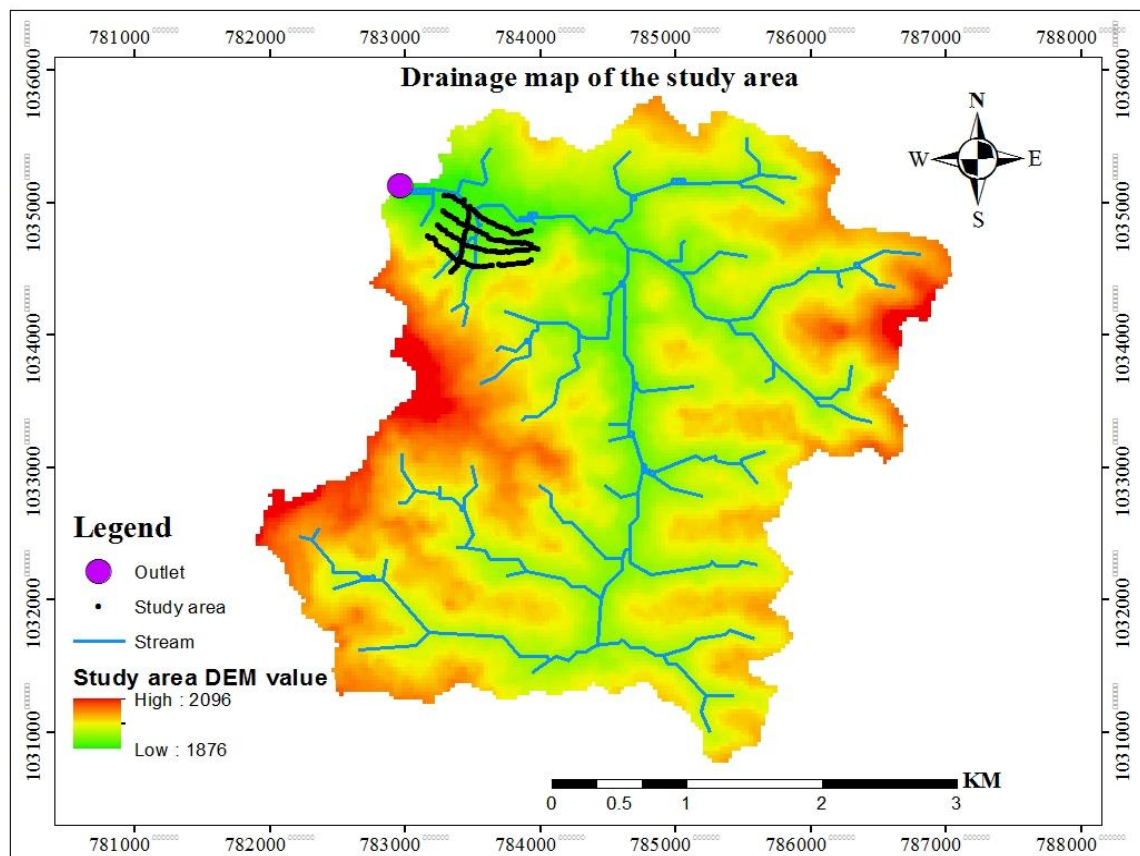


Figure 9.Drainage Map of the study area

3.1.4.Topography

The study of topography is particularly important in understanding groundwater occurrence and flow direction, as the landforms in the study area help capture rainfall and contribute to groundwater recharge and distribution. In other words, ground water occurs

because of the topographic land formations and flows from high topographic to low topographic locations.

3.1.5.Climate

The research area's climate is suitable for human habitation and a variety of activities. The climate in this research region is suitable for animal breeding and various area production from June to August and between October and January, respectively. When it rains, the air gets cooler.

3.1.6.Groundwater Recharge And Discharge

The study of groundwater flow networks and water budgets depends on an understanding of groundwater recharge and outflow, two significant components of the global hydrological cycle. Recharge is the process of resupplying groundwater with precipitation that has fallen or with water that has been temporarily held on the earth's surface. Artificial recharge results from intentional or unintentional human action, such as irrigation or the direct injection of water into the subsurface, whereas natural recharge happens without human influence or improvement. The natural or human-induced upward movement of groundwater—most commonly caused by well pumping—is known as discharge. Unlike other components of the hydrological cycle, groundwater recharge and outflow are often less apparent due to their localized nature. The primary source of natural groundwater recharge is rainfall, meaning that nearly all groundwater used by humans originates from atmospheric sources and is considered meteoric in origin.

In addition to naturally leaking from the earth's crust into the ocean, springs, lakes, rivers (often referred to as "gaining streams"), marshes, and other wetlands, groundwater is compelled to leak from wells. As a result, groundwater discharge has the potential to significantly impact ecosystems. Although these activities are not legally known as discharge, groundwater may also immediately return to the atmosphere through processes including transpiration through vegetation and evaporation inside the soil. In the absence of human intervention, discharge rates typically approximate recharge rates, leading to a balanced or equilibrium state in the subsurface water budget. However, "overdrafts" caused by the overexploitation of groundwater resources can result in falling water levels (increasing pumping costs), reduced hydrostatic pressure, and other related issues, including soil subsidence.

3.2.Methods

The following three approaches are employed as methods to achieve the study's goals: pre-field studies, fieldwork, and post-fieldwork.

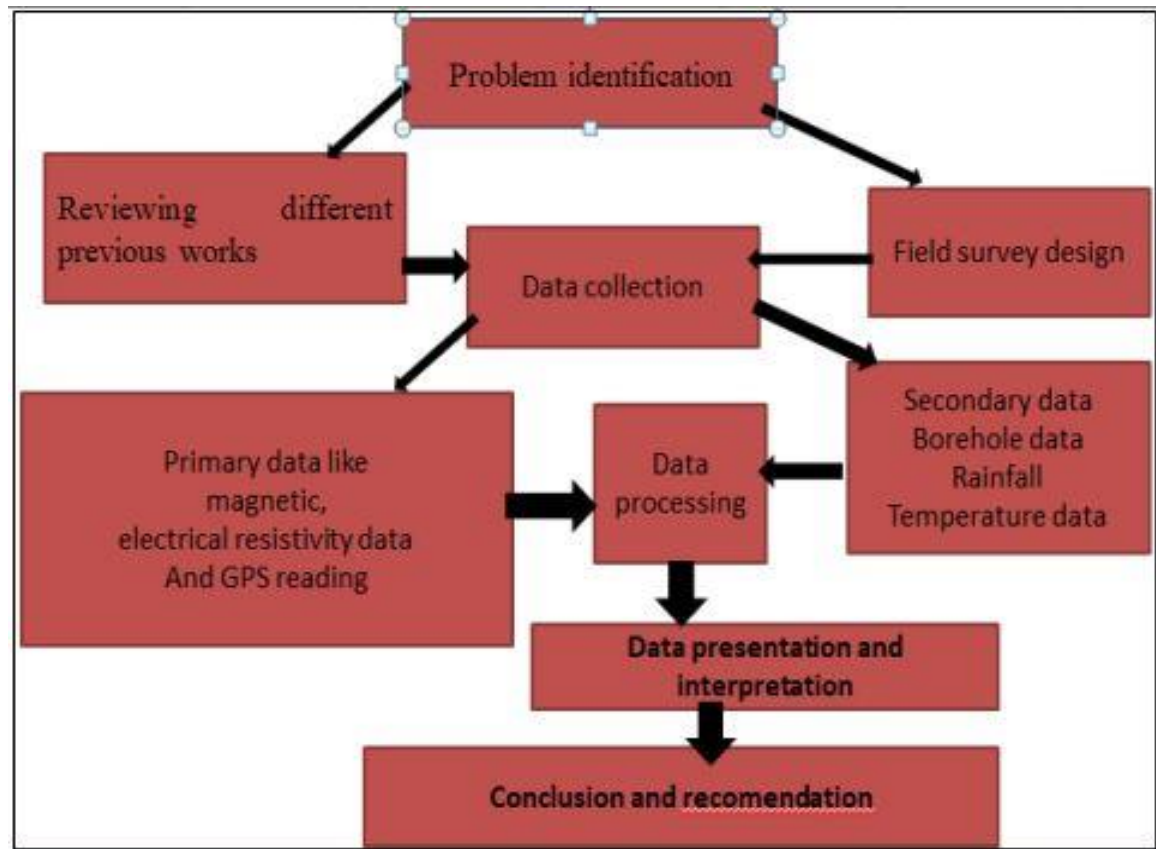


Figure 10.Flow chart of methodological approach

3.2.1.Pre-field Studies

The pre-field phase involves conducting a literature review, gathering prior data from published studies in the research area, including those on geological structures, hydrogeology, geophysics, and related topics, as well as obtaining an overview of the study region.

3.2.2.Electrical Resistivity Data Acquisition

The Schlumberger array, known for its superior depth penetration and reduced sensitivity to lateral inhomogeneities, is primarily used in vertical electrical sounding (VES). In this method, the current electrodes are progressively expanded during successive measurements, while the potential electrodes remain fixed. For this investigation, the symmetrical Schlumberger configuration was employed along four survey lines, each spaced approximately 200 meters apart. VES measurements were taken at average

intervals of 200 meters, with a maximum electrode spacing ($AB/2$) of 330 meters. In this setup, electrical current is introduced into the ground through two outer electrodes, while the inner pair of potential electrodes—positioned between them—measures the resulting voltage difference. A total of four VES measurements were conducted along each profile, resulting in comprehensive coverage across the selected lines.



A

B

Figure 11.Photographic view of the vertical electrical sounding (A) and magnetic (B) field operations.

3.2.3.Magnetic Field Procedures and Data Acquisition

Before conducting the magnetometer survey, several important factors were considered. First, a suitable site within the survey area was selected for the base station—specifically a location with minimal magnetic interference from nearby sources such as vehicles, iron-roofed buildings, roads, and power lines. Second, the base station was established at this site to allow for diurnal correction. Third, the technical readiness of the instruments was verified, including checks for sufficient power supply, availability of appropriate connecting cables and accessories, and adequate memory storage.

The magnetic method is commonly used in subsurface investigations to map structural lineaments—such as faults and fractures—that may serve as conduits for groundwater. The Garmin GPSmap 60 CSx was used to determine the coordinates and elevations of each survey station. Base station readings were taken at the beginning and end of each data collection session, specifically between 1:00 and 1:30 hours for all profiles.

At each station, measurements were taken using the Proton Magnetometer-600, and the magnetic field reading, recording time, and location (in UTM coordinates) were documented. Data were collected along five survey profiles, with magnetometer readings taken at approximately 25-meter intervals and profile spacing of about 200 meters. In total, 155 magnetic readings were manually recorded during the survey. The collected data were subsequently imported into Excel for diurnal correction and further analysis. The profile lines and data points for both vertical electrical sounding and magnetic sounding were mapped using ArcGIS 10.8 software as follows:

After data collection, the diurnal effect was computed, and the following expression was used to filter the magnetic data (Nibret & Gebissa, 2021).

$$Dc=Bn -[BSf-BSiTf-Ti][Tn-T1].....(4)$$

Where Dc is the diurnal correction, Bsf and Bsi are the final and initial total magnetic fields at the base station, respectively, and Tf and Ti are the final and initial times at the base station, respectively. Tn and T1 represent the measurement times at the nth station and the first station of the loop, respectively, while Bn is the total magnetic field at the nth station in the loop.

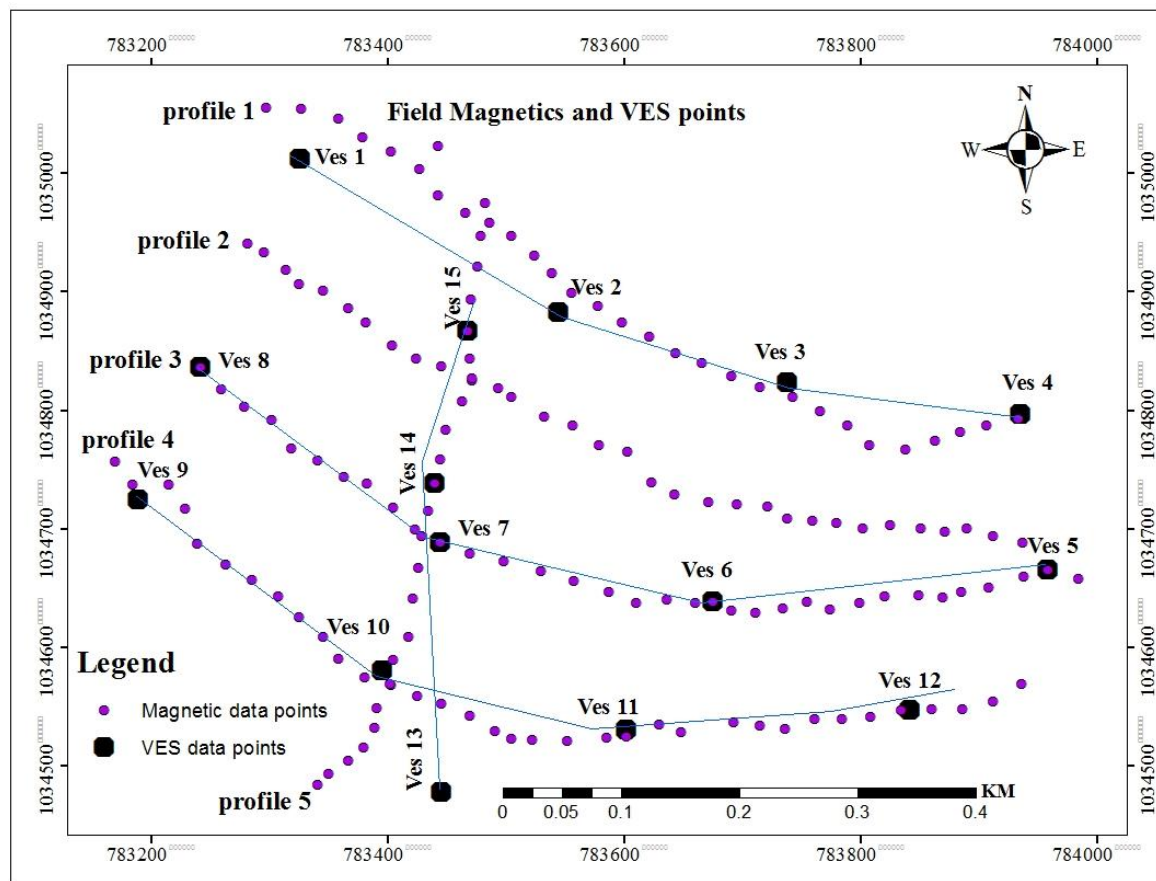


Figure 12.Field Magnetic and VES survey points

3.3.Materials

3.3.1.Materials used

I have used the following geophysical tools to carry out my investigations. GPS (Global Positioning System), a compass to choose the necessary directions, and a proton precession magnetometer to measure the strength of the earth's magnetic field were the tools used in magnetic surveying. In resistivity surveying, the instruments used were the ABEM Terrameter LS, a power supply storage battery, some cable electrodes, and a meter.

3.3.2.Software's

A variety of software programs were used to process and evaluate the fieldwork data. Data were provided for both qualitative and quantitative interpretations using these software programs, which ultimately made it possible to generate the results in the form of geophysical anomaly maps, sections, and profiles.

The programme is used to interpret the data set at the time of data acquisition. This software includes:

- IPI2WIN: This commercial programme generates accurate resistivity values.
- Surfer 10: This powerful scientific programme is used to create depth and thickness maps as well as for data mapping, modelling, and analysis features.
- IPI-res3 is a computer tool used to interpret data from Vertical Electrical Sounding (VES) surveys, a geophysical method for mapping subsurface geological formations.

IPI2win, IPI-res3, and Surfer 10 (32-bit) software, along with updated versions, were used to interpret the data and information gathered from various sources, based on a fundamental understanding of geophysical methodologies. The geophysical findings were then correlated for the interpretation of VES data.. Oasis Montaj will be largely utilized to evaluate the magnetic survey data.

3.4.Data Processing And Presentation

3.4.1.Qualitative Analysis

Determining the thickness and resistivities of subsurface layers is the goal of understanding field VES curves in order to acquire the subsurface's geological image. However, prior to a detailed quantitative interpretation, it is necessary and advantageous to undertake brief qualitative evaluations of the field curves. Such a strategy offers important criteria at the beginning of geophysical survey programs that could affect how the data-gathering process develops further. Furthermore, this contributes to the dissemination of some helpful background information regarding the geoelectric characteristics of the region being studied. Plan maps and depth pseudo-sections can be used to illustrate the spatial distribution of electrical parameters at the latter (processing and interpretation) stage. In this instance, the pseudo-depth values ($AB/2$) and apparent resistivity (ρ_a) have been used to plot the smoothed field data from spatially aligned consecutive soundings as pseudo-sections. These plots make it possible to geoelectrically describe the region in both lateral and vertical directions.

3.4.2. Quantitative Analysis

Initially, the Schlumberger sounding curves obtained from field measurements were analyzed using the conventional curve-matching method with two-layer master curves and auxiliary point charts. This manual interpretation determines the number of layers, their thicknesses, and their resistivities. These variables aid in creating an initial conceptual multilayer earth model of the research region.

The results of sounding will be displayed as interpretations of resistivity curves, apparent resistivity pseudo-sections, and apparent resistivity geoelectric sections, i.e., $AB/2$ values.

- The lateral and vertical variations of electrical characteristics inside the subsurface are qualitatively shown by a pseudo-section.

Geo-electric sections are considered to offer a more accurate representation of the subsurface geoelectrical conditions, as they typically display the distribution of layer resistivities and thicknesses. In reality, these portions would provide the foundation for the majority of the quantitative interpretation.

The base station readings obtained during the survey were used to adjust the observed magnetic data for diurnal fluctuation. To eliminate unpredictable patterns that most likely stem from cultural noise, the resulting magnetic data was smoothed using a moving average filter. The total magnetic map, residual map, analytical signal map, and upward continuation map were the formats in which the adjusted and smoothed total field magnetic values were displayed.

4.RESULT AND DISCUSSIONS

The field data required a qualitative and quantitative analysis and interpretation to achieve the objective of the study. With the use of a drill lithological log data, the interpretation was developed by combining the findings from magnetic and vertical electrical sounding data. To correlate these various units with the geoelectrical section and understand the vertical geological variation of the study area, borehole data were used. The borehole utilized for interpreting the geophysical data is located near the study area and was drilled by the Oromia Water and Energy Bureau for water supply purposes to Bila town.

Source: West Wollega Water and Energy Office.

4.1.Resistivity Interpretation

This section presents the interpretation of VES resistivity point data along all profiles. For qualitative analysis, the results of the resistivity sounding survey are displayed as VES curves, apparent resistivity pseudo-depth plots, and geo-electric sections, which together support a more comprehensive quantitative interpretation.

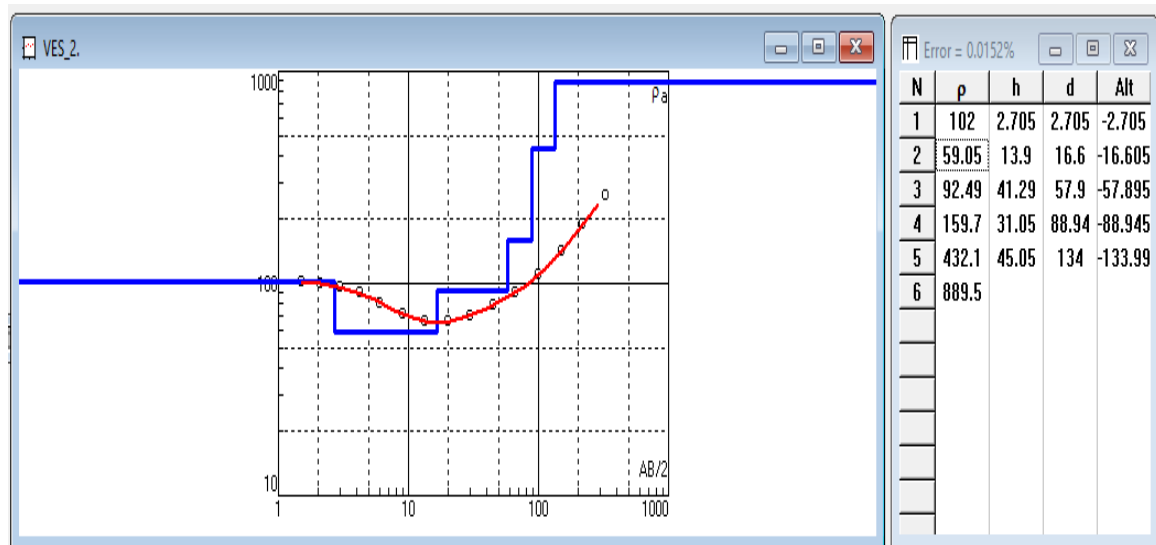
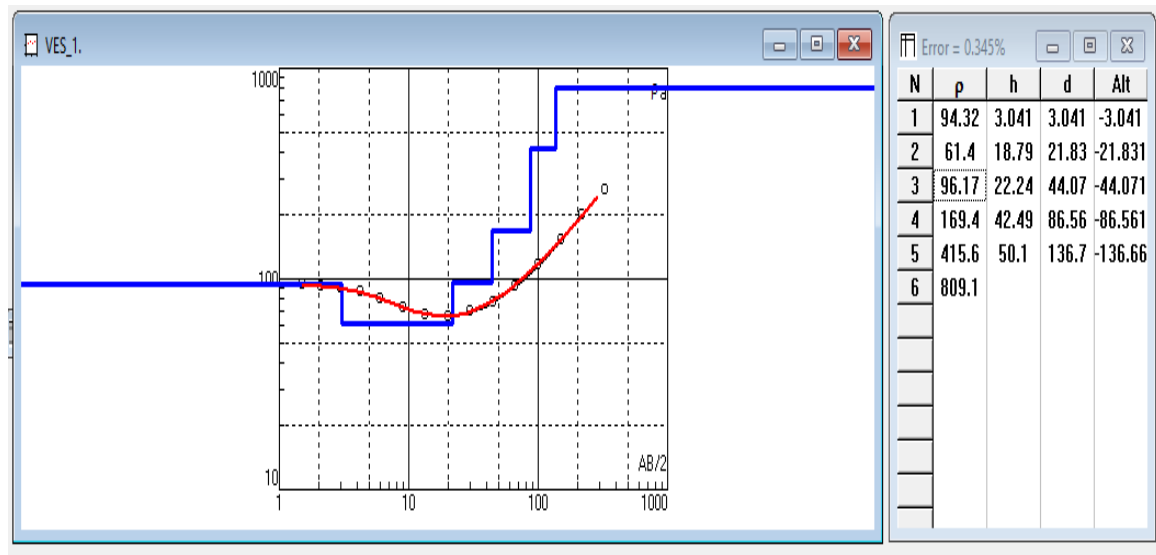
4.1.1.Interpretation of Resistivity Curves

The geo-electric resistivity method is a geophysical technique employed to study subsurface conditions by measuring the resistivity of underlying rock formations. Assessing the rock's resistivity value based on surface measurements is the aim of the geo-electric survey. The measurement value can be used to determine the real resistivity value (Nibret & Gebissa, 2021). The curves of all VESs, which obtained from inverted apparent resistivity data was presented in the following Figures. The interpretation of geo-electric parameters (true depth/thickness and true resistivity) was presented by VES curves.

4.1.1.1.Curve interpretation along profile one

Figure 13 illustrates the results for the VES points along Profile 1 (VES 1, VES 2, VES 3, and VES 4), indicating the presence of five distinct resistivity layers. For all four VES points, the data suggest that the lithologic divisions can be categorized into five layers. The curves for each VES point exhibit the resistivity pattern $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, which corresponds to an HA-type layer configuration. Specifically, the VES 1 resistivity

curve indicates five layers with a resistivity sequence of $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, characterizing an HA-type layer. VES 2 similarly shows five layers, with a resistivity sequence of $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, also indicative of an HA-type layer. VES 3 follows the same pattern, showing five layers with the resistivity sequence $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, consistent with an HA-type layer. The VES 4 curve for this profile also divides the lithologic formation into five layers, following the same resistivity pattern of $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, which is characteristic of an HA-type layer.



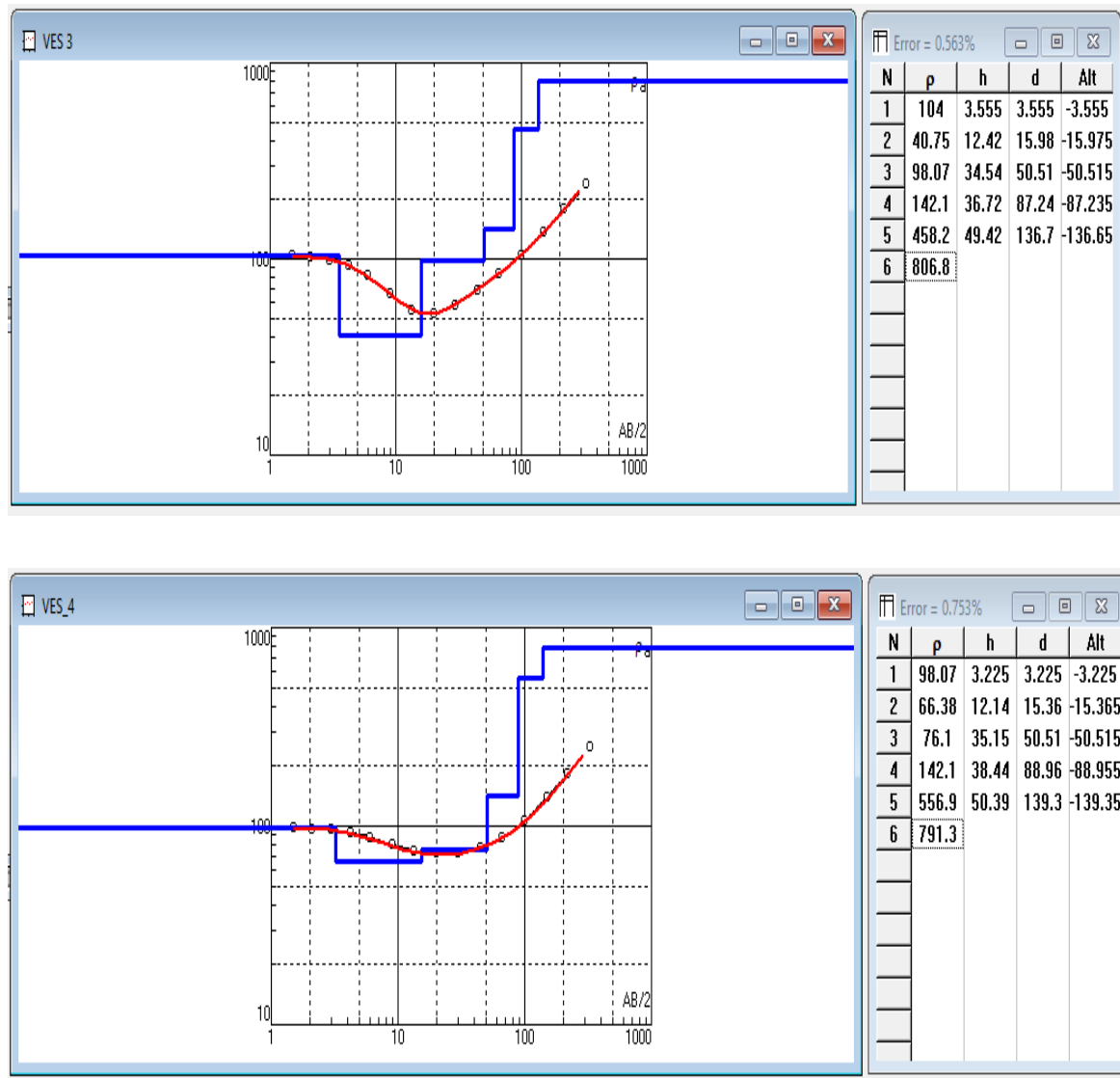


Figure 13.Electrical resistivity curve of VES 1,VES 2,VES 3 and VES 4

4.1.2.Pseudo cross-section along profile one

The pseudo-section, which helps determine the distribution of resistivity values both laterally and vertically, was created using the VES data along all survey lines. This section illustrates typical lateral and vertical variations in resistivity within the subsurface, represented in pseudo-depth maps derived from apparent resistivity data. The pseudo-section for all VES points along Profile 1 is shown in Figure 14 below. The pseudo-depth section along Profile 1 (Figure 14) reveals that the central areas of VES 3 and VES 4 exhibit low apparent resistivity values, likely indicating high groundwater potential. In contrast, the lower sections of all VES points along profiles 1 (VES 1, VES 2, VES 3, and VES 4) show high resistivity values. The upper sections of all VES points along profile 1

display resistivity values ranging from 91 Ωm to 109 Ωm , indicating medium resistivity. This is likely representative of clay soil overlying dry soil composed of various-sized hard rock materials. The deeper sections of all VES points along profile 1 exhibit high resistivity, suggesting the presence of massive meta-volcanic rock.

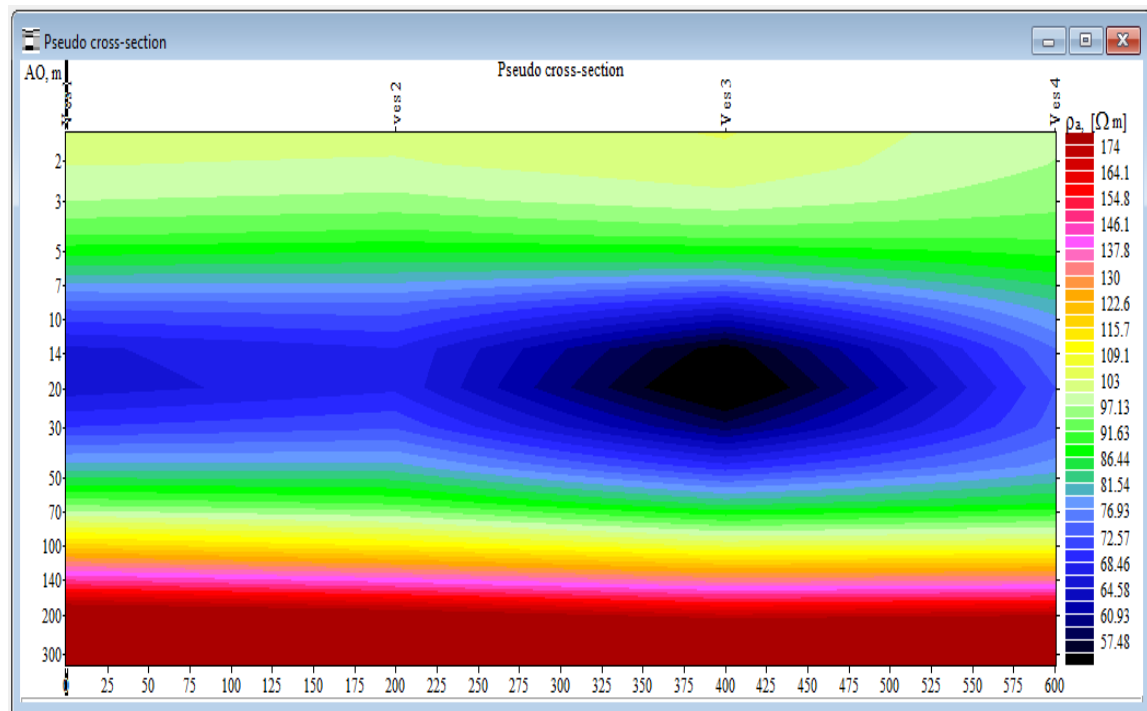


Figure 14. Pseudo section along profile one

4.1.3. Geo electric section of profile one

The geo-electric section of Profile 1 was constructed using the interpreted layer parameters from VES 1, VES 2, VES 3, and VES 4 in the study area, as shown in Figure 15. This section consists of five distinct layers, each with varying thicknesses and resistivity values, as depicted in the figure below. The geo-electric section of Profile 1 reveals a promising aquifer beneath VES 3 and VES 4 in the third layer, which has a thickness of 35 m, a resistivity range of 76-98 Ωm , and a depth of 51 m. A similar aquifer potential is observed in the fourth layer, which has a thickness of 38 m, a resistivity of 142 Ωm , and a depth of 89 m. The most productive aquifer is anticipated beneath VES 3 and VES 4, as this layer lies at a greater depth and is situated between fractured and weathered meta-volcanic rocks, which are conducive to groundwater accumulation.

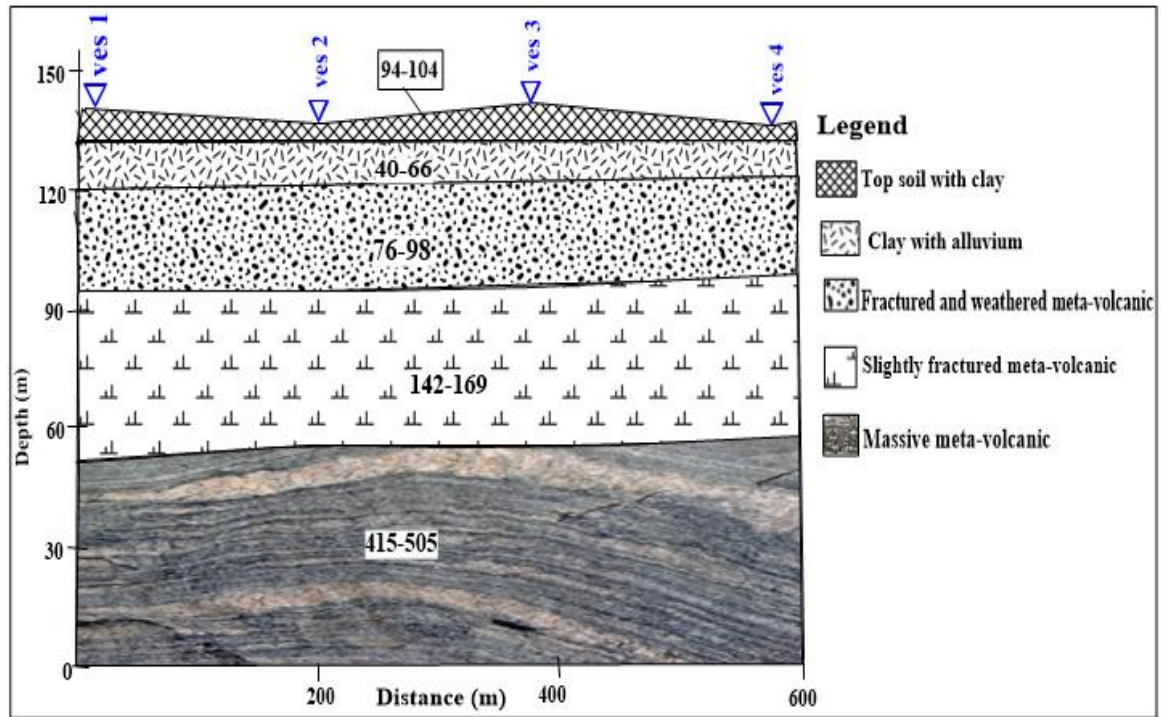
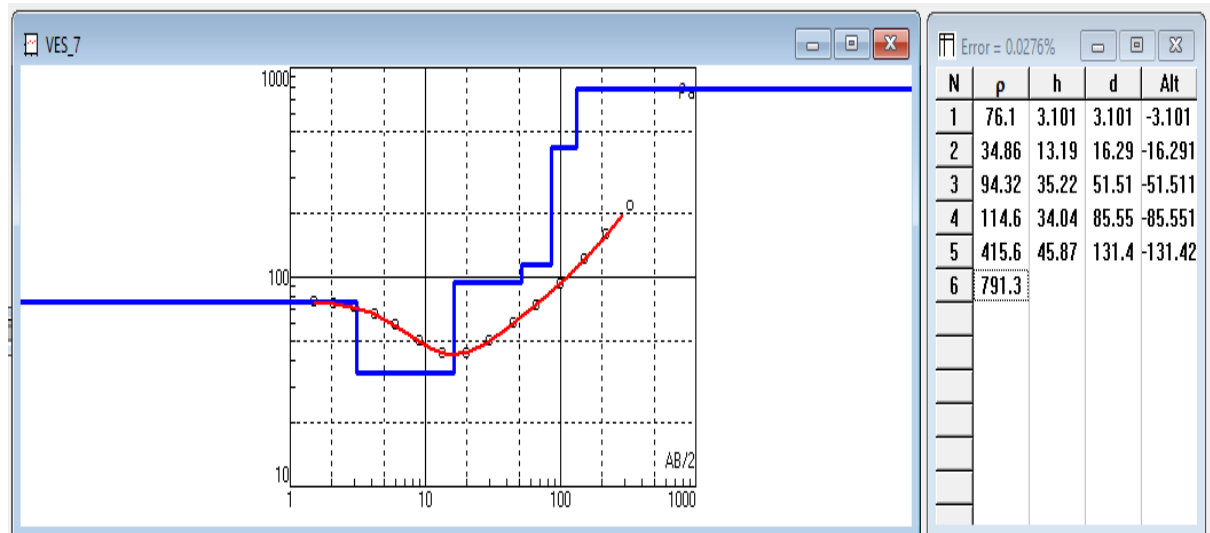
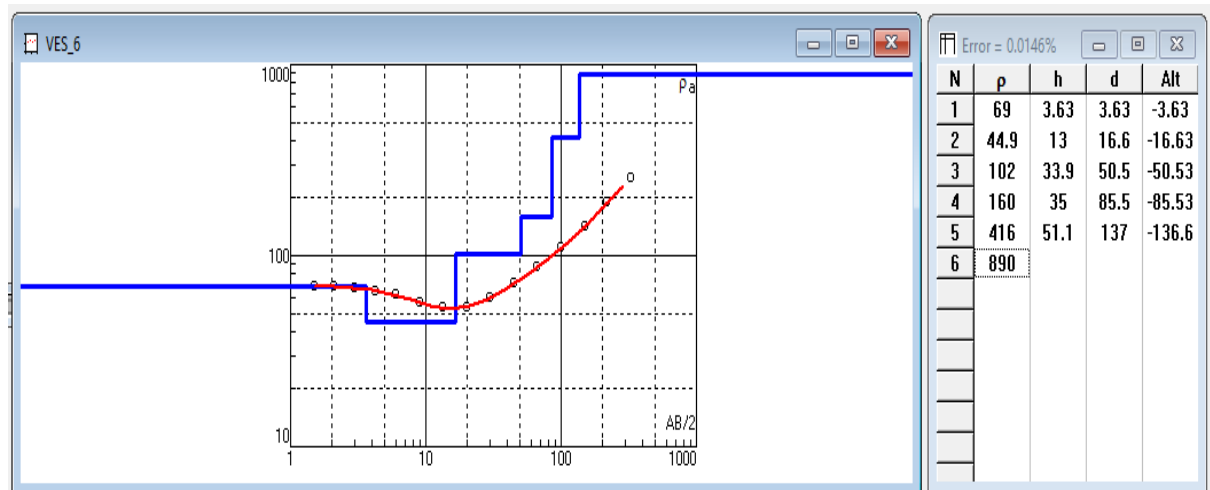
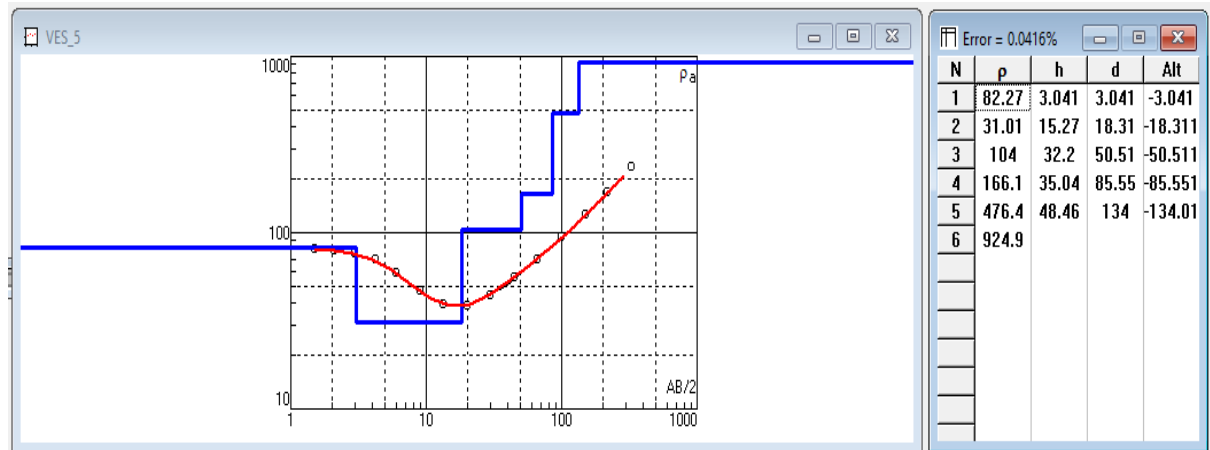


Figure 15.Geo electric section of profile one

4.1.4. Curve interpretation along with profile two

The results from Figure 16 for the VES points along Profile 2 (VES 5, VES 6, VES 7, and VES 8) show a five-layer resistivity model. The VES data for Profile 2 reveal that VES 5 exhibits a five-layer structure, with its curve characterized by the sequence $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, which corresponds to an HA-type curve. Similarly, the VES 6 curve also follows the pattern $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, indicating another HA-type curve, and it too consists of five layers. The VES 7 curve, with five layers, demonstrates the same resistivity pattern ($\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$), again representing an HA-type curve. Likewise, the VES 8 curve consists of five layers, following the same resistivity pattern ($\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$), which also classifies it as an HA-type curve.



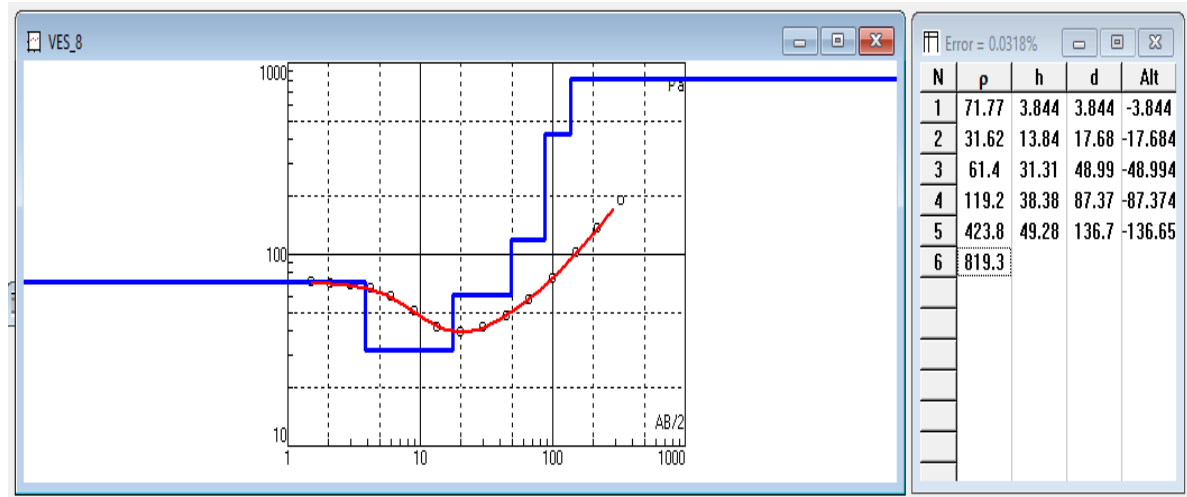


Figure 16.Electrical resistivity curve of VES 5, VES 6, VES 7 and VES 8

4.1.5.Pseudo cross-section along with profile two

Figure 17 shows the apparent resistivity along Profile 2, which includes data from VES 5, VES 6, VES 7, and VES 8. The pseudo-depth section along Profile 2, presented in Figure 18, reveals three distinct regions. The upper layers exhibit moderate apparent resistivity, which likely indicates the presence of loosely compacted, clayey soil, formed from the in-situ breakdown of underlying rock formations. The lower portion of all VES points along Profile 2 exhibits high resistivity values. Notably, the middle section of VES 8 shows lower resistivity values, which suggests high groundwater potential in this area.

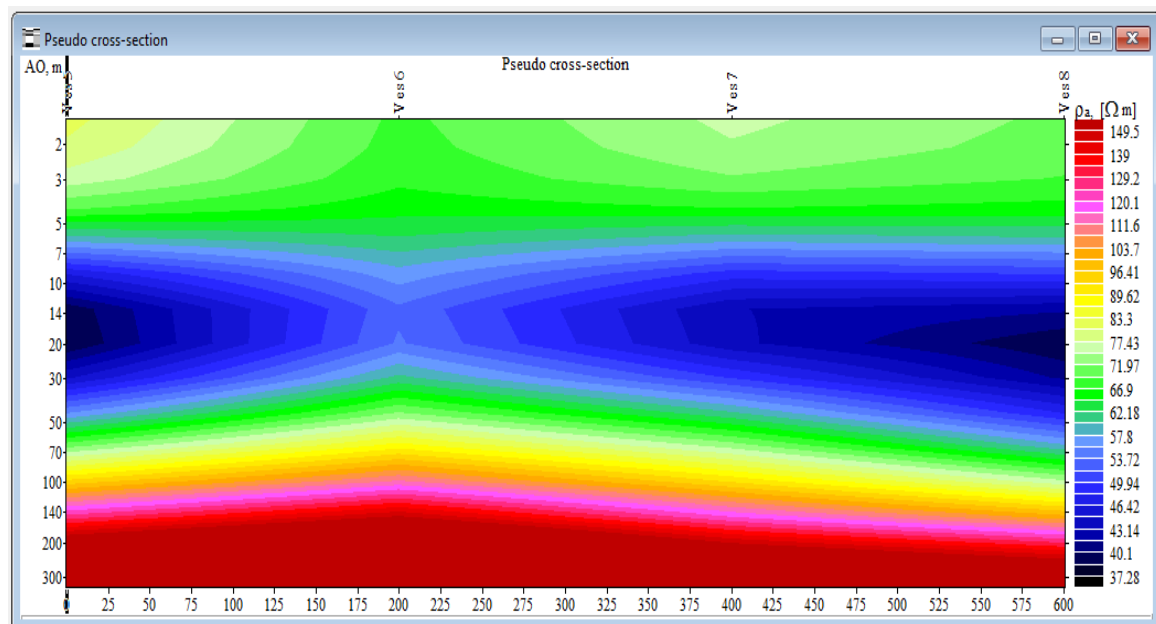


Figure 17.Pseudo sections along profile two

4.1.6. Geo electric section of profile two

The geoelectric section of Profile 2 was constructed using the interpreted layer parameters from VES 5, VES 6, VES 7, and VES 8 in the study area, as shown in Figure 18. This section consists of five layers, each with varying thicknesses and resistivity values. The geoelectric section of Profile 2 identifies a promising aquifer beneath VES 8 in the third layer, which has a thickness of 31 m, a resistivity of 61 Ωm , and a depth of 49 m. A similar aquifer potential is observed in the fourth layer, with a thickness of 38 m, a resistivity of 119 Ωm , and a depth of 87 m. The most productive aquifer is likely located beneath VES 8, as this layer lies at a greater depth and is situated between fractured and weathered meta-volcanic rocks, which are associated with high groundwater potential in the study area.

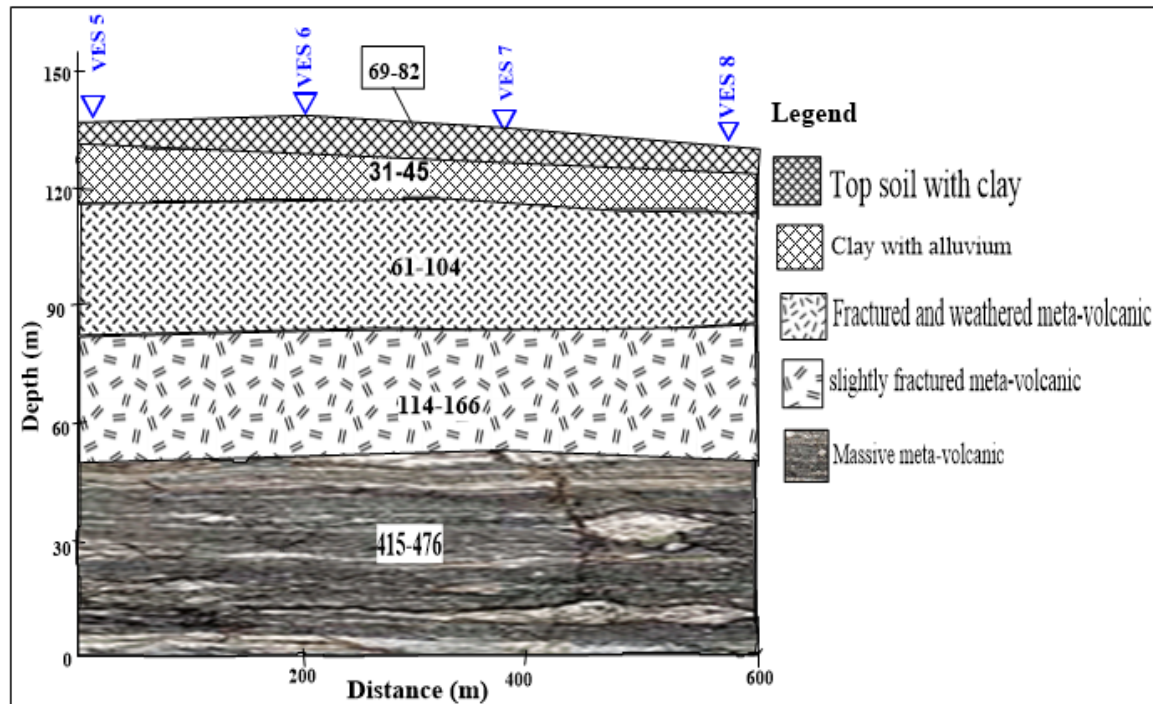
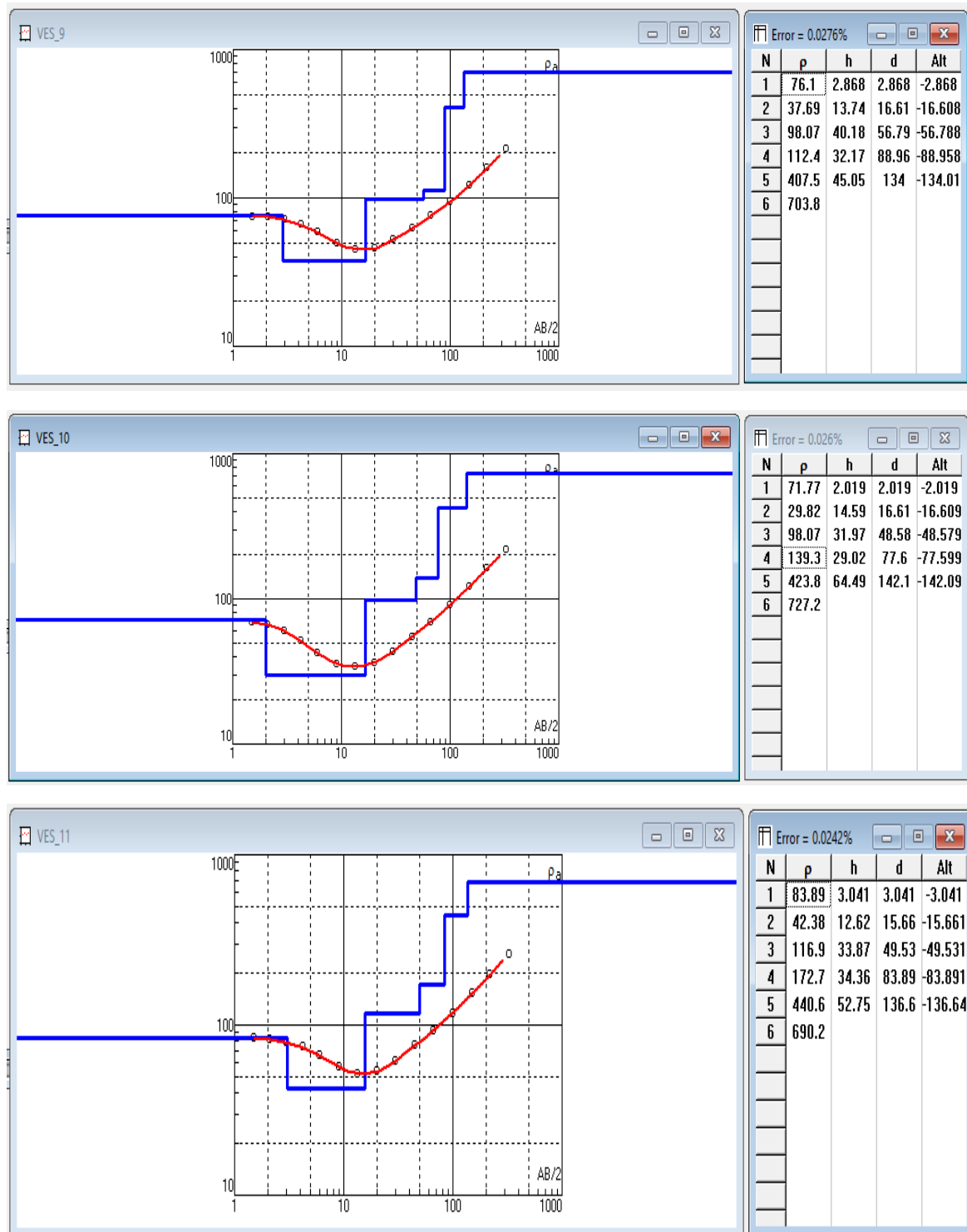


Figure 18.Geo electric section of profile two

4.1.7. Curve interpretation along with profile three

As shown in Figure 19, the results for the VES points along Profile 3 (VES 9, VES 10, VES 11, and VES 12) are modeled using a five-layer resistivity structure. VES 9 divides the lithologic formation into five layers, with a curve representing $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, indicating an HA-type curve. Similarly, VES 10 classifies the lithologic formation into five layers, with its curve following the pattern $\rho_1 > \rho_2 > \rho_3 < \rho_4 < \rho_5 < \rho_6$, which

also corresponds to an HA-type curve. The VES 11 curve also represents the pattern $\rho_1 > \rho_2 > \rho_3 < \rho_4 < \rho_5 < \rho_6$, classifying it as another HA-type curve with five layers. Finally, VES 12 divides the lithologic formation into five horizons, and its curve follows the same pattern $\rho_1 > \rho_2 > \rho_3 < \rho_4 < \rho_5 < \rho_6$, confirming it as an HA-type layer as well.



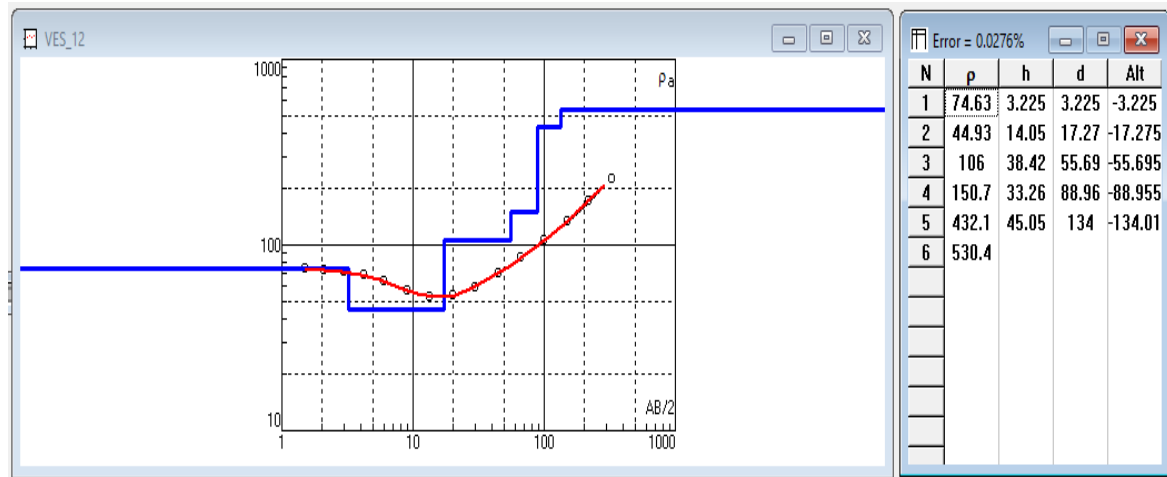


Figure 19.Electrical resistivity curve of VES 9, VES 10, VES 11 and VES 12

4.1.8.Pseudo cross-section along with profile three

Figure 20 displays the pseudo-depth section for VES 9, VES 10, VES 11, and VES 12 along survey Profile 3. The figure reveals high resistivity values in the bottom layer. The top section of all VES points along Profile 3 shows medium resistivity values, while the middle section exhibits relatively low resistivity values. Among the four VES points, the middle section of VES 10 displays low resistivity values, with values falling below 71 Ωm , suggesting a high groundwater potential in this area due to the large thickness of the low-resistivity zone.

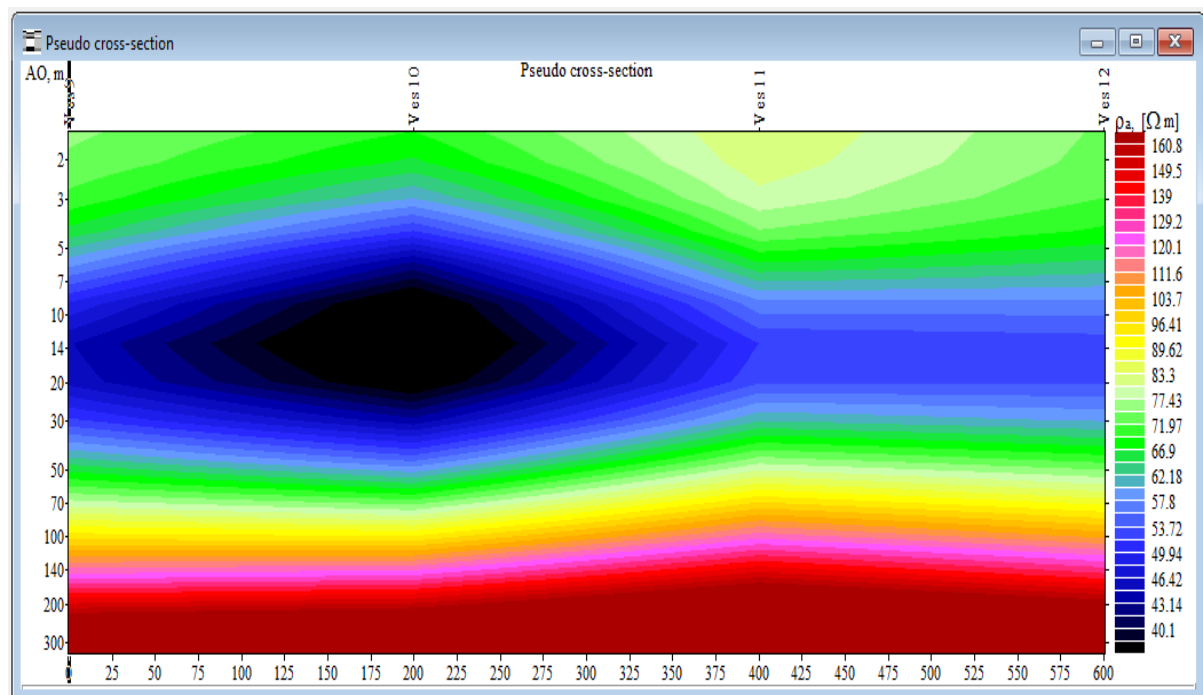


Figure 20.Pseudo sections along profile three

4.1.9. Geo electric section of profile three

The geoelectric section of Profile 3 was constructed using the interpreted layer parameters from VES 9, VES 10, VES 11, and VES 12, as shown in Figure 21. This section comprises five layers, each with varying thicknesses and resistivity values, as illustrated in the figure. The third layer in VES 9 and VES 10, with a thickness ranging from 32 to 40 m, a resistivity of 98 Ωm , and a depth extending from 49 to 57 m, along with the fourth layer, which has a thickness of 29 to 32 m, a resistivity range of 112 to 139 Ωm , and a depth extending from 78 to 89 m, is identified as a potential aquifer. These layers were interpreted as highly fractured and weathered meta-volcanic rock types. The considerable thickness of the third and fourth layers in VES 9 and VES 10 suggests a high level of groundwater saturation in the study area.

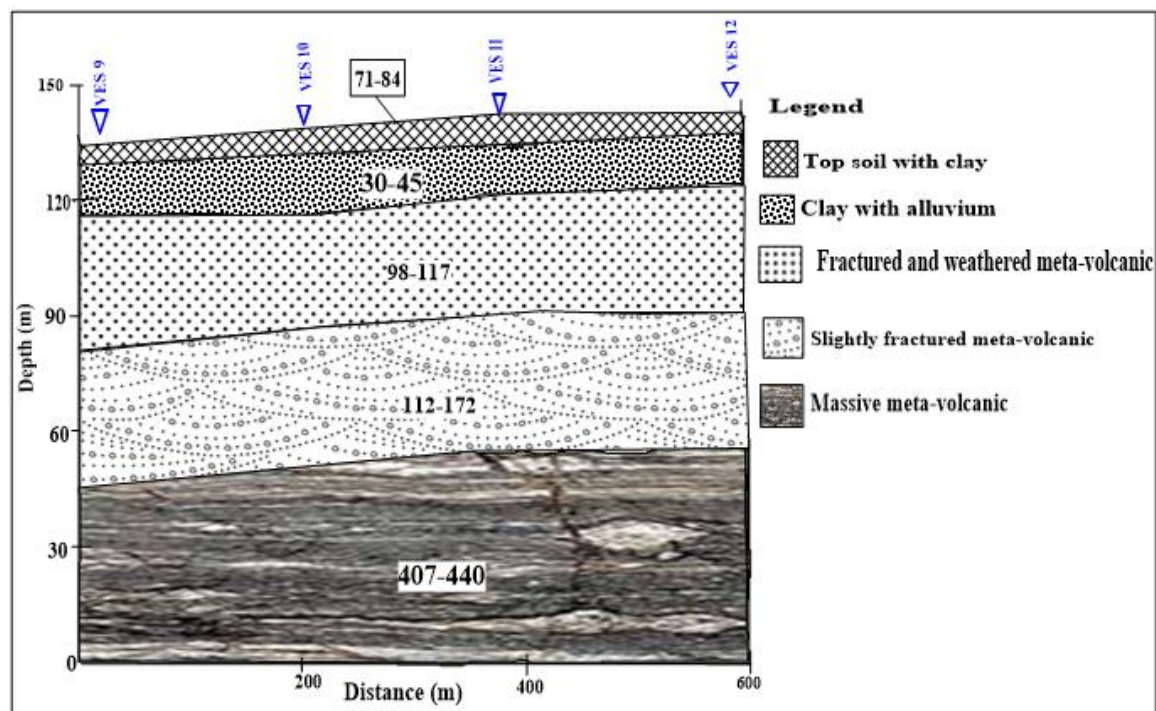


Figure 21.Geo electric section of profile three

4.1.10. Curve interpretation along with profile Four

The results presented in Figure 22 for the VES points along Profile 4 (VES 13, VES 14, and VES 15) show a five-layer resistivity model. The VES data for Profile 4 reveals that VES 13 consists of five lithologic layers, with its curve characterized by $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, which corresponds to an HA-type curve. Similarly, the VES 14 curve also follows the pattern $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$, representing another HA-type curve with

five layers. Likewise, the VES 15 curve exhibits five layers and follows the same resistivity pattern ($\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5 < \rho_6$), confirming it as an HA-type curve as well.

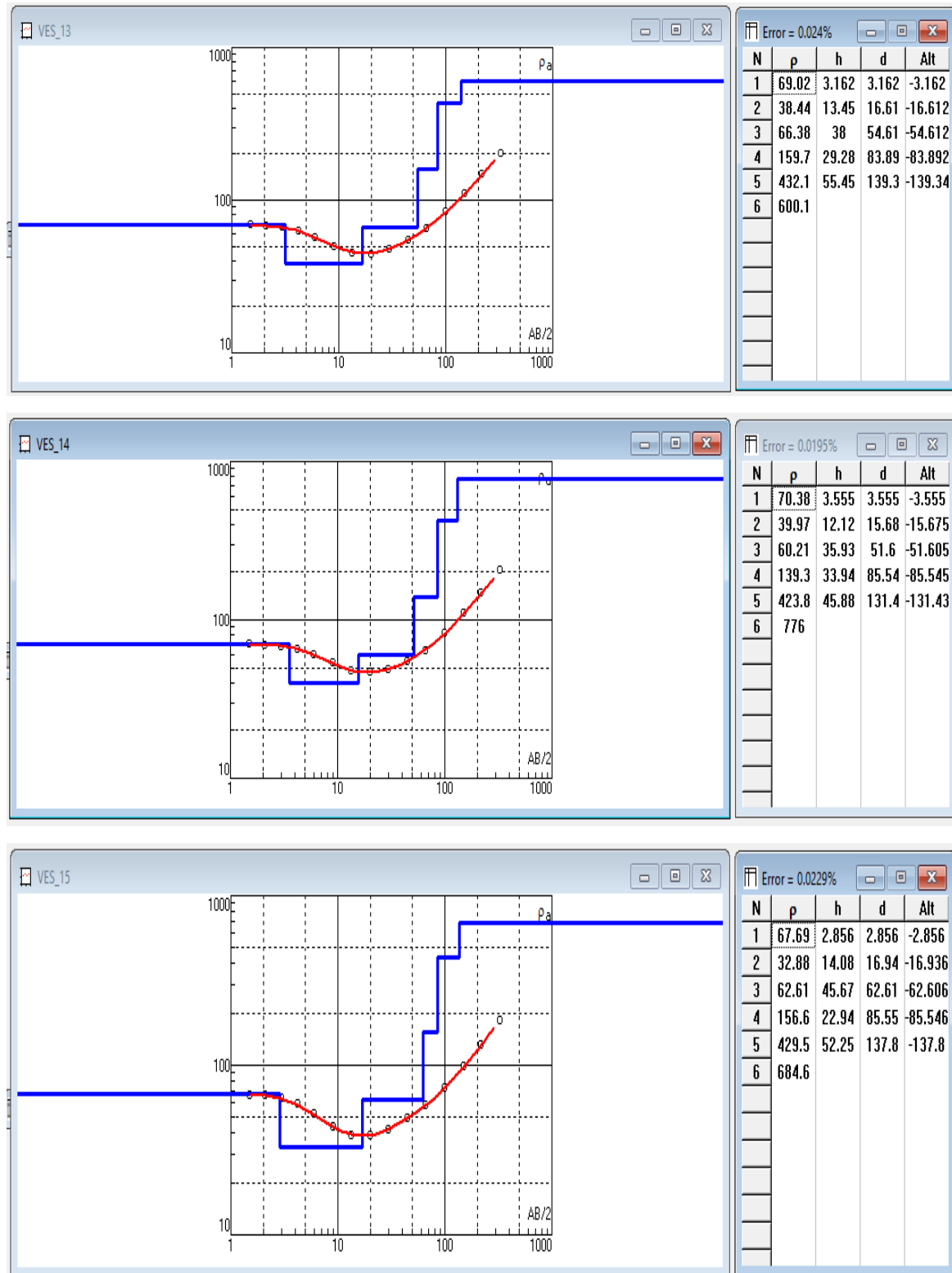


Figure 22.Electrical resistivity curve of VES 13, VES 14, and VES 15

4.1.11. Pseudo cross-section along with profile four

Figure 23 shows the pseudo-depth section for VES 13, VES 14, and VES 15 along the survey line, which runs from southwest to northeast. The section highlights both lateral and vertical variations in resistivity, with higher resistivity values observed in the lower layers at all VES points. The middle sections, from VES 13 to VES 15, show lower resistivity values. The top layer of all VES points along Profile 4 (VES 13, VES 14, and VES 15) exhibits relatively medium resistivity values. Notably, the middle layer of VES 15 has lower resistivity values with significant thickness, indicating high groundwater potential in this area.

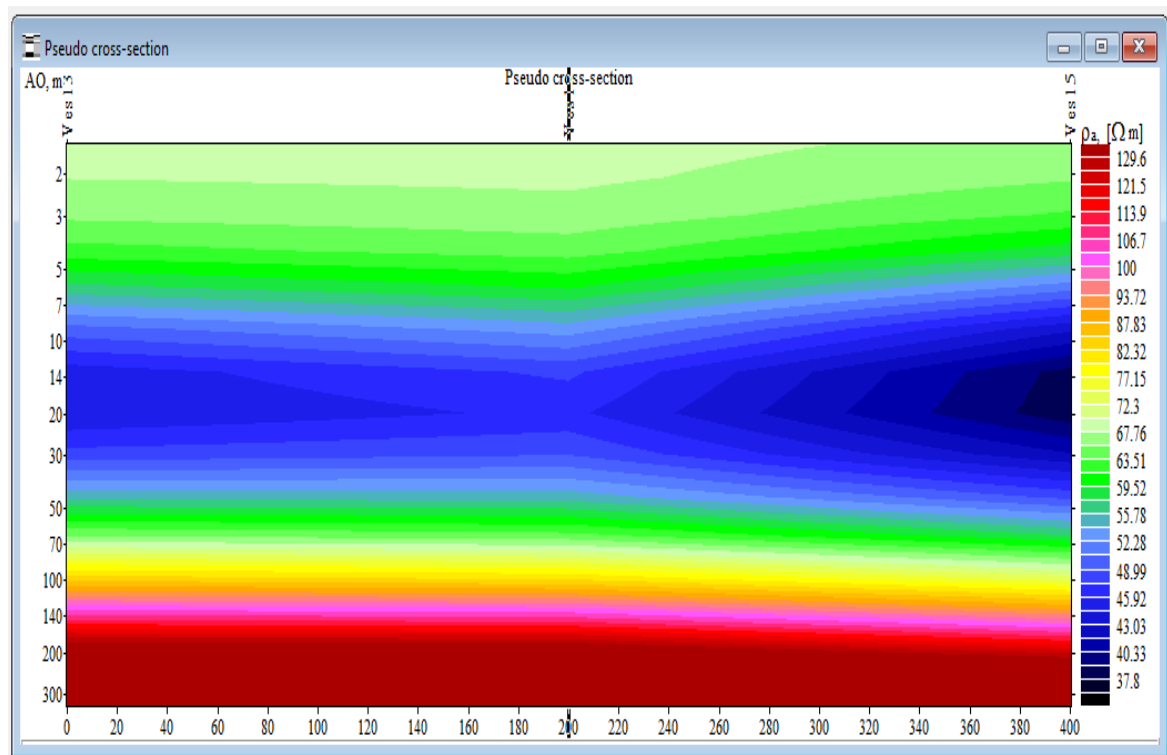


Figure 23. Pseudo sections along profile Four

4.1.12. Geo electric section of profile Four

The geoelectric section of Profile 4, shown in Figure 24, was constructed based on data from three VES points. The 3rd layer of VES 15, with a thickness of 48 m, resistivity of $62 \Omega m$, and a depth of 62 m, is identified as a promising aquifer zone. These layers are likely composed of fractured and weathered meta-volcanic rocks. The lower resistivity zone within this layer, combined with its large thickness, suggests that structures with low

resistivity and significant thickness are likely to represent good groundwater potential areas. This layer is probably the primary aquifer zone in the study area.

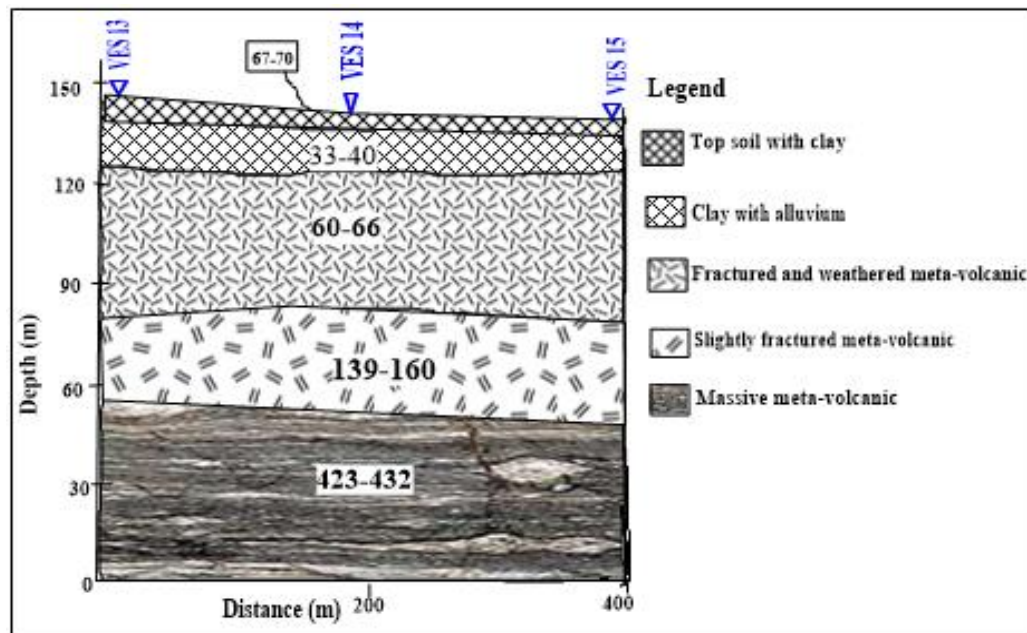


Figure 24.Geo electric section of profile Four

4.2.Result and Interpretation of Magnetic Data

The results of the magnetic surveys were also presented through various maps, including the total magnetic field, residual magnetic field, analytical signal magnetic field, and upward continuation maps, all of which were used for qualitative interpretation.

4.2.1.Total Magnetic Intensity Field Anomaly map

The total magnetic anomaly map of the study area is presented in Figure 25 below. This map, showing the total magnetic intensity field anomaly, offers valuable insights into the overall subsurface structure of the area. As illustrated in Figure 25, the anomaly values of the total magnetic field vary from 35,174 nT to 35,711 nT. The northwest and northeastern regions (A, B, C, D, and E) exhibit a lower magnetic response, with intensity variations between 35,174 nT and 35,592 nT. In contrast, the central part of the map (1, 2, 3, 4, 5, 6, 7, 8, and 9) shows a higher magnetic response, with anomaly values ranging from 35,629 nT to 35,711 nT. Regions I and II exhibit medium magnetic responses, with anomaly values ranging from 35,592 nT to 35,629 nT.

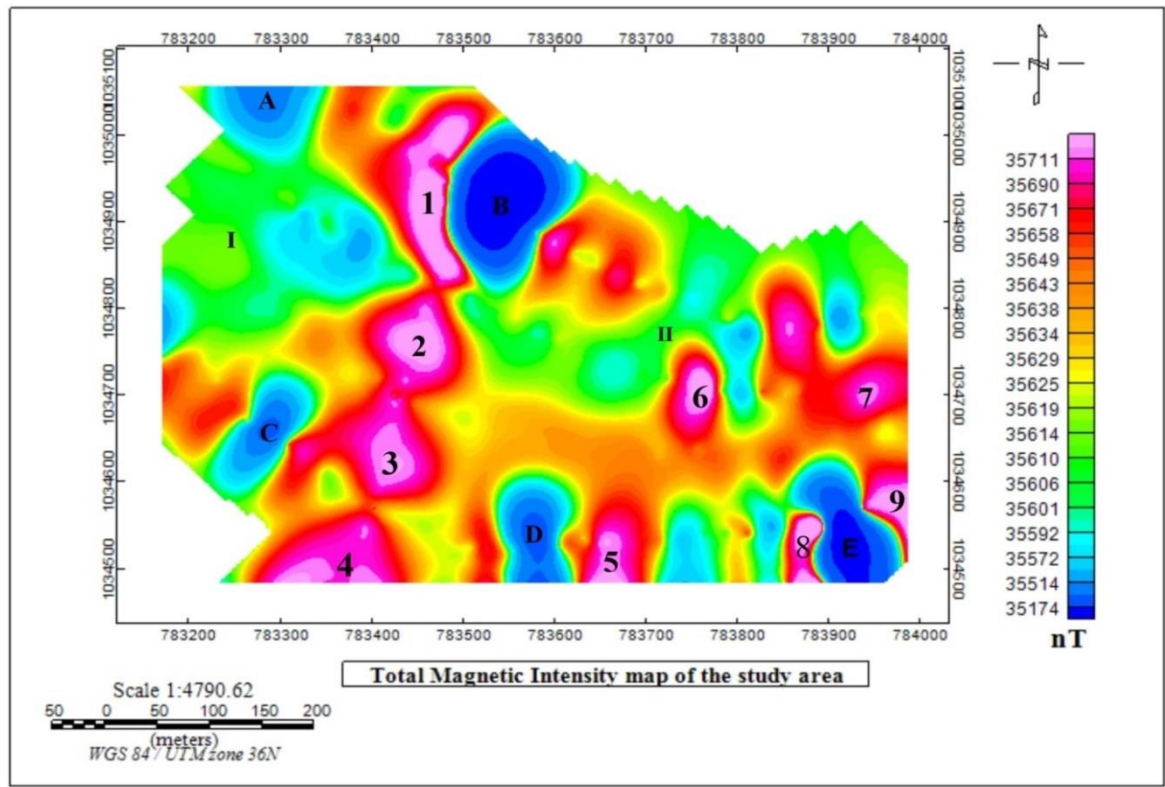


Figure 25.Total magnetic intensity anomaly map

4.2.2. Residual Magnetic field Intensity Anomaly map

Residual anomalies represent the short-wavelength, small-scale variations in the magnetic field. It shows the impact of local anomalies, mineralization, and near-surface geological features superimposed on the regional field. The residual anomaly is obtained by subtracting the estimated regional field from the observed total magnetic anomaly (Zone, NZone, N. W. (2024). Integrated Geophysical Investigation for Mapping Groundwater Potential Zones of the Mersa-Girana Sub. 3(1), 2024).

Residual maps shows local magnetic variations, which may have exploration significance. The amplitude of the residual magnetic field intensity ranges from -398 to 118.9 nT, as shown in Figure 26. Low (negative) magnetic responses were observed at A, B, C, and D, and the anomaly of residual magnetic field intensity variation is between -398 nT and -12 nT, whereas the high (positive) magnetic response is observed at the top section of the map plot in the north direction towards the eastern part of the study area (1, 2, 3, 4, 5, 6, 7, 8, 9, and 10), and the anomaly of residual magnetic field intensity variation is between 21.5 nT and 118.9 nT. The I, II, and III indicates medium in residual magnetic responses.

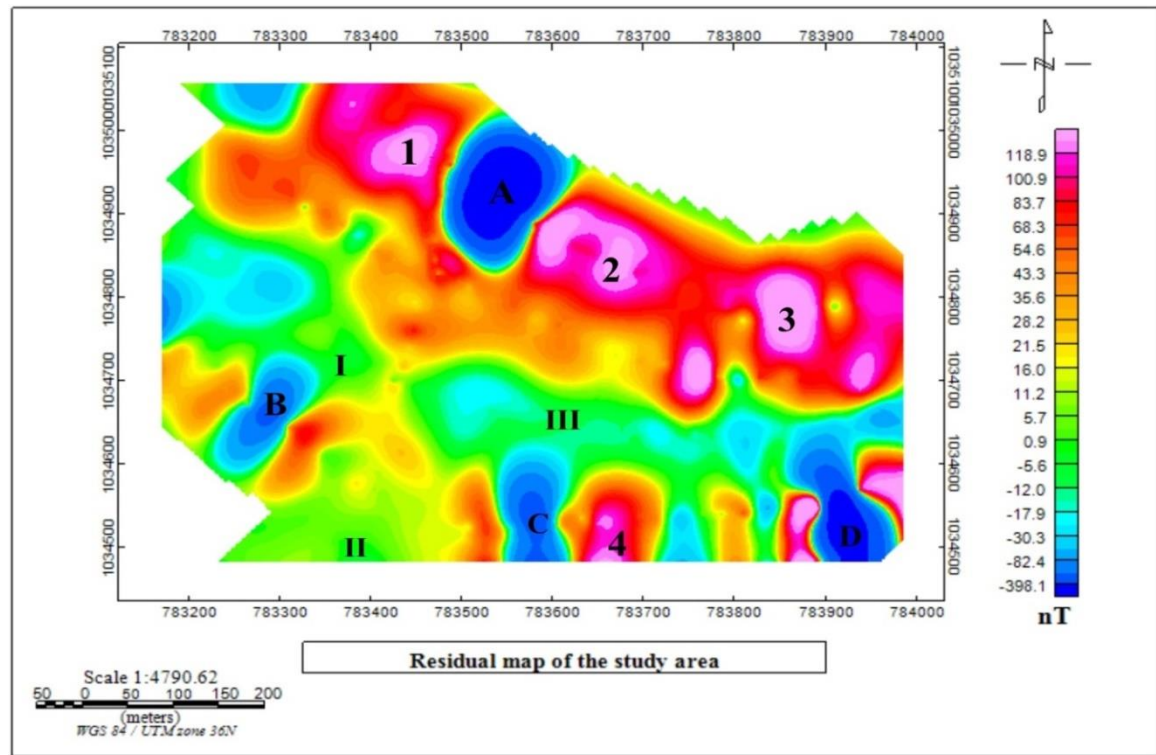


Figure 26.Residual magnetic field intensity (RMI) map of the study area

4.2.3. Analytical signal magnetic map

An analytical signal map was generated from the residual magnetic anomaly data, as shown in Figure 27, to support the qualitative interpretation of magnetic features—such as estimating structural settings, source depths, and subsurface formations. The analytical signal produces a response directly over the causative bodies, with its shape depending on their locations rather than their magnetization direction. This makes the method particularly effective in low magnetic latitude regions. The map specifically resolves near surface (shallow) anomaly sources very well and is good at locating the edges of shallow bodies, for the reason that the amplitude of the simple analytical signal peaks (attains maxima) over magnetic contacts (Haile & Ayele, 2014)

Since the analytical signal map shows the response of anomalous bodies from their upper portions, it is very useful to visualize the near-surface conditions (Nibret & Gebissa, 2021). Accordingly, there are six weak zones in the surveyed area, which are indicated by a black line on the map. The analytic signal map is used to show shallow anomaly sources. This analytical signal map shows that the anomalous bodies are in the northern, southeastern, and eastern parts of the survey area.

From Figure 27, it was observed that analytical signal map low amplitudes were located in the southwest, and the central part of the map plot , whereas the high magnetic amplitudes were located in the top portion of the north direction, southeast, and eastern part of the study area.

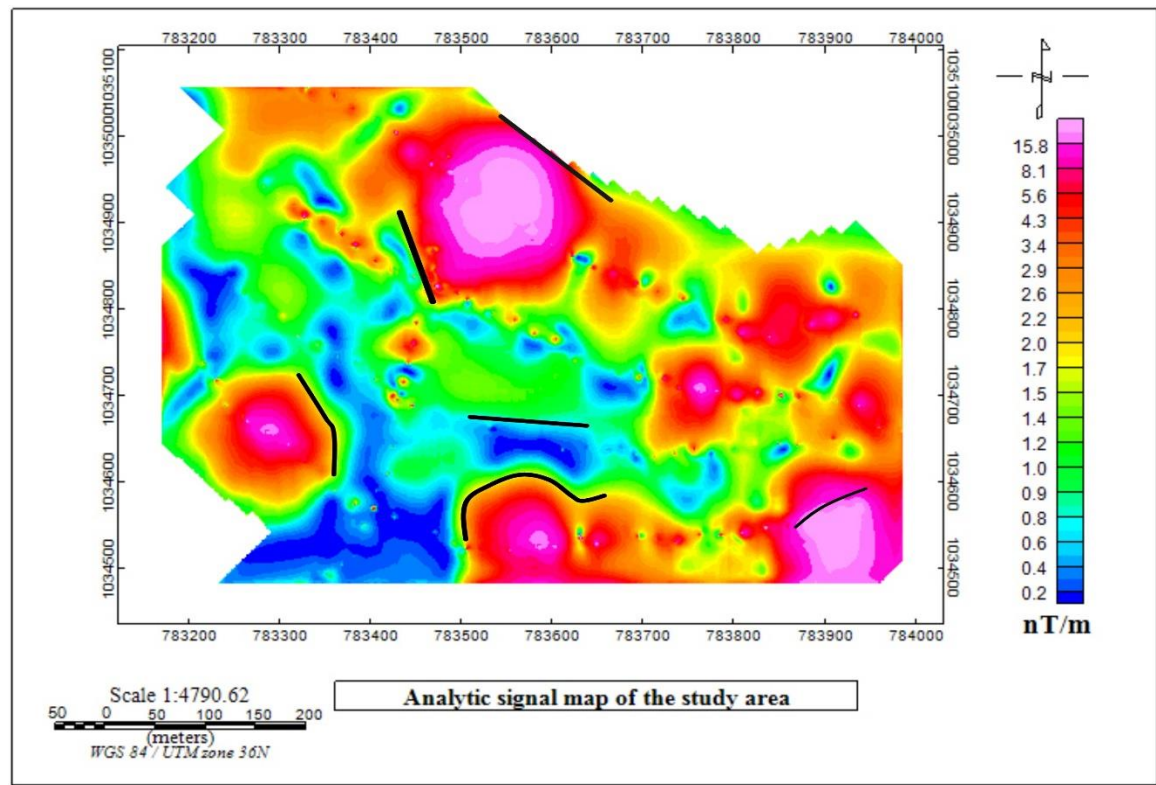


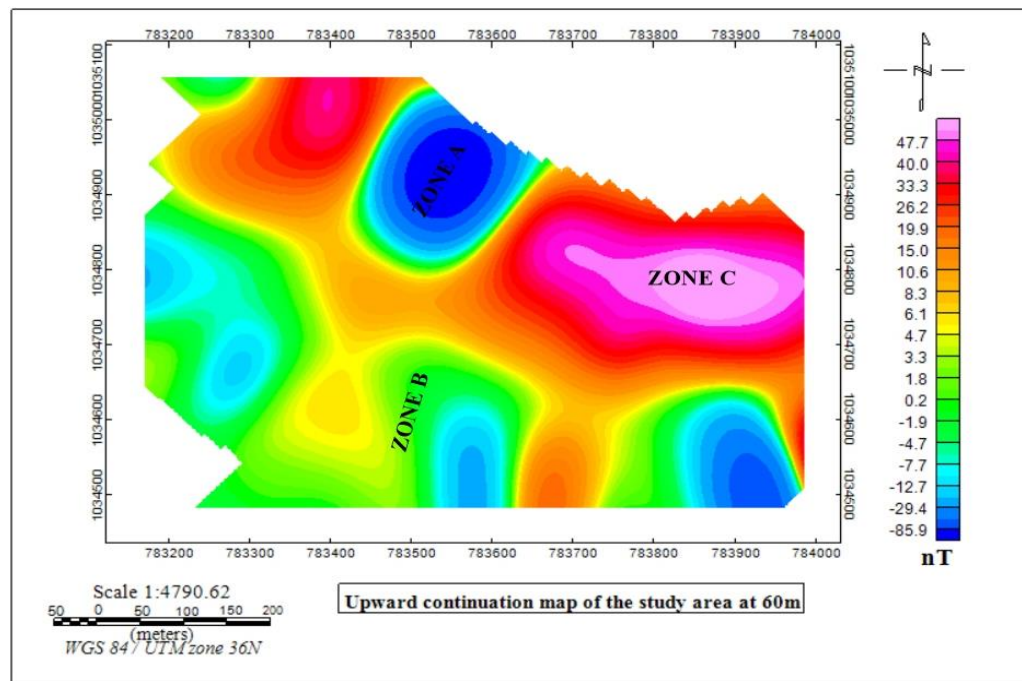
Figure 27. Analytical signal magnetic map

4.2.5. Upward Continued Magnetic Field of Anomalous Maps

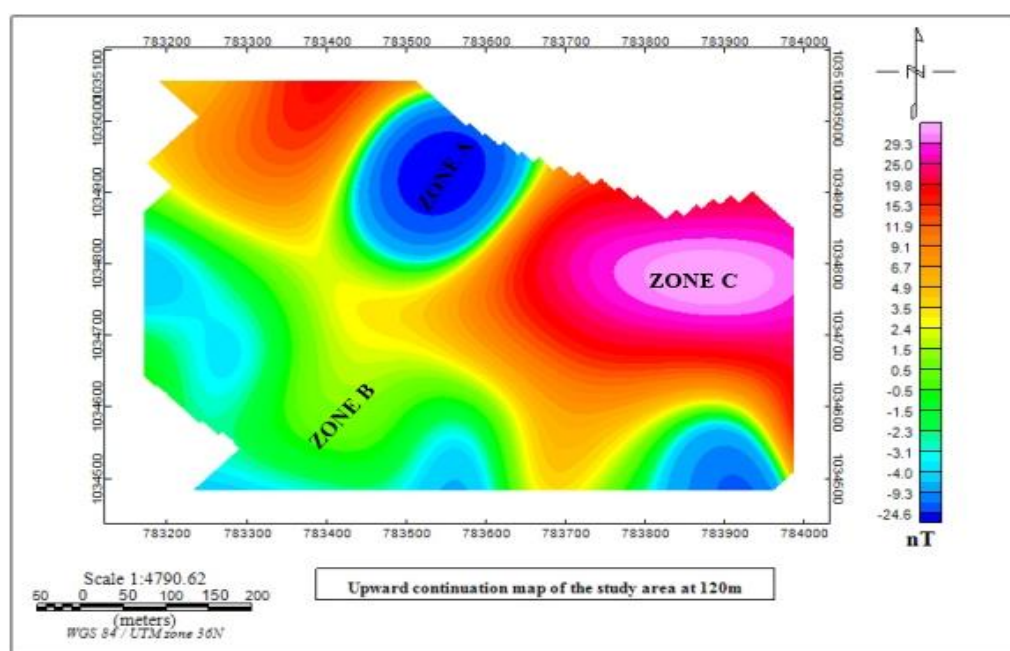
An enhancement method that raises the level of the observed magnetic field data on a surface is the upward continuing map. Features are attenuated near the surface (high frequency) since the magnetic data is almost upward. This method estimates field values at a higher elevation by using measurements made at a lower elevation.

Upward continuation is a mathematical technique that projects geophysical data from a given elevation to a higher one. This process smooths out short-wavelength (high-frequency) anomalies by reducing their intensity, as it simulates increased distance from the source. It is particularly useful for enhancing large-scale, deep-seated features while

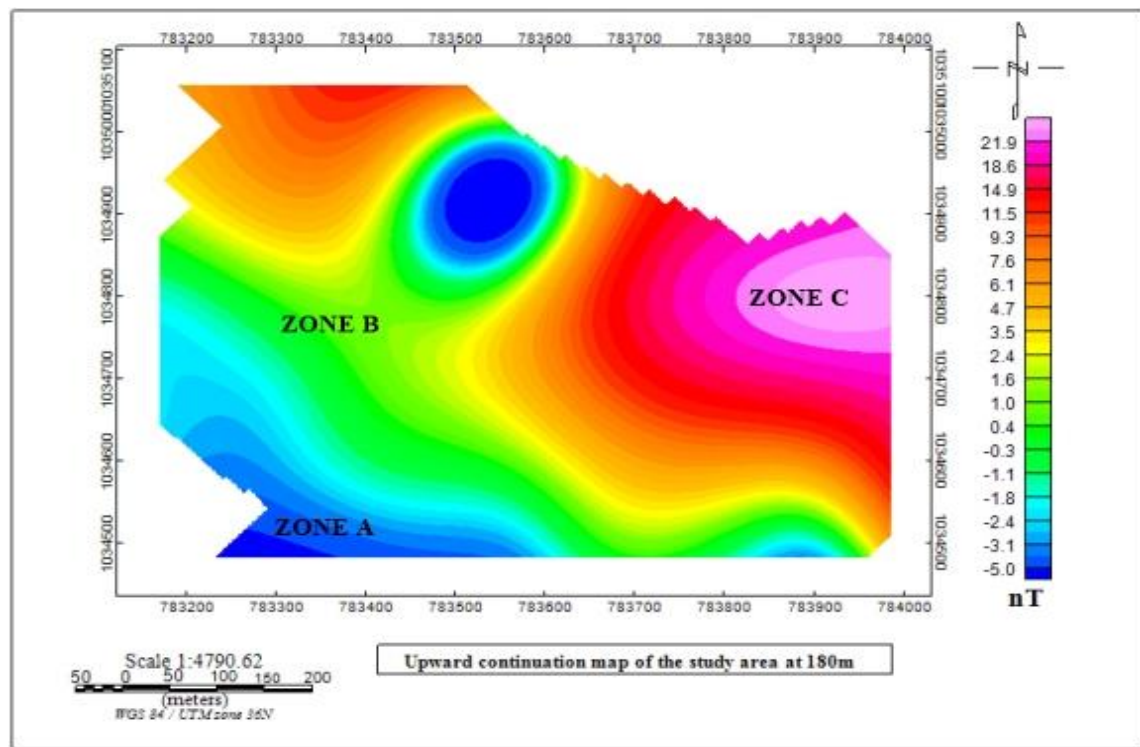
suppressing the influence of shallow sources. In this study, upward continuation maps were generated from the residual magnetic field data (Figure 28) to better highlight deeper geological structures. The residual magnetic field anomaly map was continued upwardly from 60 m up to 240 m with a 60 m interval as shown below. From that upward continued map of the residual magnetic field anomaly, different structure trends were observed, as shown in Figure 28 (Figure A to Figure D) below.



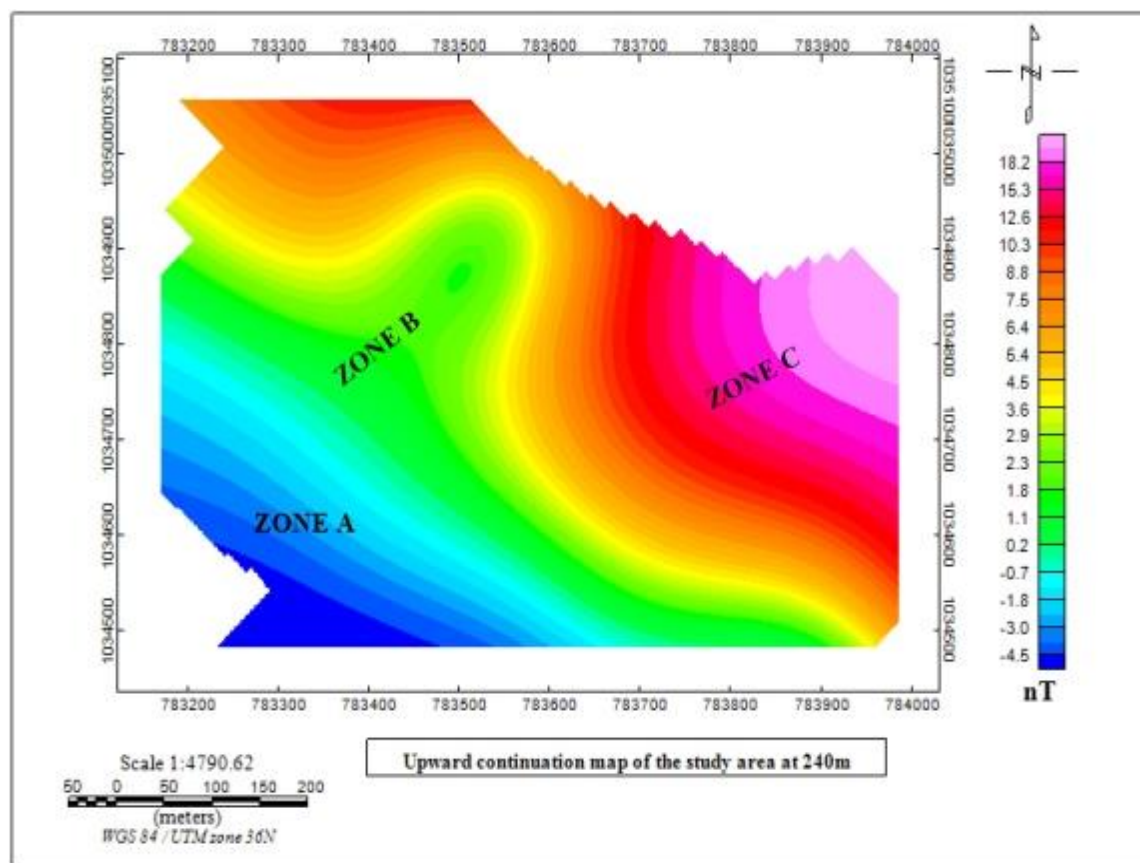
A



B



C



D

Figure 28. Upward continued map of Residual magnetic field anomaly (60m -240m)

Upward continued map of the residual magnetic field at 60 m, as shown in Figure 28A, respectively; some irregular sharp anomalies were observed. These anomalies disappeared when the residual magnetic field anomaly continued up to 120 m and 180 m, as shown in Figures 28 B and C above. Overall, the upward continued map of the residual magnetic field anomaly up to 240 meters, as shown in Figure 28D, reveals a high magnetic response in the northern, northeastern, and eastern parts of the study area. The application of the upward continuation filter demonstrates that as the continuation depth increases, shallow features become smoothed out, thereby enhancing the visibility of deeper subsurface structures.

5.CONCLUSION AND RECOMMENDATIONS

5.1.Conclusion

Geophysical surveys, vertical electrical sounding (VES), and magnetic surveys were carried out to assess the groundwater potential of the Ento catchment. According to the results of vertical electrical sounding, the high degree of weathering of the rock in the study area caused the electrical resistivity readings to display a low resistivity signature. Therefore, the significant yield of groundwater potential in the research area is indicated by the vast thickness and low resistivity along profile 1, VES 3 and VES 4 in a third layer. This continues into a fourth layer at VES 4 indicating favorable aquifer conditions. At VES 8, the third layer and the fourth layer also suggesting aquifer potential. Similarly, the third layer at VES 15, is identified as a promising aquifer zone. The research site's groundwater potential is stored and transmitted by the more prevalent rock formation, which appears as weathered meta-volcanic to extensively fractured and weathered meta-volcanic rock.

The results of the field magnetic operation showed that the study's southwest to northwestern regions had low magnetic responses on the upward continuation maps. The low magnetic anomaly response in the study area suggests the presence of weak zones and a high degree of weathering and fracturing in the rock formations. According to the upward continued magnetic field anomaly map, the southwestern regions exhibit particularly low magnetic anomalies, indicating the presence of highly fractured and weathered meta-volcanic rocks. These geological features are likely responsible for storing and transmitting groundwater in the area.

5.2.Recommendations

- 1) To qualify the region for a large-scale groundwater assessment, the use of the previously suggested geophysical techniques should be complemented by further research from relevant fields. For example, integrating the geophysical techniques with hydrogeological and geostructural techniques is essential.
- 2) To further enhance the accuracy of groundwater potential assessments, it is recommended to integrate vertical electrical sounding and magnetic methods with additional geophysical techniques, such as electrical resistivity tomography and seismic refraction. These complementary methods can significantly improve the interpretation of subsurface structures and the characterization of groundwater systems.

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Appendix

Appendix A: Geological well log data: Bila, Bodji Dirmejji District.

Table 3: Geological well log data

Depth	Lithological Descriptions	Formation
0-3	Reddish clay soil	Soft
3-8	Yellowish clay with gravel alluvium	Soft
8-16	Grayish decomposed basement	Medium
16-50	White gray water zone of meta-volcanic	Hard
50-75	Grayish silicified and fractured meta-volcanic	Hard
75-80	White gray slightly fractured and weathered meta-volcanic	Hard
80-100	Grayish massive meta-volcanic	Hard

Hydrogeological characteristics of the well

Water struck	17
Water increase	25-50, 75-80
Static water level	0

Appendix B: Survey Parameters

➤ *Resistivity Survey Parameters*

- Survey Type: Vertical Electrical Sounding (VES)
- A maximum current electrode spacing (AB/2) of 330 m
- Instrument used: ABEM Terrameter LS, GPS (Global Positioning System)
- Data Acquisition Method: Schlumberger Array

➤ *Magnetic Survey Parameters*

- Instrument: Proton Precession Magnetometer -600,GPS
- Survey Line Spacing: 25 m
- Magnetic Data Processing: Diurnal correction and regional field removed from total field

Appendix C:Data Processing and Interpretation

1.Electrical Resistivity Data Processing

The resistivity data collected from the Vertical Electrical Sounding (VES) points were processed using the **IPI2Win** software for inversion and interpretation. A typical resistivity curve (e.g., **Type HA**) observed in the study is shown in the figure. The layer resistivities were derived based on the apparent resistivity values obtained from the survey.

2.Magnetic Data Processing

The magnetic data were processed using **MagMap** software for anomaly reduction and map generation. The data were corrected for diurnal variations and background magnetic field disturbances. The magnetic anomalies were then interpreted to identify subsurface features related to groundwater potential.