



WALLAGA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

COLLEGE OF NATURAL AND COMPUTATIONAL

SCIENCES DEPARTMENT OF EARTH SCIENCES

Groundwater potential assessment using electrical resistivity tomography and magnetic methods: a case of ganja catchment, west wallaga zone, gimbi area

A Thesis Submitted to the School of Graduate Studies of Wallaga University in Partial Fulfillment of the Requirements for the Degree

of

Master of Science

In

Exploration Geophysics

By

Misgana Tesema Efa

June 2025

Nekemte, Ethiopia



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APPROVAL SHEET FOR SUBMITTING FINAL THESIS

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 Misgana Tesema Efa under the Title Groundwater Potential Assessment Using Electrical Resistivity Tomography and Magnetic Methods: A Case of Ganja Catchment, west wallaga zone, Gimbi area 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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Advisor's declaration

I hereby declare that the thesis entitled “*Groundwater Potential Assessment Using Electrical Resistivity Tomography and Magnetic Method: A Case of Ganja Catchment, West Wallaga Zone, Gimbi Area*”, submitted by **Misgana Tesema**, has been carried out under my close supervision and guidance as a requirement for the partial fulfillment of the **Master of Science (MSc) degree in Exploration Geophysics**. To the best of my knowledge, this thesis is the original work of the student and has not been submitted to any other institution for the award of any academic degree or diploma. The student has appropriately cited all references and acknowledged the works of others wherever they have been used in the preparation of this thesis. I have reviewed the thesis and found it to be methodologically sound, academically valid, and in line with the research standards expected at this level. Therefore, I approve and recommend the thesis for submission.

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Thesis Advisor

Statement of the Author

I Mr. MisganaTesema Efa hereby declare and affirm that the thesis entitled “***Ground water potential assessment using Electrical Resistivity Tomography and Magnetic method, a case of Ganja Catchment west wallaga Zone, Gimbi area***” 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 Wallega 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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Biographical Sketch

Misgana Tesema was born on August 18, 1992, in Warra Daye Kebele, Nole Kana Woreda, West Wallaga Zone, Oromia Region, Ethiopia, as the son of Tesema Efa and Birhane Gamtessa. He began his formal education at Ula Babu Elementary School, completing his primary studies before moving on to Jorga Nole High School and Jorga Nole Preparatory School for his secondary and preparatory education. Misgana then pursued higher education at Adama Science and Technology University, where he earned a Bachelor of Science (BSc) degree in Geology. Over the past seven years, he has accumulated extensive professional experience in various roles including construction project supervisor, site geologist, and university lecturer, demonstrating strong skills in fieldwork, project management, teaching, and operational coordination. Throughout his career, Misgana has shown a dedicated commitment to scientific exploration, geophysical research, and public service. Currently, he is advancing his expertise by pursuing a Master of Science (MSc) degree in Exploration Geophysics, aiming to deepen his knowledge in subsurface investigations to support resource development and environmental management.

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List of Acronyms and Abbreviations

2D	:	two-dimensional
3D	:	three Dimension:
ANS	:	Arabian-Nubian Shield
BS	:	Base station
DC	:	Direct Current
DEM	:	Digital Elevation Model
EM	:	Electromagnetic
ERT	:	Electrical Resistivity Tomography
FVD	:	First Vertical Derivative
GPR	:	Ground Penetrating Radar
GPS	:	Global Position System
MB	:	Mozambique Belt
MSc	:	Master of Science
NNE	:	North-North-East
RTP	:	Reduction to the Pole
SVD	:	Second Vertical Derivative
TDB	:	Tulu Dimtu Belt
TMI	:	Total Magnetic Intensity
UTM	:	Universal Transverse Mercator
VES	:	Vertical Electrical Sounding
WES	:	West-East South
WHO	:	World Health Organization

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ABSTRACT

Gimbi Town in the West Wallaga Zone of the Oromia Region, Ethiopia, is facing growing pressure on its water resources due to rapid population growth, expanding agriculture, and an unreliable surface water supply. According to the World Health Organization (WHO), Ethiopia is classified as a developing country where access to sufficient water remains a major challenge. In Gimbi Town, the daily water supply from surface reservoirs falls significantly short of meeting the population's needs, resulting in a substantial deficit compared to WHO's recommended per capita water consumption. This water shortage has serious implications for public health, economic activity, and community well-being. To address this, the study assesses the groundwater potential of the Ganja Catchment using integrated geophysical techniques—Electrical Resistivity Tomography and magnetic survey. The main objective is to evaluate groundwater potential, with specific goals of mapping subsurface resistivity, identifying aquifer-bearing zones, detecting geological structures, and targeting highly fractured and weathered rock formations. ERT data collected along five profiles using the Wenner array and processed with RES2DINV revealed three resistivity zones: low resistivity 38.8–90.6 Ωm in weathered and fractured materials with high groundwater potential; moderate resistivity 121–138 Ωm in partially weathered transition zones with moderate yield; and high resistivity 323–754 Ωm in compact bedrock with minimal potential. Productive aquifers are mainly located in the weathered and fractured schist and gneiss formations. Magnetic data, collected along five traverses and processed in Oasis Montaj, showed low magnetic anomalies –6.245 to 2.821 nT in the southern region, indicating weathered, porous zones ideal for groundwater storage. Transitional anomalies 3.502 to 9.117 nT in the central-eastern area reflect mixed lithology with moderate potential, while high anomalies 9.725 to 25.087 nT in the central, northern, and western parts correlate with compact rocks (gneiss, amphibolite) of low potential. The integrated ERT and magnetic survey results confirm that the southern and northeastern parts of the Ganja Catchment have the highest groundwater potential. Transitional zones offer moderate potential, while compact zones show minimal potential. These findings provide a reliable geophysical basis for effective well placement and groundwater resource planning.

Keywords: Groundwater potential, ERT, Magnetic survey, Ganja Catchment, Aquifer zone.

CHAPTER-ONE

INTRODUCTION

1.1. Background of the Study

Water is the foundation of life, shaping ecosystems, sustaining communities, and driving economies. It exists in various forms surface water in lakes and rivers, groundwater stored beneath the Earth, and atmospheric moisture in clouds. Essential for drinking, agriculture, industry, and energy production, water cycles through evaporation, precipitation, and infiltration, ensuring its continuous movement and renewal. Its availability and quality determine health, food security, and environmental balance, making responsible management crucial for sustainability.

Beneath the Earth's surface, groundwater collects in the porous layers of sedimentary rocks and flows through fractures and voids within crystalline metamorphic and igneous rocks, forming an essential part of the planet's freshwater system (Bowen, 1986). Its primary source is precipitation, including rain and snow, which infiltrates the ground and percolates downward to refill underground reservoirs. Water is not merely essential for sustaining life on Earth; it is also a powerful agent of change, actively forming the landscapes and driving the geological processes that shape our planet (Rockström et al., 2014). From the erosion of valleys by flowing rivers to the dissolution of limestone formations into subterranean caves by groundwater, the movement and presence of water are central to the evolution of both the Earth's surface and subsurface environments. Understanding the complex interplay between water, and geology is essential for disintegrating the questions of our planet's past, present, and future. Water's various forms and pathways deeply impact geological phenomena at multiple scales. In most cases drinking water comes from two sources Surface water and groundwater (Sasakova et al., 2018). Surface water, such as rivers, lakes, and oceans, erodes, transports, and deposits sediments, shaping the topography of landscapes over geological time scales. Groundwater sources are underground aquifers, and geologic arrangements containing water. Groundwater is obtained by penetrating a well into the underground water source and pumping the well water up to the surface (Bakalowicz, 2015). Groundwater, percolating through porous and fractured rock formations, dissolves minerals, creates caverns, and alters aquifers' chemistry, leaving signatures of its passage in geological formations.

Understanding the geological factors, that control the occurrence, distribution, and movement of groundwater is essential for effectively confirming the long-term viability of groundwater resources. Geological factors such as lithology, structure, stratigraphy, and hydrogeological properties strongly influence groundwater occurrence and behavior (Kirsch, 2006). Variations in geological formations can create different aquifer systems with contrasting hydraulic properties, affecting groundwater storage capacity, flow paths, and recharge rates (Deepika, Avinash, & Jayappa, 2013). Moreover, geological structures such as faults, fractures, and sinkholes features can enhance or hinder groundwater movement, leading to spatial variability in groundwater potential and availability. Currently, the geophysicist provides essential data for understanding modern groundwater resources and for evaluating current groundwater usage and contaminant (Khan, Zia-ul-haq, Umar, & Yu, 2021). Geophysical methods are non-intrusive techniques used to investigate subsurface geological structures and properties without the need for direct drilling or excavation. These methods depend on measuring various physical properties of the Earth, such as electrical resistivity, magnetic susceptibility, seismic wave velocity, and density, to infer the characteristics of subsurface materials, including the presence and distribution of groundwater.

In groundwater potential assessment, geophysical methods play a great role in delineating subsurface geological formations, characterizing aquifer properties, and identifying potential groundwater resources. Some geophysical methods used in groundwater investigation and assessment include the Electrical method. Ground Penetrating Radar (GPR), Seismic Refraction and Reflection; Magnetic Susceptibility Survey; Gravity Survey, and Electromagnetic Surveys (Sasakova et al., 2018)

The electrical method in groundwater potential assessment involves measuring the electrical conductivity of subsurface materials to infer the presence of groundwater. A variety of electrical techniques, such as Vertical Electrical Sounding and Electrical Resistivity Tomography, are employed in groundwater evaluation (Živanović, Jemcov, Dragišić, Atanacković, & Magazinović, 2016). Electrical Resistivity Tomography involves measuring the electrical resistivity distribution of subsurface materials by injecting electrical current into the ground and measuring the resulting potential differences. Variations in resistivity can indicate changes in lithology, moisture content, and the presence of groundwater (Perrone, Lapenna, & Piscitelli, 2014).

Magnetic methods, such as magnetic gradiometry and magnetometry, detect variations in the Earth's magnetic field caused by subsurface geological structures and materials (Likkason, 2014). These methods are specifically, useful in identifying structural features such as faults, folds, and lithological boundaries that may influence groundwater flow patterns and aquifer distribution. Integrating geophysical data with geological, hydrological, and hydrogeological information allows for a more comprehensive assessment of groundwater potential. This approach enhances the understanding of subsurface conditions and helps in identifying optimal locations for groundwater exploration and development. The main objective of this study was to use Electrical Resistivity Tomography and the magnetic method to improve the enhancement of groundwater potential assessments in the study area.

1.2 Statement of the problem

The use of geophysical methods, plays a key role in evaluating groundwater potential and ensuring reliable access to safe water for communities, particularly where surface water is insufficient. According to the World Health Organization (WHO) guidelines, daily water usage per person varies depending on the development level of a country. In developed countries, individuals in urban areas require between 100 to 200 liters per day, while those in rural areas need 100 to 150 liters. In developing countries, urban residents need 50 to 100 liters of water per day, and rural inhabitants require 20 to 50 liters. For undeveloped countries, water usage is lower, with urban areas needing 20 to 50 liters per person daily, and rural areas requiring only 5 to 20 liters (*World Health Organization (2003). Domestic Water Quantity, Service Level and Health. Geneva: WHO. <https://www.who.int/publications/i/item/9241591509>*). Given these standards, accurately assessing groundwater potential is critical to ensure communities have an adequate water supply for drinking, cooking, hygiene, and other essential domestic needs.

Ethiopia would be classified as a developing country, in the study area Gimbi town, the total daily water supply from various sources, including surface water reservoirs like Gafare and Gelel, is only 2,500 cubic meters (2,500,000 liters) (Gimbi Municipality. (2023). Urban Water Supply Assessment Report). With a population of 121,233 people, this amount falls significantly short of the water requirements outlined by the World Health Organization (WHO). According to WHO guidelines, the population would need approximately 9,092.475 cubic meters (9,092,475 liters) of water each day, assuming an average usage of 75 liters per person. This results it indicates that the

shortfall of 6,592.475 cubic meters brings attention to the serious lack of water available for the community. Therefore, employing advanced geophysical techniques, such as Electrical Resistivity Tomography and magnetic methods, is essential for accurately assessing groundwater potential. This study attempts to apply these geophysical techniques to enhance the assessment of groundwater potential, ensuring that communities in Gimbi have access to sufficient and safe water supplies, in line with WHO guidelines.

1.3 Objectives:

1.3.1 General objective

The main objective of this study is Assessment Groundwater Potential Using Electrical Resistivity Tomography and Magnetic Methods a case of Ganja catchment.

1.3.2. Specific Objectives:-

The specific objectives of the study include:-

- ✓ To identify the resistivity distribution of the subsurface layers
- ✓ To identify the lithology
- ✓ To identify the geological structures
- ✓ To identify high ground water potential sites
- ✓ To pinpoint areas with high levels of fracturing and weathering

1.4 Significance of the Study

The significance of this study lies in its pivotal role in advancing both the scientific understanding and practical assessment of groundwater potential in the Ganja Catchment area of Gimbi, West Wallaga Zone, Ethiopia. By applying integrated geophysical methods—Electrical Resistivity Tomography and magnetic surveys—the study provides a comprehensive understanding of the subsurface conditions, including resistivity distribution, lithology, and geological structures such as faults and fractures. These insights are essential for identifying areas with high groundwater potential and locating zones with intense fracturing and weathering, which often serve as pathways for groundwater movement and storage. The findings will support sustainable water resource development by guiding the optimal placement of boreholes and minimizing the risk of drilling failures, thereby reducing associated costs. Additionally, the study contributes to academic knowledge in the field of hydrogeophysics and serves as a valuable reference for future

investigations in similar geological settings. Overall, the research promotes informed decision-making for water resource management and enhances access to reliable water supplies, which is vital for the socio-economic development of the region.

1.5 Scope of the Study

This study focused on assessing groundwater potential in Ganja Catchment, West Wallaga Zone, Gimbi area, using Electrical Resistivity Tomography and magnetic methods. It mapped subsurface structures, identified high groundwater potential zones, and analyzed the impact of faults and fractures on groundwater flow. The findings aim to support sustainable groundwater potential assessments and provide a model for similar studies in other regions.

1.6 Limitations of the Study

Despite the valuable insights gained from the integration of Electrical Resistivity Tomography and magnetic methods in assessing groundwater potential within the Ganja Catchment, several limitations were Situations or Problems that may have influenced the scope and precision of the study results:

- ✓ During the study, certain areas could not be accessed due to political instability or their Closeness to security-sensitive zones such as military installations. These restrictions limited the ability to carry out field surveys in potentially important parts of the study area, resulting in incomplete data collection and potential underrepresentation of groundwater resources. To address this limitation, an official work permit or permission letter can be obtained from relevant government bodies from the Mayor of Gimbi town offices. This letter formally authorizes the activity, helps build trust with local officials, and may grant safe access to restricted zones.
- ✓ Community Resistance or Lack of Awareness: - Local populations may restrict access due to misunderstandings or fear of equipment. Ensure early and continuous Participation with community members. Hold discussions where people can voice concerns, ask questions, and provide feedback.

1.7 Research questions

- 1) What is the relationship between magnetic anomalies and geological structures that influence groundwater potential in the Ganja Catchment?
- 2) What are the dominant geological controls affecting groundwater occurrence in the Ganja Catchment?
- 3) What zones within the Ganja Catchment are most favorable for groundwater development based on geophysical data?
- 4) What improvements in groundwater resource mapping accuracy can be achieved through the integration of ERT and magnetic data in the region?

CHAPTER -TWO

LITERATURE REVIEW

2.1 Background

Groundwater potential can be determined using several formation parameters. The attributes of soil, rainfall, land use, hydrology, hydrogeology, geomorphology, topography, lineament density, drainage density, and permeability were outlined (Igwe, Ifediegwu, & Onwuka, 2020). For example, factors like rainfall, geology, geomorphology, slope, lineament density, drainage density, soil texture, and land use were all taken into consideration when evaluating the groundwater potential in the Brantas Groundwater Basin in East Java Province, Indonesia (James, Karim, Awing, & Zulhazman, 2020). Numerous factors, such as topography, geology, hydrology, and hydrogeology, were used to assess and define possible groundwater zones in the Tissent Basin in South-east (Echogdali et al, 2023)

Comparably, variables including geology, geomorphology, Digital Elevation Model, slope, rainfall, soil, drainage density, dug well density, bore well density, and land use/land cover were taken into account in the Kamina sub-watershed of the Bhima River Basin in Pune District, Maharashtra, India. Vulnerability maps were made in the Tara National Park in Western Serbia using variables including susceptibility and hazards, which were then combined to determine the risk of groundwater pollution (Živanović, Jemcov, & Dragišić, 2022). Groundwater possibilities mapping in India's semi-arid and dry regions was also done using variables such as land use, geology, elevation, slope, lineament, lineament density, drainage density, and geomorphology. Several authors—geologists, hydrogeologists, and geophysicists have conducted studies and developed mapping strategies to explore and provide data on groundwater potential across different zones, each with unique lithological, hydrological, and petrophysical characteristics (Yehualaw, 2020). In Ethiopia, most hydrogeological studies have emphasized major watershed basins, leaving significant gaps in knowledge about localized hydrogeology and groundwater conditions (Ayenew, 2001). Although many past studies have used different types of data like soil, rainfall, land use, and Geographic Information System (GIS) maps to estimate where groundwater might be found, they mostly looked at surface-level information. However, these studies often did not directly examine the subsurface, which is where groundwater actually flows and is stored.

As a result, their predictions can be uncertain, especially in areas with complex underground structures like faults and fractures.

In Ethiopia, and specifically within areas of the Ganja Catchment, the application of geophysical techniques such as Electrical Resistivity Tomography (ERT) and magnetic surveys remains limited. Although these methods offer significant advantages in subsurface characterization and groundwater potential assessment by providing more accurate and reliable data than traditional surface-based approaches, they have not been widely adopted in local scale studies. To date, no comprehensive geophysical investigation has been conducted in the Ganja Catchment area, highlighting a critical knowledge gap that this study seeks to address. This literature review provides a comprehensive summary of the essential background relevant to the study. It offers an overview of the geological characteristics that influence groundwater availability and explains the fundamental principles behind geophysical methods such as electrical resistivity imaging and magnetic surveys. These methods are crucial for investigating subsurface structures, including faults, fractures, and aquifers, which significantly affect groundwater potential. The review also highlights the geology of the specific study area Ganja Catchment in West Wallaga and outlines the geophysical techniques most commonly used in groundwater prospecting.

2.2 Geology

2.2.1 Regional Geology

Ethiopia's geology is composed of rocks from the Neoproterozoic East African Orogeny, Jurassic marine sediments, and volcanism associated with the Quaternary rift. It has been significantly influenced by the assembly and disintegration of Gondwana, as well as the current African rift. The oldest geological formations in Ethiopia are rocks that date back 880–550 million years, during the East African Orogeny (Abbate, Bruni, & Sagri, 2015). The ancient Mozambique Ocean closed due to orogeny.

The Trans-Gondwanan Super-mountain is a massive mountain range that runs north-south (in today's coordinates) and was formed simultaneously by the rocks of Ethiopia, the Mozambique Belt, and the Arabian-Nubian Shield. The geology of the western region of Ethiopia is made up of metamorphic, sedimentary, and volcanic rocks (Abbate et al., 2015). The region is a component of the East African Rift System, a region characterized by regular volcanic eruptions and active tectonic activity.

These volcanic rocks consist of tuff, rhyolite, and basalt. Along with sedimentary rocks from the Paleozoic and Mesozoic eras, the highlands also contain limestone, sandstone, and shale. The western region of Ethiopia is home to metamorphic rocks that originated in the Precambrian period. Marble, schist, and gneiss are among these rocks.

High-grade gneiss and migmatites are classified as lower complex based on the stratigraphy of the Western Ethiopian Precambrian Terrain, whereas low-grade meta volcanic sedimentary rocks are classified as upper complex, (Aalbers et al., 2023; Dercourt et al., 1986; Kazmin, Shifferaw, & Balcha, 1978). "Geo-chronological data indicate that the mafic-ultramafic, meta-volcanic-sedimentary, and gneissic rocks of Western Ethiopia show similar ages and involved between 900 Ma and 500 Ma,"(Kazmin et al., 1978). A large fraction of the Precambrian rocks in Western Ethiopia are granitoid. The granitoid rocks that intruded into the high-grade gneisses, low-grade meta-sedimentary, and meta-volcanic rocks were recently the subject of field relationships as well as studies by (Scanlon et al., 2023). Concerning petrography, geochemistry, and petrogenesis. Western Ethiopia's geology generally has a convoluted geological past. The Precambrian basement rocks' geology can be categorized into four litho-structural domains based on lithological associations, deformation style, and metamorphism.

2.2.1.1 Precambrian Basement Rock

The volcano-sedimentary terrain, gneissic terranes, and ophiolitic rocks that make up the Precambrian topography of western Ethiopia are comparable to the Neo-Proterozoic rocks of the ANS and the MB (Abbate et al., 2015). The lithological components found in this location incorporate; high-grade rocks; ophiolite belt; dioritic (grano-dioritic) batholiths and related halfway volcanic; and meta-volcanic sedimentary rock. The Precambrian cellar of Western Ethiopia amplifying northward from 60N for almost 650 km is the biggest Precambrian square in Ethiopia (Brodie, 2015). Consenting to the Kazmin topography of western Ethiopia Precambrian territory is considered to contain lithological components common to both the Arabian-Nubian Shield within the north and the Mozambique Belt within the south. The geology of the range is categorized into five structural zones in this regard: (1) An eastern square of high-grade pre-Pan-African rocks; (2) an ophiolite belt; (3) a zone of dioritic /granodioritic batholiths and related halfway volcanic; (4) a met volcanic sedimentary belt; and (5) a western square of the high-grade pre-Pan-African cellar.

This western Ethiopia within the Gimbi-Asosa region, the Tulu Dimtu Belt comprises a variety of direct to high-grade gneisses and direct review meta-sedimentary rocks invaded by distorted and undeformed ultramafic, mafic, middle, and felsic molten bodies.

This basement complex comprises the oldest rocks in the area, dating back to the Precambrian era. It consists primarily of Meta sediments, which are metamorphosed sedimentary rocks such as schist, slate, and marble, as well as intrusive granitoids such as granite and granodiorite. These rocks form the foundation of the geological structure and may exhibit complex folding, faulting, and metamorphic features resulting from ancient tectonic activity.

2.2.1.2 Quaternary Sediments

These sediments are the youngest geological deposits in the area and typically consist of unconsolidated materials such as sand, silt, and clay. They are often associated with recent depositional environments such as floodplains, river terraces, and alluvial fans.

2.2.1.3 Tertiary Basalt

The massive lava known as the tertiary or trap series, which emerged from fissures and centers, covers most of Ethiopia's Mesozoic rocks in the north and center. This flow includes the Gimbi region and its surroundings. Aphanitic basalt with some plagioclase phenocryst is found to have a hard texture in the study area. This rock type represents volcanic activity from the Tertiary period and is characterized by its fine-grained to aphanitic texture. Tertiary basalts are common in volcanic regions and may form extensive lava flows, basaltic plateaus, or volcanic cones.

2.2.1.4 Buried River Sediment

These sediments represent ancient river deposits that have been buried over time due to geological processes such as sedimentation, tectonic activity, or erosion. They may consist of sand, gravel, and occasional layers of clay, reflecting the depositional environment of ancient river systems. Beneath the thin basaltic layers at the Ganja River sites was a significant buildup of soil, gravel, and silt from a former river. The surrounding terrain is dominated by Precambrian rocks such as meta-sediments and intrusions of granite. The spatial distribution of regional rock units and tectonic features is displayed in Figure (1): Regional Geological Map of the Study Area, providing essential background for site-specific geological analysis. These rocks typically form ridges that are aligned northwest-southeast and north-south along the Ganja Catchment and the escarpments of the ridges.

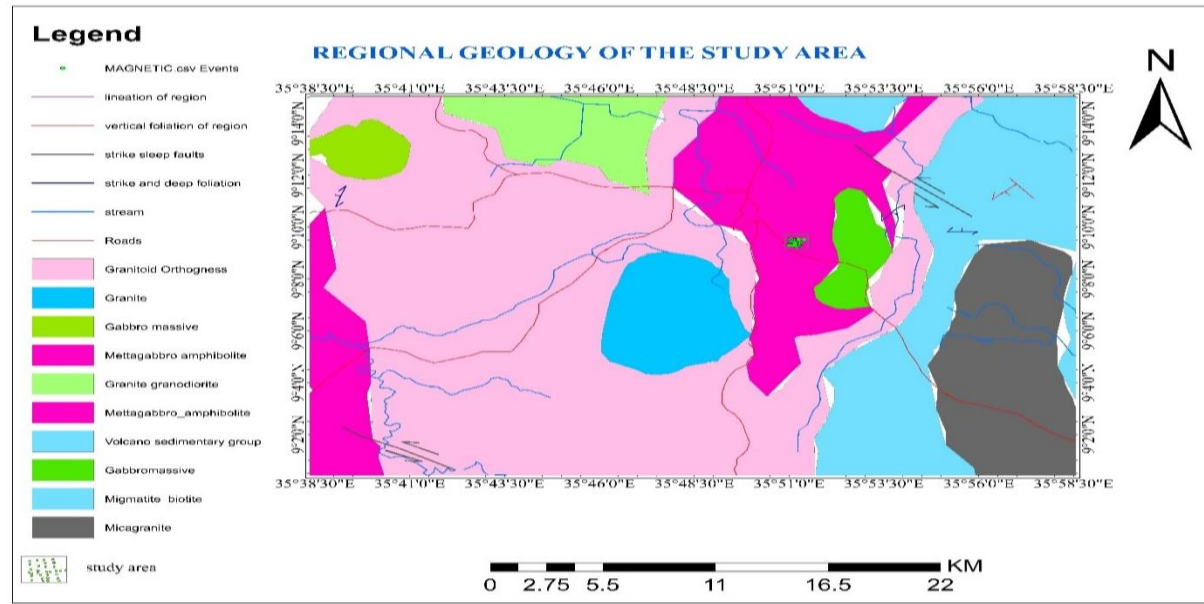


Figure 1 Regional Geological map of the study area (Gimbi Geological Map sheet 2001)

2.2.2 Local Geology

The Precambrian exposures in the Western Ethiopian Shield lie within the younger Neo-Proterozoic shell of the Middle Eastern Nubian Shield and the older Mozambique Belt, mainly composed of gneiss. Besides volcanic and sedimentary rocks, this area also contains Precambrian rocks like gneiss, schist, and marble. These rocks are classified into lower complex (high-grade gneiss and migmatites) and upper complex (low-grade Meta volcanic sedimentary rocks) based on stratigraphy. The gneissic rocks, Meta volcanic sedimentary rocks, and mafic-ultramafic formations in Western Ethiopia have similar ages (Kazmin et al., 1978). Figure (2) presents the local geological map of the study area, highlighting major rock formations and structural trends.

The provided geological map illustrates the local geology of the study area, which spans approximately between 35.804°E to 35.916°E longitude and 9.120°N to 9.236°N latitude. The region is geologically diverse, composed of various igneous and metamorphic rock units.

The main lithological units identified include migmatite, micagranite, metagabbro-amphibolite, granitoid orthogneiss, and granite. Migmatite, occupying the eastern part of the map, indicates intense metamorphic activity likely associated with high temperature and pressure conditions. The presence of micagranite in the central area reflects igneous intrusions rich in mica minerals, while the granitoid orthogneiss and granite units suggest high-grade metamorphic and intrusive igneous

processes respectively. The metagabbro-amphibolite, found in limited sections, represents metamorphosed mafic rocks, indicative of a more complex tectonothermal history.

Structurally, the map reveals several features such as strike and dip foliations and linear structures. These are represented by black and pink lines, respectively, and suggest deformation events that affected the region, including folding and shearing. The orientation of these features helps in interpreting the tectonic stress regime that shaped the current geological architecture. Hydrologically, the area is traversed by both major and minor streams, depicted in dark and light blue, respectively. These drainage patterns are structurally controlled and play a vital role in surface water distribution and potential groundwater recharge. The presence of roads and survey points indicates human accessibility and field investigation points, respectively. Overall, the study area displays a complex geological setting formed through multiple phases of magmatism, metamorphism, and deformation. This indicates a long and dynamic geological evolution, likely related to regional tectonic processes that have shaped the East African crust..

2.3 Groundwater Studies in Ethiopia

Groundwater studies in Ethiopia are essential for understanding and managing the country's water resources, which are crucial for both domestic consumption and agricultural activities (Berhanu, Seleshi, & Melesse, 2014). Groundwater serves as the primary source of water in many rural and semi-arid areas, where surface water is either limited or seasonal. These studies focus on the characterization, distribution, and movement of groundwater within the country's diverse geological and hydrological settings. Ethiopia's hydrogeological conditions are highly varied, ranging from volcanic rocks in the highlands to sedimentary formations in the lowland regions, each presenting unique challenges and opportunities for groundwater exploration and management.

Research in groundwater in Ethiopia typically involves the use of traditional methods, such as well logging and aquifer testing, along with more advanced geophysical techniques like Electrical Resistivity Tomography, and magnetic surveys. These techniques help identify potential aquifers, map their extent, and assess their groundwater potential. Additionally, groundwater quality studies are conducted to monitor issues such as salinity, contamination from agricultural chemicals, and

the presence of naturally occurring elements like fluoride, which pose health risks in certain regions.

One of the key challenges in groundwater studies in Ethiopia is the lack of comprehensive and reliable data. Many regions lack detailed baseline information, making it difficult to conduct in-depth analyses of aquifer systems or predict long-term water availability. Furthermore, the uneven distribution of groundwater resources and the difficulty of accessing remote areas complicate the study and monitoring efforts. Climate variability, such as droughts and changing rainfall patterns, also affects groundwater recharge rates and can lead to the over-exploitation of aquifers in some areas. Despite these challenges, groundwater studies in Ethiopia are gaining increased attention, especially with the rise in population, agricultural demands, and urbanization. There is a growing recognition of the need for integrated water resource management that incorporates groundwater as a key component of national water supply strategies. As a result, the Ethiopian government, alongside international organizations and research institutions, is investing in research and technological advancements to enhance groundwater exploration, management, and sustainability. By improving knowledge of groundwater systems and their sustainable use, these studies contribute to ensuring reliable access to clean water for future generations and enhancing the resilience of communities to the impacts of climate change.

Ethiopia's groundwater system is shaped by a dynamic interplay of geological, climatic, and environmental factors. Complex hydrogeology, shaped by factors like tectonic activity and climate fluctuations, leads to spatial variability in groundwater distribution (Kirsch, 2006). These contribute to the complexity and spatial variability of groundwater occurrence across different regions of the country. The following are the primary factors influencing this variability:

- ✓ **Tectonic Activity:-** The East African Rift System, which cuts through Ethiopia, has significantly influenced the country's hydrogeological framework.

Tectonic movements have created faulted and fractured zones, volcanic terrains, and grabens, which act as both conduits and barriers for groundwater flow. This structural complexity leads to uneven aquifer distribution, with some areas having highly productive fractured rock aquifers while others are water-scarce.

- ✓ **Geological Diversity:-** Ethiopia's subsurface is composed of a wide range of rock types, including volcanic, sedimentary, and crystalline basement rocks. Each lithological unit exhibits distinct hydrogeological properties in terms of porosity, permeability, and storage capacity. Groundwater availability varies greatly across regions, depending on the dominant rock type and its weathering profile.
- ✓ **Climate Variability:-** Ethiopia experiences diverse climatic zones, ranging from humid highlands to arid lowlands, with seasonal and interannual rainfall fluctuations. Rainfall variability directly affects groundwater recharge, particularly in areas dependent on seasonal rains for aquifer replenishment. Areas with higher and more consistent rainfall tend to have better groundwater potential, while arid zones face recharge limitations.
- ✓ **Topographical Variation:-** Ethiopia's topography ranges from high mountains to deep rift valleys. Elevation differences influence surface runoff, infiltration rates, and groundwater flow direction. High-relief areas may serve as recharge zones, whereas low-lying regions may function as discharge areas, altering groundwater accumulation patterns.
- ✓ **Weathering and Fracturing:-** The extent of rock weathering and the presence of secondary porosity (fractures and joints) significantly influence aquifer productivity. Weathered and fractured zones enhance water storage and transmission in otherwise low-permeability rock formations. Zones with intense weathering and fracturing are often targeted for groundwater exploration due to their higher potential.
- ✓ **Human Activities and Land Use:-** Expanding agriculture, urbanization, and deforestation affect infiltration, recharge, and groundwater quality. Altered land cover and over-extraction can lead to reduced recharge and localized depletion. Sustainable groundwater use requires integrated land and water management policies that consider human-induced impacts.

In terms of regional geodynamics, Ethiopia's geological history is shaped by complex processes including continental flood basalt eruptions, rift valley formation, river valley incision, sedimentation, peneplanation, glaciations, Gondwana breakup, and marine transgression-regression cycles (Alemu, 2019). These events have profound and enduring effects on Ethiopia's hydrology, groundwater resources, and landscape. Understanding Ethiopia's hydrogeology relies heavily on its geology. The country's unique features, such as vast flood basalts, closed basin lakes, and the Great East African Rift, attract significant national and international scientific interest in fields like global geodynamics, rift evolution, and paleoclimate reconstruction.

2.4 General Concept of Geophysical Method

Geophysical methods represent a combination of powerful techniques to investigate the Earth's subsurface without direct physical intervention (Foti, 2012). Fundamentally, geophysics utilizes principles derived from physics to measure and analyze a multitude of physical properties within the subsurface, providing valuable insights into its composition, structure, and dynamics. This approach serves as a cornerstone in understanding groundwater potential, as it enables the assessment of subsurface conditions that influence the occurrence and distribution of groundwater. Since groundwater is typically located beneath the Earth's surface, direct observation is often challenging. However, it plays a crucial role in supporting various human activities and maintaining ecosystem health. Indirect approaches for characterizing subsurface hydrogeological properties necessary for groundwater assessment are provided by geophysical methods, which fill this gap.

In the groundwater potential assessment, geophysical methods play a important role in mapping aquifers, delineating geological structures, and identifying potential groundwater pathways (Mandal et al., 2016). The Geophysical Methods, particularly Electrical Resistivity Tomography and the Magnetic Method, are powerful, non-invasive techniques used to investigate subsurface geological structures. ERT works by injecting electrical current into the ground through electrodes and measuring the resulting potential differences. This method maps the subsurface resistivity distribution, which is influenced by factors like soil type, moisture content, rock composition, and voids. ERT is especially valuable for identifying groundwater zones, geological layers, fractures, and contaminant plumes with high accuracy.

On the other hand, the Magnetic Method measures natural variations in the Earth's magnetic field caused by the presence of magnetic minerals like magnetite in the subsurface. This technique is ideal for detecting geological structures, fault zones, and mineral deposits, and is widely used in mapping igneous and metamorphic rocks. When used together, ERT and Magnetic methods provide complementary data, offering a clearer, more detailed understanding of the subsurface, making them essential tools in environmental studies, groundwater exploration, engineering site investigations, and mineral prospecting.

2.4-1 Theory of Magnetic Methods

The magnetic method is a geophysical technique used in groundwater potential assessment by detecting variations in the Earth's magnetic field caused by different subsurface materials. Since groundwater is often associated with specific geological formations, such as fractures, faults, and weathered zones, magnetic surveys help identify these features by mapping subsurface rock types and structural discontinuities. This method is particularly useful in distinguishing between permeable and impermeable formations, aiding in the identification of potential groundwater reservoirs (Kaufman, Hansen, & Kleinberg, 2009). Geophysicists have been able to develop a mathematical model for the earth's magnetic field, i.e., its shape and intensity across the surface of the earth. If two magnetic poles of strength m_1 and m_2 are separated by a distance r , a force, F , exists between them. If the poles are of the same polarity the force will push the pole apart and if they are of opposite polarity, the force is attractive and will draw the poles together (Coey, 2010). The equation for force (F) is the following:

$$F = \frac{\mu_0 m_1 m_2}{4\pi \mu_R r^2} \quad (2.1)$$

Where μ_0 and μ_R are constants corresponding to the magnetic permeability of the vacuum and the relative magnetic permeability of the medium separating the poles while r is the distance between them. Magnetometer surveys indicate that there are many unexpected variations which are magnetic anomalies.

A magnetic high anomaly is where the measured field strength is higher than the value predicted by the global model, and a magnetic low is where the measured field strength is lower than the value predicted by the global model (Hemant & Maus, 2005).

Anomalies in the earth's magnetic field are caused by induced or remnant magnetism. Induced magnetic anomalies are the result of secondary magnetization induced in a ferrous body by the earth's magnetic field. Magnetic prospecting looks for variations in the magnetic field of the earth that are caused by changes in the subsurface geologic structure or by differences in the magnetic properties of near-surface rocks. Most magnetic surveys are designed to map the geologic structure on or inside the basement rocks the crystalline rocks that lie beneath the sedimentary layers or to investigate subsurface geology based on the anomalies in the earth's magnetic field resulting from

the magnetic properties of the underlying rocks. In general, the magnetic content/susceptibility of rocks is extremely variable depending on the type of rock and the environment it is in. Common causes of magnetic anomalies include dykes, faults, and lava flows. Where the rocks have high magnetic susceptibility, the local magnetic field will be strong; where they have low magnetic susceptibility, it will be weaker. Rock units with higher susceptibility will show up as areas of high magnetic field strength.

2.4.1.1 Principle of magnetic method

The magnetic method is a valuable geophysical technique used in the assessment of groundwater potential, particularly in identifying subsurface geological structures that influence groundwater occurrence and movement (Anastasios et al., 2019). The basic principle of the magnetic method lies in detecting variations in the Earth's magnetic field caused by differences in the magnetic properties of subsurface materials (Nabighian et al., 2005). In the context of groundwater exploration, this method helps in delineating basement topography, locating faults and fractures, and identifying the interface between weathered and fresh bedrock, which are critical for groundwater accumulation.

Among the key concepts are induced and remnant magnetization. Induced magnetization occurs when magnetic minerals like magnetite respond temporarily to the Earth's magnetic field, while remnant magnetization refers to the permanent magnetization a rock retains from its formation (Stacey, 2012). Groundwater is typically found in weathered or fractured zones above the magnetic basement. These zones often show lower magnetic susceptibility compared to fresh basement rocks. Therefore, magnetic surveys help detect such contrasts, which indirectly point to potential groundwater-bearing formations.

The instruments used in magnetic surveys for groundwater studies include proton precession magnetometers and optically pumped magnetometers, which measure the total magnetic field intensity (Hrvoic & Newitt, 2010). These instruments are portable and suitable for ground-based surveys, although airborne magnetometers may be used for regional-scale groundwater assessments. Data acquisition and processing involve systematically measuring magnetic field intensity along a grid or profile over the study area. A base station magnetometer is used to record background variations in the Earth's magnetic field, allowing for correction of diurnal variations. The collected data are further corrected for factors like latitude, elevation, and noise from cultural

sources. After these corrections, the data are plotted to produce magnetic anomaly maps that highlight spatial variations in magnetic intensity.

Interpretation of magnetic data in groundwater studies involves identifying zones of low magnetic intensity that may correspond to weathered or fractured bedrock, which are more likely to store groundwater (Hasan, Shang, & Jin, 2018). Steep magnetic gradients may indicate fault zones that act as conduits for groundwater movement. In crystalline terrains, for example, mapping the depth to magnetic basement is critical in evaluating the thickness of overburden or regolith where groundwater can accumulate. The applications of the magnetic method in groundwater potential assessment are wide-ranging. It is used to map basement topography, delineate aquifer boundaries, identify fracture zones, and support the design of further surveys such as electrical resistivity methods. This method is particularly useful in hard rock terrains, where groundwater typically occurs in weathered and fractured zones.

Among its advantages, the magnetic method is non-invasive, rapid, and cost-effective, making it suitable for preliminary reconnaissance surveys over large and inaccessible areas. It also provides indirect but critical geological information that aids in groundwater exploration. However, there are limitations. The method does not detect groundwater directly; it only maps geological features that may control groundwater occurrence. Also, interpretations can be ambiguous due to the non-unique nature of magnetic anomalies, and the presence of man-made structures or magnetic noise can affect data quality. In summary, while the magnetic method does not directly locate groundwater, it plays a crucial supporting role in groundwater potential assessment by mapping the subsurface geological framework essential for groundwater storage and flow, particularly when integrated with other geophysical and hydrogeological data.

2.4.2 Theory of Electrical Resistivity Tomography

The subsurface distribution of electrical resistivity, which is correlated with the make-up, moisture content, and pore fluid conductivity of geological materials, can be imaged using ERT, a geophysical technique (Van Dam, 2012). The basis of ERT is the idea that the electrical resistivity values of various geological materials vary. For instance, materials that are dense and dry have a higher resistivity than rocks and soils that are highly porous and moist. ERT surveys involve setting up an array of electrodes on the ground, using one pair to inject electrical current into the subsurface and another pair to measure potential differences. A resistivity profile or subsurface

image can be generated in Electrical Resistivity Tomography by systematically varying electrode configurations and measuring the corresponding voltage responses. Two dimensional images of the subsurface resistivity distribution are produced by processing and inverting the resistivity data obtained from ERT surveys. While high resistivity anomalies may point to bedrock or lithological boundaries, low resistivity anomalies may point to possible groundwater zones, such as saturated aquifers or clay-rich layers.

Surface electrical resistivity surveying is based on the principle that the electrical potential distribution in the ground around a current-carrying electrode depends on the resistivity and distribution of nearby rocks and soils. In this method, a direct current (DC) is typically applied between two electrodes inserted into the ground, and the potential difference is measured between two additional electrodes that do not carry current. These potential electrodes are usually aligned between the current electrodes, though their placement can vary. The types of current used include low frequency alternating current (AC), commutated direct current (square-wave AC), and pure DC, with DC being the basis for most interpretations and analyses.

Resistivity surveys are useful for locating anomalous subsurface materials and estimating bedrock depth where changes in lithology correlate with resistivity variations. Groundwater levels in coarse-grained soils can often be detected by abrupt changes in resistivity due to changes in saturation, whereas fine-grained soils may not exhibit such clear transitions. Since pore water conditions primarily determine resistivity, values cannot directly define specific soil or rock types. However, with support from local field or borehole data, characteristic resistivity zones can be associated with certain geological units.

This makes resistivity surveying a cost-effective method to extend investigations into poorly known areas and to detect anomalies for further study using other geophysical techniques or drilling. Despite its usefulness, electrical resistivity surveying has limitations. Measurements reflect a weighted average of a large subsurface volume, with nearby materials having a stronger influence, leading to smooth curves that can obscure detail. Like other potential field methods, resistivity surveying often allows for more than one possible interpretation of a surface potential distribution. Therefore, it is recommended to use resistivity surveys in combination with other geophysical techniques in an integrated exploration program to reduce uncertainty and improve reliability.

Data from resistivity surveys are typically presented and interpreted in the form of values of apparent resistivity ρ_a . An equation giving the apparent resistivity in terms of applied current, distribution of potential, and arrangement of electrodes can be arrived at through an examination of the potential distribution due to a single current electrode. The effect of an electrode pair (or any other combination) can be found by superposition. The principle of superposition states that the measured voltage at any point in the subsurface is the sum of the voltages produced by each electrode pair acting independently.

Consider a single point electrode, located on the boundary of a semi-infinite, electrically homogeneous medium, which represents an imaginary homogeneous earth. The Wenner array is a commonly used electrode configuration in electrical resistivity surveying, consisting of four electrodes arranged in a straight line with equal spacing between them. The two outer electrodes are used to inject current into the ground, while the two inner electrodes measure the resulting potential difference. This equal spacing simplifies calculations and enhances data interpretation. The Wenner array is especially useful for vertical electrical sounding and provides good resolution of subsurface layers. Figure (3) Electrode array configurations for resistivity measurements by Wenner. It is widely applied in geotechnical, hydrogeological, and environmental studies due to its straightforward setup and sensitivity to vertical changes in resistivity. If the electrode carries a current (**I**), measured in amperes (**a**), the potential at any point in the medium or on the boundary Wenner method formula is given by:

$$U = \rho I / (2\pi r) \quad (2.2)$$

where U = potential, ρ = resistivity of the medium, I = Injected current, r = distance from the electrode. For an electrode pair with current (I) at electrode A, and $-I$ (a sign indicates opposite direction) at electrode B Figure (3), the potential at a point is given by the algebraic sum of the individual contributions: This array's four electrodes are all similarly spaced apart and are called a . Equation (2.3) can be used to calculate the apparent resistivity since it demonstrates that the geometric component $K = a$.

$$U = \frac{\rho I}{2\pi r_A} - \frac{\rho I}{2\pi r_B} = \frac{\rho I}{2\pi} \left[\frac{1}{r_A} - \frac{1}{r_B} \right], \quad (2.3)$$

Where r_A and r_B are distances from the point to electrodes A and B.

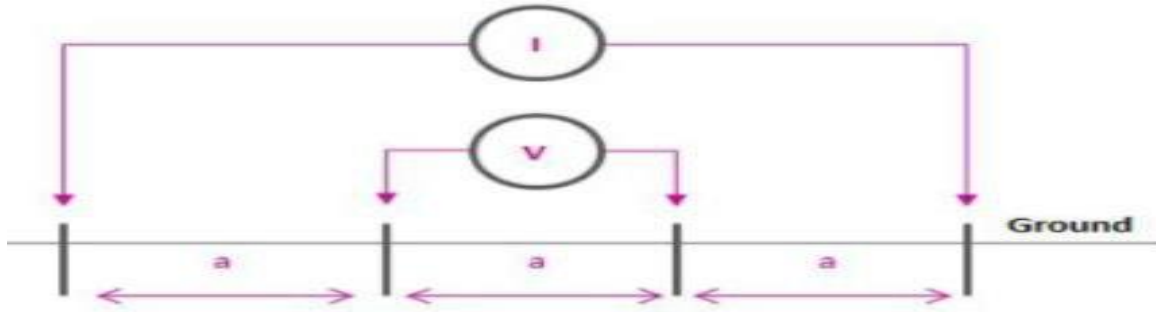


Figure 2 Electrode array configurations for resistivity measurements by Wenner (Kearey et al., 2002)

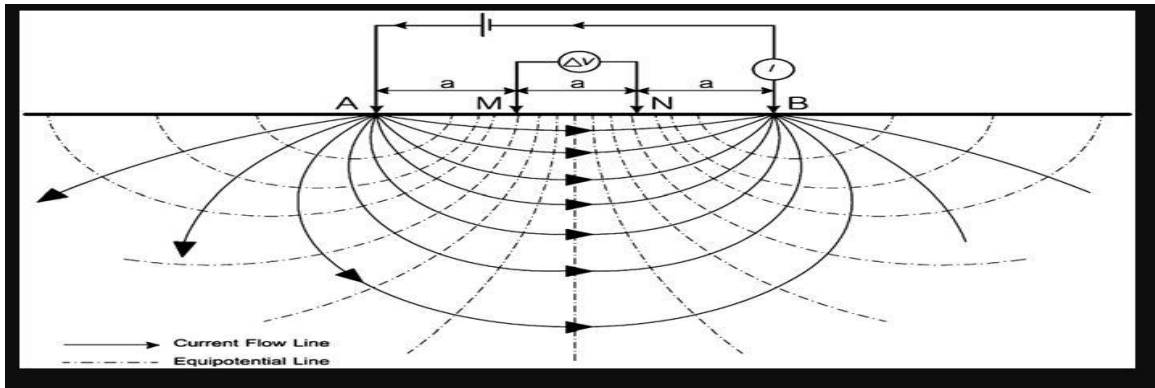


Figure 3 Equipotentials and current lines for a pair of current electrodes A and B

The above Figure (3) illustrates the electric field around the two electrodes in terms of equipotentials and current lines. The equipotentials represent imaginary shells, surrounding the current electrodes, and on any one of which the electrical potential is everywhere equal. The current lines represent a sampling of the infinitely many paths followed by the current, paths that are defined by the condition that they must be everywhere normal to the equipotential surfaces. In addition to current electrodes A and B, shows in figure (4) a pair of electrodes M and N, which carry no current, but between which the potential difference V may be measured. Following the previous equation equal(2.4), the potential difference V may be written as

$$V = U_M - U_N = \frac{\rho I}{2\pi} \left[\frac{1}{AM} - \frac{1}{BM} + \frac{1}{BN} - \frac{1}{AN} \right], \quad (2.4)$$

Where U_M and U_N are potentials at M and N, which is $(1/AM - 1/BM)$ and $(1/AN - 1/BN)$ respectively and AM is the distance between electrodes A and M. These distances are always the actual distances between the respective electrodes, whether or not they lie on a line. The quantity inside the brackets is a function only of the various electrode spacings and is denoted $1/K$, which allows rewriting the equation as:

$$V = \frac{\rho I}{2\pi} \frac{1}{K}, \quad (2.5)$$

where K = array geometric factor and where solved for ρ to obtain:

$$\rho = 2\pi K \frac{V}{I}, \quad (2.6)$$

The resistivity of the medium can be found from measured values of V , I , and K , the geometric factor. K is determined by the physical configuration of the electrodes and is not influenced by other factors such as the materials used in the electrodes, environmental conditions, or external influences.

2.4.2.1 Principle of Electrical Resistivity Tomography

The basic principle of ERT is based on the varying electrical conductivity of the subsurface materials, which depends on many factors, such as rock type, porosity, permeability, connectivity of pores, temperature, salinity, clay content, nature of the fluid/water, weathering degree, fractures/faults, and water-rock interaction, (Hasan, Shang, Meng, Shao, & Yi, 2021).

Generally, a wide range of electrical resistivity for most materials suggests the varying water content. In hard rock terrains, electrical resistivity can vary over a large range depending on weathering degree, and water saturation (Belle et al., 2019). Electrical resistivity decreases with increasing the weathering degree and water content. Hence, a contrast in resistivity values of the saturated weathered/fractured rock and fresh/unweathered rock is observed (Hasan et al., 2021).

The principle of ERT involves using electrical resistivity measurements to visualize and characterize subsurface structures and properties, making it a valuable tool in geological, environmental, and engineering investigations (Perrone et al., 2014). Electrical resistivity surveys are used to determine the sounding earth volume's resistivity distribution. The earth is exposed to artificially created, electric currents, and the potential differences that result are measured.

The principle involves injecting a current into the ground through electrodes and measuring the resulting voltage at other electrodes. The layout used for the data acquisition is illustrated in Figure (4), which shows the typical arrangement of electrodes in a 2-D electrical resistivity survey. The resistivity of the subsurface materials affects how the current flows, and the voltage measurements are used to create a 2D or 3D image of the subsurface resistivity distribution. Variations in resistivity can indicate different materials, such as water, rock, or soil, and can help identify structures like faults or underground voids.

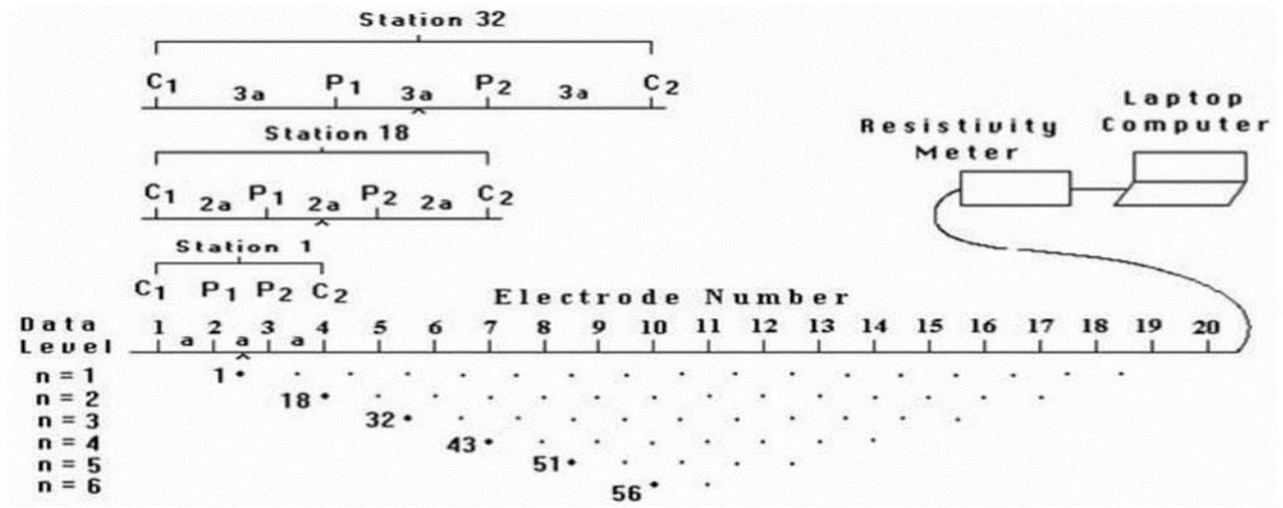


Figure 4 Arrangement of electrodes for a 2-D electrical survey

In the geophysics, the resistivity (ρ) of a material is a measure of its ability to resist the flow of electric current. It's typically measured in ohm-meters ($\Omega \cdot m$). The resistivity (ρ) of a simple body, such as a geological formation or a layer of the Earth's crust, is defined as follows:

$$P = R \times (A/L) \quad (2.7)$$

With R the electrical resistance in ohm-meters ($\Omega \cdot m$), L is the length of the material in the direction of current flow in meters (m), and A is the cross-sectional area of the material perpendicular to the direction of current flow in square meters (m^2). The relationship between resistivity (ρ) and conductivity (σ) is fundamental in understanding the electrical properties of materials, including those found in the Earth's subsurface. Resistivity (ρ) is a measure of how strongly a material resists the flow of electric current, while conductivity (σ) is a measure of how well a material conducts

electric current. These two properties are inversely related to each other and can be mathematically expressed as:

$$\sigma = 1/\rho \quad (2.8)$$

Where σ (sigma) is the conductivity of the material, measured in siemens per meter (S/m) and ρ (rho) is the resistivity of the material, measured in ohm-meters ($\Omega \cdot m$). This equation indicates that conductivity (σ) is the reciprocal of resistivity (ρ). In other words, materials with high resistivity have low conductivity, and vice versa. For instance, materials such as rubber and glass exhibit high resistivity and poor conductivity, whereas metals display low resistivity and excellent conductivity.

2.4.2.2. Electrode Configuration:-

In Electrical Resistivity Tomography, electrode configuration plays a vital role in determining the resolution, depth of investigation, and quality of subsurface imaging (Daily, Ramirez, Binley, & LeBrecque, 2004). ERT involves injecting electrical current into the ground through a pair of electrodes and measuring the resulting potential difference using another pair. This four-electrode system can be arranged in various configurations depending on the survey objectives, terrain, and desired depth coverage. Common configurations in ERT include Schlumberger, Dipole-Dipole, Pole-Dipole, Pole-Pole, and Wenner arrays. Each of these setups influences how current flows through the subsurface and how sensitively resistivity variations are detected.

The choice of configuration directly affects the geometry of the sensitivity distribution in the subsurface. Among these, the Wenner configuration is particularly popular in ERT due to its simplicity and balanced performance. In the Wenner array, electrodes are placed in a straight line with equal spacing between adjacent electrodes (C1–P1–P2–C2), where 'C' refers to current electrodes and 'P' to potential electrodes. The electrode configuration is referred to as a Wenner array when four electrodes are equally spaced in a straight line at the earth's surface, with the two outer electrodes (A and B) serving as the current, or transmission, electrodes and the two inner electrodes (M and N,) serving as the potential, or receiving, electrodes figure (6) (Okpoli, 2013). This uniform spacing allows for straightforward data interpretation and consistent sensitivity patterns, making it ideal for horizontal stratification studies and 2D or 3D resistivity imaging. The apparent resistivity is calculated using the formula.

$$\rho_a = 2\pi a(V/I) \quad (2.9)$$

where 'a' is the spacing between adjacent electrodes, V is the potential drop and I is the applied current.

In ERT, the Wenner configuration is especially useful for detecting shallow subsurface features and for applications in environmental studies, groundwater exploration, and archaeological investigations. Figure (5) shows the type of array used during the measurement, specifically the Wenner array arrangement. By increasing the distance between the electrodes while keeping the array's center point in the same place, the Wenner array is used to determine the resistivity of subsurface layers (Herman, 2001).

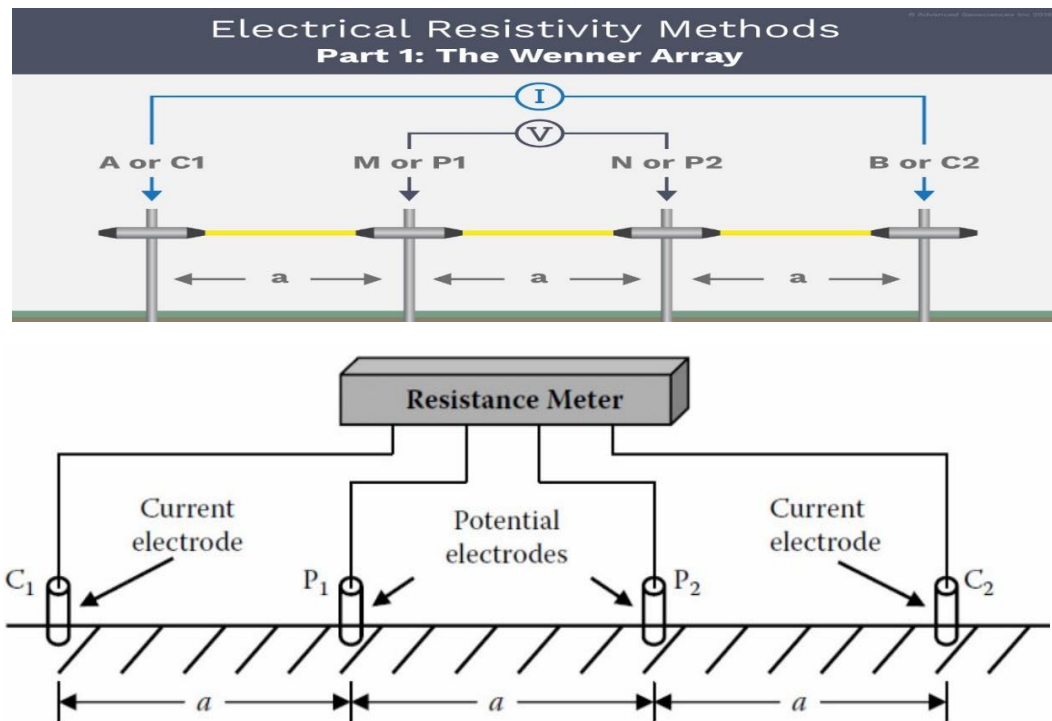


Figure 5 Type of array used in measurement and Wenner Array arrangement

CHAPTER -THREE

METHODS AND MATERIALS

3.1 Description of the study area

3.1.1 Location

The study area is located in the West Wallaga Zone, Gimbi area, Ganja Catchment it has a latitude and longitude of $9^{\circ}10' 13''\text{N}$ $35^{\circ}50'6''\text{E}$ with an elevation between 1845 and 1995 meters above sea level. It is the administrative center of Gimbi town. It gets 1000 mm to 1800 mm and 10°C to 30°C normal yearly rain falls and temperature respectively(Tadesse, 2022). The geographical setting of the study is illustrated in Figure (6), which presents the location map of the study area

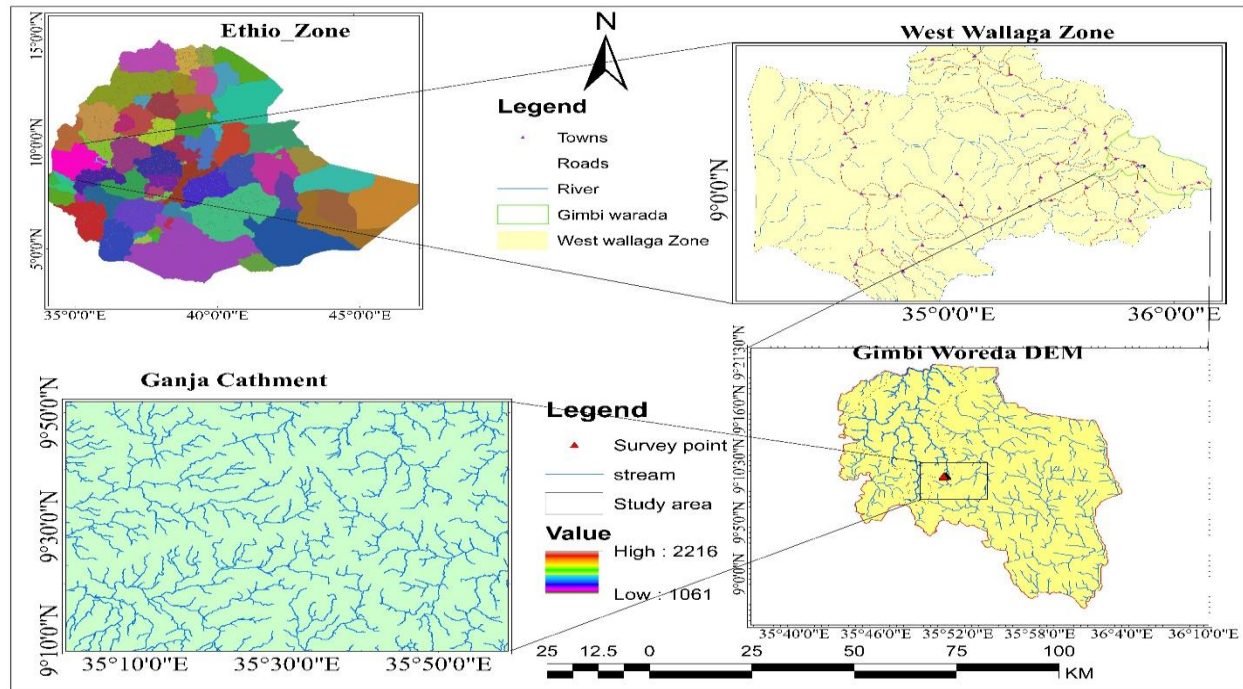


Figure 6 Location map of the Study area

The study area exhibits a diverse topography characterized by gently sloping hills, Steep and rocky areas, and slightly elevated flatlands. The catchment lies within elevations ranging from approximately 1912 to 1979 meters above sea level. The area is marked by a series of ridges and valleys shaped by fluvial erosion, with streams and rivers forming the primary drainage network. The steep slopes and separated landscapes are distributed with relatively flat or gently sloping areas, which are often utilized for agriculture, particularly for corn, wheat ,coffee, Sprout

multiplication and other crops. The topography significantly influences in soil erosion, water retention, and land-use patterns within the catchment, thereby serving as an essential factor in the effective direction of groundwater potential and enhancing agricultural productivity. Additionally, the varying elevation provides diverse Climatic variations, supporting the region's ecological richness and its role as a critical area for groundwater recharge.

The study area is organized around a Main Road, which serves as the primary route for high-capacity traffic, likely connecting key regions or destinations. Surrounding this central route are Local Roads, smaller pathways designed to provide access to nearby residential areas, businesses, and services, ensuring smooth movement within the community. The flow direction of a water feature—such as a river, stream, or drainage channel—is also marked, indicating the natural or engineered movement of water across the area. This integration of transportation and hydrology suggests that the area has been carefully planned to balance efficient traffic flow with environmental considerations, such as managing water drainage and mitigating flood risks. The layout highlights both connectivity and the ability to adapt to the physical characteristics of the land. Figure (7) shows the satellite image of the catchment, which helps visualize the extent and surface features of the study area.

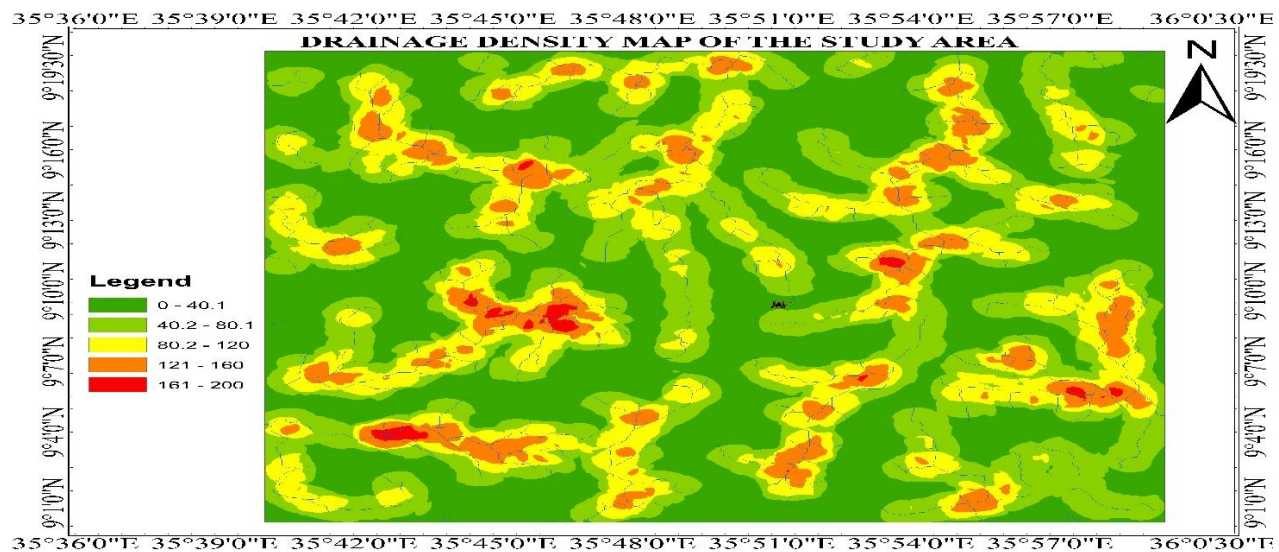


Figure 7 Drainage density map of catchment

3.1.3 Digital Elevation Model map of Ganja Catchment

The groundwater potential of the Ganja Catchment, inferred from the DEM, is closely tied to its topographic and hydrological features. The elevation gradient and slope variations play a critical role: steep high-elevation zones likely exhibit limited groundwater recharge due to rapid surface

runoff and erosion, reducing infiltration. Conversely, flatter low-lying areas near the catchment's outlet or along gentler slopes may act as groundwater recharge zones, where slower runoff allows water to percolate into aquifers. The stream network suggests potential interaction between surface water and groundwater, particularly in valleys or depressions where sediments could accumulate, enhancing subsurface storage. The survey points may indicate monitoring of groundwater levels or aquifer characteristics, essential for assessing sustainable extraction potential. However, the steep eastern regions might restrict groundwater availability, prioritizing recharge in the western or central lowlands. Overall, the DEM highlights that groundwater potential is highest in areas with gentle slopes, proximity to streams, and finer sediments, aligning with the catchment's discharge-focused hydrology. As shown in Figure (8), the DEM reveals significant elevation differences that influence surface runoff and drainage patterns

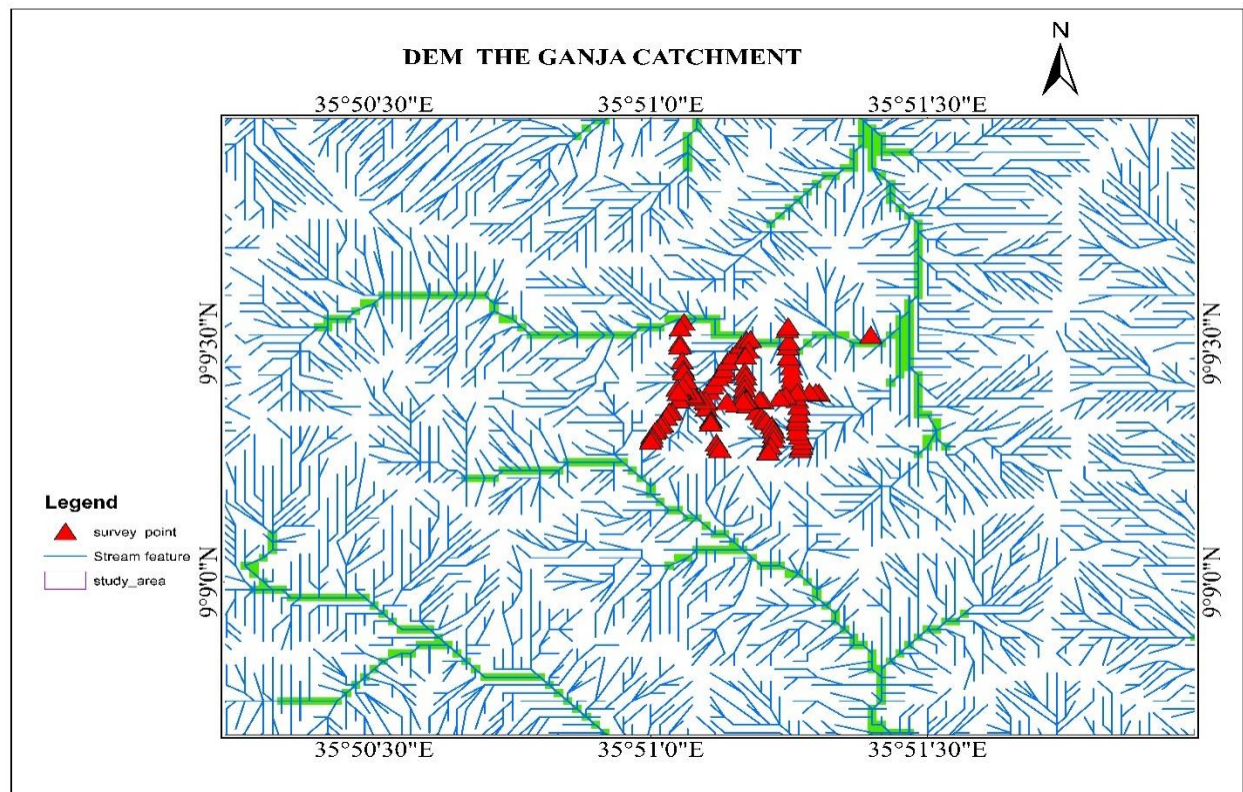


Figure 8 DEM map of the study area

3.1.4 Accessibility of the Study Area:

The study area shows particular features or conditions that shape the level of comfort during fieldwork and data acquisition. The regarded zone is essentially open by street/ public road, with

major courses interfacing it with the adjacent urban centers. The essential get to focuses include from Addis Ababa to Asosa and Dambi Dollo. These streets are encouraging helpful transportation for queries about workouts. The considered range is available by transport administrations, with Gimbi being a central point for open transportation. Analysts can utilize these administrations for cost-effective and economical travel inside the location. Once inside the considered range, neighborhood transportation administrations such as taxis, rental cars, or enlisted vehicles are accessible, giving adaptability for analysts to reach particular areas inside the study area.

3.1.5 Climatic and Rainfall Conditions of the Study Area

There are opportunities and challenges in the Gimbi area of the West Wallaga Zone's Ganja Catchment that are influenced by the local climate. The Study Area meets unquestionable seasons, including a wet season characterized by heavy precipitation and a dry season with lower precipitation. Researchers should arrange field visits between periods of optimal weather conditions to minimize challenges related to wet and sloppy areas. Consider area's availability is directly and easily influenced by both the total amount and the distribution of precipitation (rainfall, snowfall, etc.). During the wet season, specific streets and pathways might be closed, which affects transportation both to and within the study area. Researchers should consider these designs when planning activities and arrange them appropriately. The climatic conditions directly impact the vegetation and cover inside the Catchment. The think-about region shows distinguished day-night temperature variances. The diurnal variations influence the thermal properties of geological materials and alter the conductivity of subsurface layers, which are crucial considerations for geophysical surveys. Table (1) presents the monthly climate and rainfall data of the study area, which are critical for understanding seasonal variability and the graphical representation of monthly climate and rainfall trends in the study area is shown in Figure (9)

Table 1 Monthly Climate & Rainfall of the Study Area (National Meteorology Institute (NMI, 2024))

No	Months of the Year	Temperature Per Month in 0c	Rainfall Per Month in mm
1	January	15	20
2	February	25.4	40
3	March	16.1	65
4	April	15.2	95
5	May	15.3	115
6	June	13.9	160
7	July	13.8	263
8	August	13.6	268
9	September	13.9	283
10	October	14.1	56
11	November	14.5	17
12	December	14.9	13

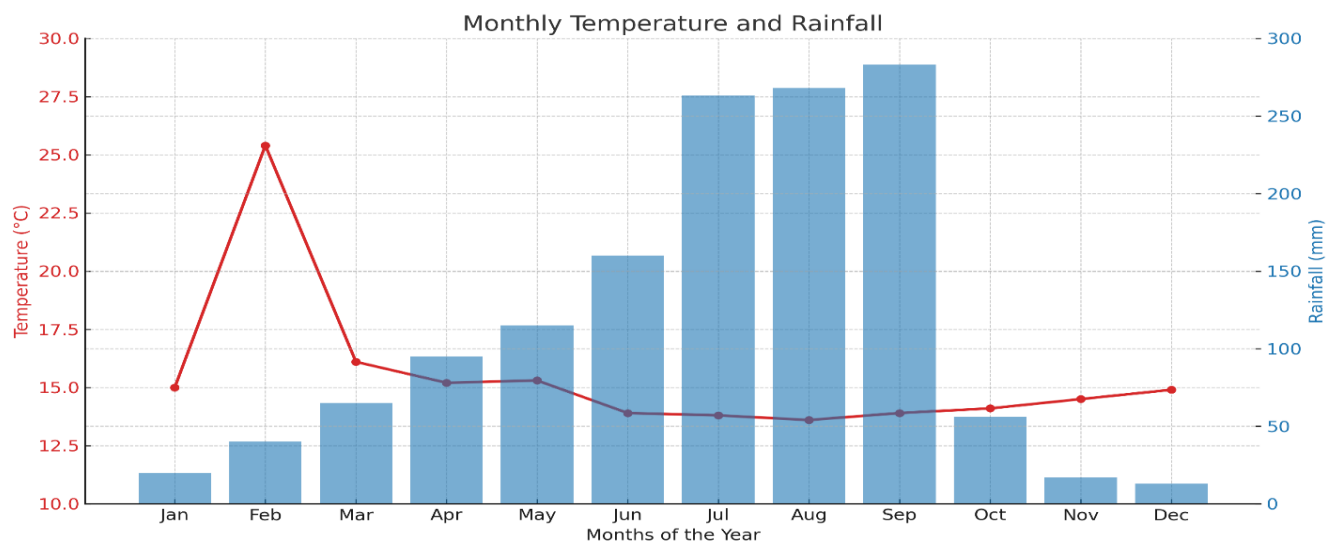


Figure 9 Monthly climate and rainfall in the study area (Table 1 above)

Based on the given graphical representation of monthly climate and rainfall in the study area, here are some key concepts: Bimodal Rainfall Pattern: The rainfall shows a clear peak from June to

September, with the highest rainfall in September (283 mm). This suggests a strong rainy season or wet period during these months, which is typical of tropical highland climates.

Temperature Stability with Minor Variations: Monthly temperatures are relatively stable, mostly ranging between 13.6°C to 25.4°C. The highest temperature occurs in February (25.4°C), while July and August are the coolest months (~13.6–13.8°C). **Inverse Temperature-Rainfall Relationship:** As rainfall increases from April to September, temperature slightly decreases, indicating a possible inverse relationship between temperature and rainfall during the rainy season. **Dry Season Identification:** Months such as December, January, February, and November show very low rainfall (under 40 mm), identifying them as dry months. **Agricultural Implication:** The rainy months (June–September) are optimal for rain-fed agriculture, while dry months might require irrigation or are better suited for harvesting/storage.

3.1.6 Topographic Features:

The physical characteristics of the Earth's surface, including natural and artificial landforms such as mountains, valleys, hills, plains, rivers, and lakes refer to the topographic features of the Earth's surface (Council et al., 2010). These features play a significant role in shaping landscapes and influencing geological processes such as erosion, sedimentation, and tectonic activity. In geological, topographic features are essential for understanding the structure, composition, and evolution of the Earth's crust. They are often studied and analyzed using methods such as topographic mapping, remote sensing, and geographic information systems to assess their impact on various geological phenomena and processes. In the Ganja Catchment, elevation measurement plays an important role in understanding the hydrological dynamics of the region. Researchers studying the topographic profile and relief features of the Ganja use elevation data to analyze how variations in elevation impact groundwater flow. For instance, high-elevation areas like the peaks of the Ganja act as recharge zones, where precipitation infiltrate the ground, and Return groundwater reserves. Conversely, low-lying areas such as valleys and foothills serve as discharge zones, where groundwater emerges as springs or feeds into rivers and streams. By examining slope gradients, researchers can assess the speed and direction of groundwater flow.

Steeper slopes tend to accelerate the movement of groundwater, potentially leading to rapid runoff and erosion, while gentler slopes facilitate groundwater recharge and retention. In the rugged terrain of the Ganja, characterized by high relief and diverse geological formations, groundwater

flow patterns are complex and influenced by factors such as rock types, soil properties, and vegetation cover. Conversely, in the Central Valley region, which features relatively uniform elevation and gentle slopes, groundwater behavior may be more predictable, making it suitable for agricultural irrigation and water management strategies.

3.1.7 Physiographic and drainage characteristics of the study area

In the study area, geological and hydrological features characterize the landscape and water flow patterns within the area being studied. Drainage characteristics, which refer to the patterns of water flow and the arrangement of rivers, streams, and watersheds, play a significant role (Mahala, 2020). This study area exhibits diverse physiographic features, including varying elevations, slope gradients, and landforms, all of which influence groundwater recharge rates, flow paths, and storage capacities. By understanding the distribution of hills, valleys, and flats, researchers can delineate groundwater flow patterns and identify potential recharge areas. The drainage pattern of the Ganja Catchment reflects the natural pathways of surface water runoff, impacting groundwater recharge and discharge processes. The density and alignment of streams, rivers, and drainage networks within the study area significantly influence groundwater flow directions and velocities (Abrahams, 1984). The detailed network of Waterways, along with the main stem of the Ganja River, dictates the movement of groundwater beneath the surface. Through the assessment of drainage characteristics, researchers can identify areas where groundwater discharges into surface water bodies, such as lakes and wetlands. Additionally, examining drainage patterns helps identify potential recharge zones along riverbanks and alluvial plains, where groundwater replacement occurs through infiltration from surface water sources.

3.1.8 Land Use Implications:

Different land use types influence groundwater recharge and discharge processes (Mishra, Khare, Gupta, & Shukla, 2014). Areas with vegetative cover, such as forests or grasslands, promote infiltration and groundwater recharge, while urbanized or paved areas may hinder infiltration, leading to increased surface runoff and reduced groundwater recharge.

Identifying land use patterns helps delineate recharge zones and discharge, which are critical for assessing groundwater potential.

In the study area of Ganja, intensive agricultural activities significantly impact groundwater recharge and discharge. Large-scale crop cultivation increases water demand, leading to excessive groundwater extraction and lowering water tables. The extensive use of fertilizers and pesticides introduces contaminants that leach into the groundwater, reducing water quality. Soil compaction from farming reduces infiltration, limiting recharge, while increased surface runoff further alters natural water balance. These land use practices not only degrade groundwater quality but also disrupt its natural availability, affecting both the environment and local water resources

3.2 Methods

This methodology outlines the procedures for conducting a field survey using Electrical Resistivity Tomography and Magnetic Method for groundwater potential assessment.

3.2.1 Magnetic data acquisition Procedures

The data acquisitions in the study area were employed with five (5) profiles: 1st and 3rd from north to south, 2nd and 4th from south to north, and profile-5th crossed over profiles 1st, 2nd, 3rd, 4th from east to west in the study area. Data collection was conducted within an area of 0.42 km by 0.5 km, with a separation of 125 meters between the first and second profiles, second and third profiles, but a 170-meter separation between the third and fourth profiles. These measurements were taken parallel to profiles from which the Electrical Resistivity Tomography points were taken within the study area. From the magnetic site survey, a total of 124 magnetic data readings and three (3) base station (BS₁, BS₂ & BS₃) were taken directly. The magnetic survey consisted of data collection from the first, second, and fourth profiles, with measurements taken at 20-meter intervals along a 500-meter-long survey line, resulting in the collection of 25 data points from each profile. For the third profile, data points were collected along a 400-meter-long survey line, with 20 measurement points spaced at 20-meter intervals. A total of 29 magnetic data readings were obtained along Profile Five, with measurements taken at 20-meter intervals, covering a total survey length of 580 meters. The profile extends across Profiles 1 to 4. The positions of the survey stations, each station and elevations of all were determined using the GPS receiver. During the process of magnetic data collection, three base station readings were recorded for each profile.

The base stations were strategically positioned as: BS1 at the starting point of the first profile, BS2 at the junction of the second profile's end and the third profile's beginning, and BS3 at the endpoint of the fifth profile. At each station, the magnetometer reading, recording time, and location in the

Universal Transverse Mercator(UTM) coordinate were recorded. These were some of the stages involved in the magnetic method geophysical survey of the study area. Survey Area Delineation: Equipment Preparation: Field Installation: Data Collection: Process and analyze the collected magnetic data to identify anomalies: Anomaly Interpretation: Integration and Improving and Further Investigation. Finally, the collected data were imported into computer Excel software for diurnal correction. The profile line and data points of magnetic sounding were processed and mapped using Geosoft (Oasis Montaj ver.6.4.2) software. Figure (10) shows the magnetic data survey profile line, which outlines the orientation and extent of the magnetic measurements conducted in the study area

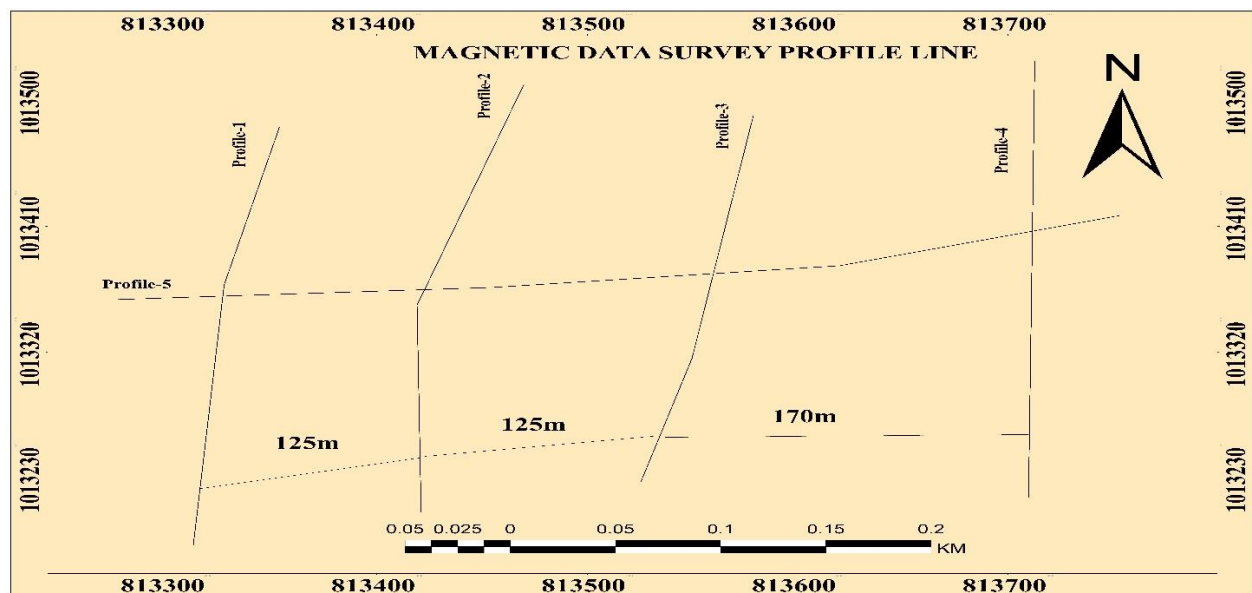


Figure 10 Magnetic data survey profile line

The magnetic data collection process involves the systematic arrangement of instruments and a structured procedure for field data acquisition. Figure (11) illustrates the instrument setup and data acquisition procedure used in the magnetic survey



Figure 11 Magnetic data acquisition Procedures

3.2.2 ERT data acquisition Procedures

Data collection took place within a 0.42 km by 0.49 km area, where profile lines were spaced 125 meters apart between profiles 1 and 2, and between profiles 1 and 5, whereas a 170-meter spacing was kept between profiles 2 and 3, which are parallel straight-line cables. These profiles were oriented in different directions: profiles 1, 2, 3, and 5 ran from north to south, while profile 4 was oriented east to west. At each location along these lines, a measurement was taken to collect data on the electrical resistivity of the subsurface, and at least twenty to twenty-five meter (20m-25m) GPS readings were taken along each profile.

To calculate the total number of resistivity data points collected in an ERT survey using the Wenner array with: 50 electrodes with 10-meter spacing between electrodes. Wenner Array uses 4 electrodes in each measurement: two for current (C1, C2) and two for potential (P1, P2). With 1691 data points, the resistivity distribution beneath the surveyed area was characterized. Figure (12) shows Electrical resistivity tomography field survey profiles measurements.

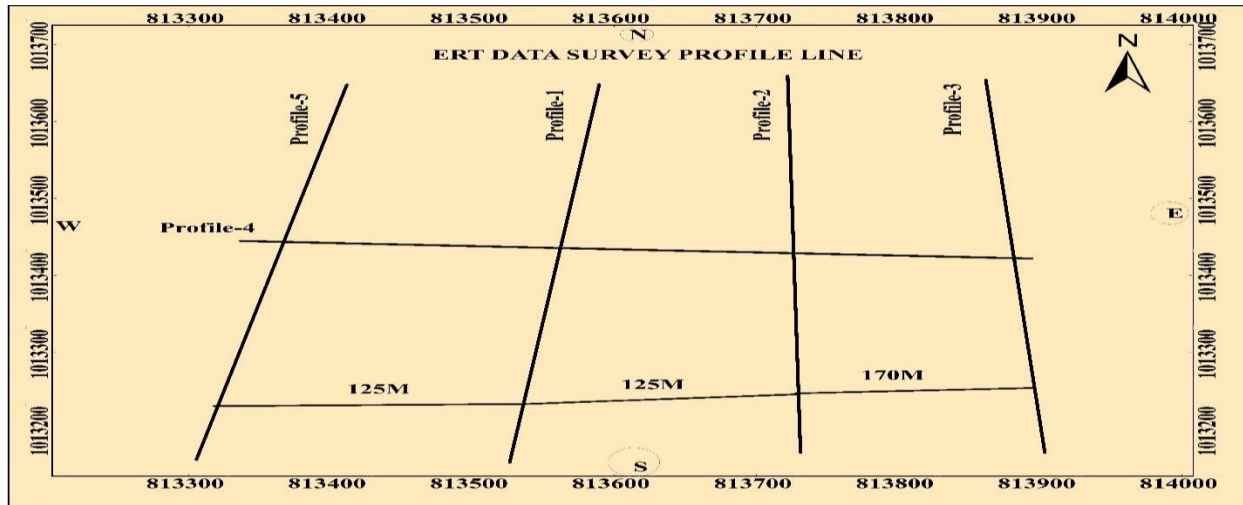


Figure 12 ERT field survey profile

During the electrical resistivity survey, a Syscal Switch device was used, connected to four cables, each 120 meters long and equipped with 48 multi-electrodes, as well as two additional cables, each 10 meters long with 1 electrodes. These cables were arranged in a straight line, covering a total distance of 500 meters, with electrodes spaced at fixed intervals of 10 meters. For this two-dimensional (2D) electrical resistivity tomography survey, five profiles were measured. Figure (13) shows the arrangement of instrument and procedure of data acquisition in field survey.



Figure 13 ERT Field Surveying Procedures

3.3 Materials

The materials commonly used for Electrical Resistivity Tomography and magnetic method surveying are electrodes, Hammer, Cables: Resistivity Meters: GPS map 60CSX, Receivers, and Battery voltage to deliver source power. In addition, software such as RES2DINV, ArcGIS

ver.10.8, ArcGISPro.exe, Ires syscal model Junior switch-72, Proton Magnetometer-600, and Geosoft (Oasis Montaj ver.6.4.2) were used to preprocess and map magnetic anomalies. The software was used to map the location of the study area, Resistivity and Anomaly of the selected study area

3.4 ERT and Magnetic data processing

3.4.1 ERT data processing

In Electrical Resistivity Tomography data processing, raw survey data is transferred to a computer and processed using software. The data is cleaned to remove noise and artifacts, followed by quality control to ensure reliability. It was then formatted and edited using RES2DINV software for 2D field data interpretation to obtain true resistivity sections.

The Syscal switch instrument recorded for profiles 1:- 335, profiles 2:- 352, profiles 3:- 349, profiles 4:- 332 and profiles 5:- 323 data points across profiles, which were automatically edited using Prosys II and RES2DINV software. The final processed data points were reduced to from profiles 1:- 252, from profiles 2:-194, from profiles 3:- 291, from profiles 4:- 318, and from profiles 5:- 222. Figure (14) Data of profile three before and after bad data points edited by RES2DINV.

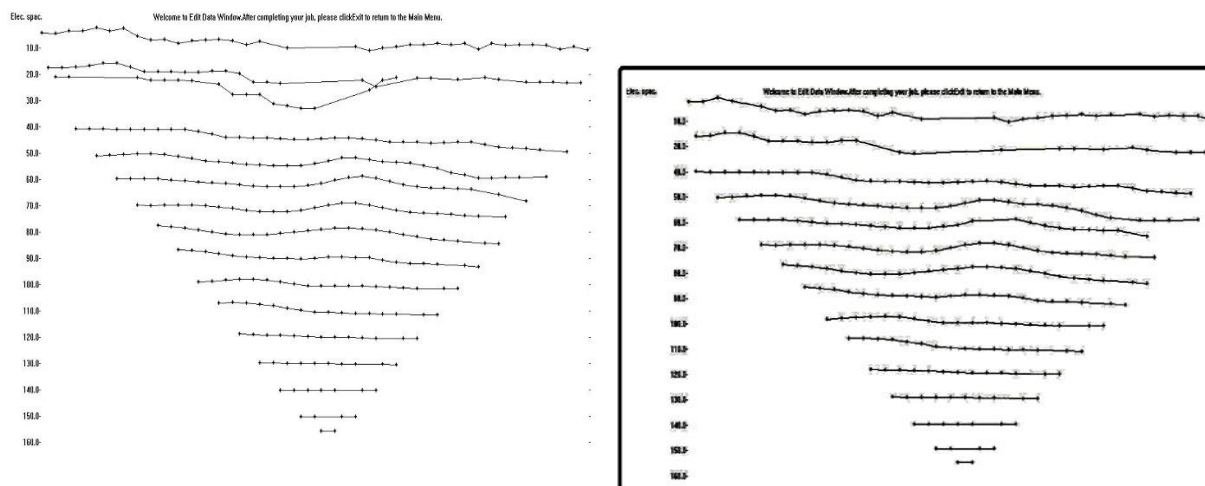


Figure 14 Data of profile three before and after bad data points edited by RES2DINV

3.4.1.1 Inverse modeling

To interpret the data accurately, it is important to identify a model that minimizes the difference between calculated and measured resistivity values. The RES2DINV software achieves this by

using a smoothness-constrained least-squares inversion method to determine the resistivity of discrete subsurface regions that best match the measured data (Günther, 2004). The software creates a pseudo-section of apparent resistivity during the inversion process, reconstructing an earth model that reflects the conductive properties of the raw data (Arboleda-Zapata, Guillemoteau, & Tronicke, 2022). This process involves solving mathematical problems to transform observed data into a 2D resistivity model, presented as images showing the horizontal and vertical distribution of resistivity, which can be related to groundwater occurrence. Forward modeling methods, such as finite element and finite difference, are used to calculate resistivity. The program divides the subsurface into small rectangular cells, generating a two-dimensional cross-section of true resistivity beneath the electrode array. The distribution and size of blocks in the model are automatically generated based on data points, with the depth of the bottom row approximating the depth of investigation. 2D electrical modeling also analyzes the potential for detecting high-resistivity zones within a lower-resistivity environment, with deeper detection achievable as resistivity contrast increases (Arboleda-Zapata et al., 2022).

Electrode array sensitivity, such as with the Wenner array, influences the choice of array for the study area. The Wenner array is effective for shallow depth investigating and lateral measurements. A good inversion method reduces data errors and misfits between observed and calculated values through optimization algorithms. These algorithms iteratively refine an initial model to minimize the difference between modeled responses and observed data, ensuring accurate results within defined constraints.

3.4.2 Magnetic data processing

In the magnetic method, data processing involves importing raw magnetic field data into specialized software, where it undergoes filtering, noise removal, and baseline correction. Enhanced techniques like analytic signal transformation and reduction to the equator are applied to improve anomaly visualization and depth estimation.

Anomalies indicating geological structures or groundwater potential are identified by analyzing their size, shape, and intensity (Jardani, Revil, Bolève, & Dupont, 2008). The processed data is visualized using magnetic maps and cross-sections, and errors are removed through editing and statistical analysis. Specialized software like Geosoft's Oasis Montaj is used to create magnetic

anomaly maps, identifying subsurface features such as aquifers, recharge zones, and faults influencing groundwater flow.

Conducting ERT and magnetic surveys in a study area using parallel or nearly parallel profile lines enhances data accuracy by ensuring consistent spatial coverage and better correlation of subsurface features. This approach allows for direct comparison between resistivity and magnetic anomalies along the same geological structures, improving the interpretation of faults, fractures, and lithological boundaries. Parallel surveys help in detecting continuous or linear features, such as groundwater-bearing zones, faulted formations, with higher precision. Additionally, maintaining a uniform survey direction minimizes errors caused by variations in terrain, instrument orientation, and external interferences, leading to more reliable results. Overlapping the two datasets along parallel profiles enables cross-validation of anomalies low-resistivity zones in ERT corresponding to low magnetic anomalies can confirm fractured or weathered rock formations that enhance groundwater flow, while high resistivity overlapping with high magnetic intensity can indicate compact, impermeable units. This systematic approach improves the accuracy of geological interpretations, and enhances groundwater resource assessments in the study area. Figure (16) presents the ERT and magnetic survey profiles conducted across the study area.

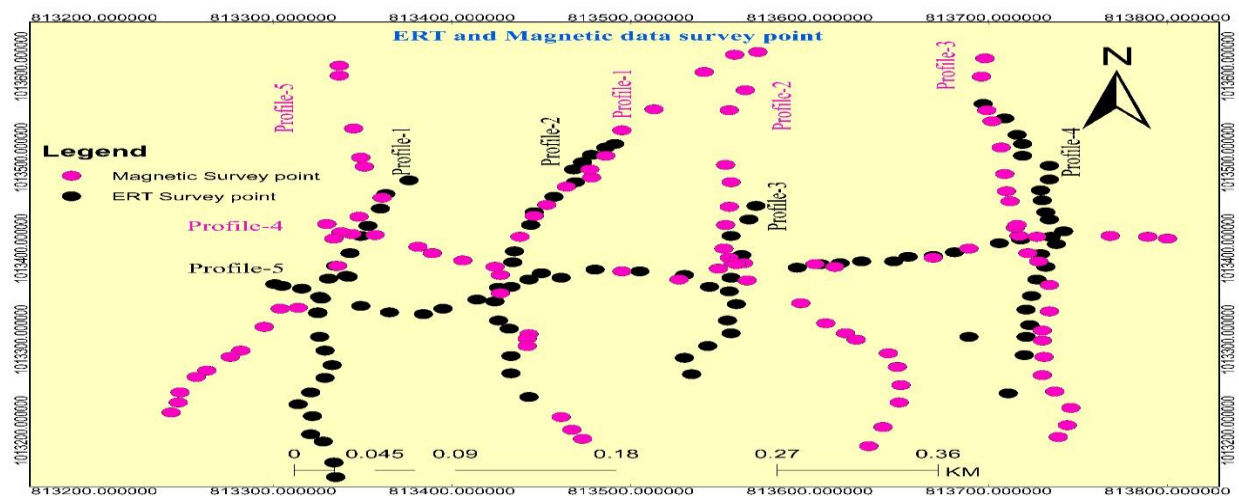


Figure 15 ERT and magnetic surveys profile in a study area

3.4.3.1 Magnetic data correction

Magnetic data correction is important in geophysics for accurate interpretation in groundwater, mineral exploration, archaeology, and more (Nabighian et al., 2005). The process adjusts for

natural variations in the Earth's magnetic field, such as secular changes and diurnal fluctuations, by using reference measurements from magnetometers to isolate target anomalies. It also corrects for distortions caused by human-made structures, local geological features, and other disturbances. In groundwater assessments, in study area, these corrections ensure reliable data by addressing variations and interference, enabling clearer identification of subsurface geological features.

3.4.4.1 Diurnal Correction

Diurnal correction addresses daily variations in the Earth's magnetic field caused by solar activity, which can introduce noise into magnetic survey data (Palmer, Rycroft, & Cermack, 2006). A base station magnetometer, placed in a stable location, records these variations over time. Field survey data is then compared to the base station readings, and the fluctuations are subtracted to remove time-dependent noise. This ensures the data reflects only subsurface magnetic anomalies related to geological features. Without diurnal correction, these variations can cause significant errors, hindering accurate interpretation of geological structures. The basic principle of diurnal correction is to subtract the recorded diurnal variations from the field measurements. The formula used for diurnal correction can be expressed as:

$$M_{\text{corrected}} = M_{\text{measured}} - (B_t - B_0) \quad (3.2)$$

Where: **M**_{corrected} :- the corrected magnetic data, **M**_{measured} :- the magnetic field measurement taken in the field, **B**_t :- the base station magnetic field value at time **t** (the time when the field measurement was taken), **B**₀ :- the base station magnetic field value at a reference time, usually the start of the day or survey period.

3.4.4.2 Latitude Correction

The Earth's magnetic field strength varies with latitude, being stronger at the poles and weaker at the equator. The Earth's magnetic field strength varies with latitude due to the structure and shape of the Earth's magnetic field, which is similar to that of a bar magnet tilted slightly from the planet's rotational axis.

Latitude correction normalizes the magnetic field measurements to a standard reference value, allowing for consistent comparison across different geographical regions (Canciani & Raquet,

2016). In the study area, the magnetic data collected would be adjusted based on the latitude of the survey area, ensuring that any observed anomalies are due to subsurface features rather than geographic position.

3.4.4.3 Longitude Correction:

Magnetic data correction for longitude is less common than for latitude because the Earth's magnetic field does not vary as systematically with longitude (Laundal & Richmond, 2017). Magnetic field variation is predictable with latitude due to the Earth's dipolar field structure, but not with longitude due to irregular, local variations. Therefore, latitude corrections are standard in magnetic surveys, while longitude corrections are not commonly applied. However, in large-scale surveys or global geomagnetic models, longitudinal variations can become significant due to the non-uniform distribution of the Earth's internal magnetic sources and external influences like solar wind. While the magnetic field is often approximated as a dipole aligned with the poles, its actual complexity requires corrections for longitudinal effects in global surveys. Geomagnetic models, like the IGRF, help account for variations in latitude, longitude, and altitude.

3.4.4.4 Regional Correction:

Regional correction is a process used to remove broad, long-wavelength anomalies (typically from deeper sources or background fields) so that the local, short-wavelength anomalies (from near-surface geological features) can be more easily interpreted (Liguo, Yu, Jiyao, & Junhao, 2022). Regional magnetic data correction involves removing broad trends in the Earth's magnetic field to isolate local anomalies linked to geological features, such as faults or fractures that could influence groundwater flow (Nabighian et al., 2005). This is typically done by fitting a polynomial surface to the data and subtracting it, allowing for the identification of localized anomalies. These corrections are vital for accurate interpretation in groundwater exploration, as regional anomalies from large geological structures can mask smaller, more relevant features. Techniques like low-pass filtering help separate regional and local variations, ensuring more precise geological assessments.

3.4.4.5 Residual Correction:

Residual correction involves isolating the short-wavelength, local magnetic anomalies by removing or suppressing the long-wavelength regional field. This makes it easier to interpret near-

surface geological structures, such as faults, dikes, mineral deposits, or voids. Subtracting the upward continued field from the original gives a residual field this is an indirect way to apply a high-pass filter.

Residual correction is directly connected to the use of filters specifically high-pass, band-pass, and sometimes upward continuation filters. Residual magnetic correction is used to separate local magnetic anomalies from large-scale regional trends. The process involves removing the regional magnetic field from observed magnetic data to obtain residual anomalies. These residual anomalies can arise from small-scale geological variations or cultural noise. Residual correction helps in refining the magnetic data, ensuring higher accuracy for interpreting subsurface geological structures or resources. In magnetic surveys, after applying a regional trend removal (low-pass filter), residual correction may involve high-pass filtering or polynomial fitting to isolate local anomalies. The formula for residual magnetic correction typically follows this structure:

$$M_{\text{residual}} = M_{\text{observed}} - M_{\text{regional}} \quad (3.3)$$

Where: M_{residual} :- residual magnetic anomaly, M_{observed} :- total observed magnetic field intensity, M_{regional} :- regional magnetic field, estimated using polynomial fitting or interpolation.

Residual magnetic corrections ensure that the final magnetic data is as close to the true magnetic field as possible, allowing for accurate interpretation and decision-making in fields like exploration geology, geophysics, and environmental assessments (Reynolds, 2011).

CHAPTER FOUR

RESULTS AND DISCUSSIONS

4.1 Results

4.1.1 Electrical Resistivity Tomography Results

The ERT surveys conducted in the study area displayed significant subsurface resistivity variations, indicating different geological formations and the presence of potential aquifers. This section focuses on the inverse model cross-sections of five profiles, analyzing the subsurface resistivity variations and their implications for groundwater potential.

4.1.1.1 Inverse Model Cross-Section of Profile One

The inverse model cross-section of Profile One reveals significant subsurface resistivity contrasts. The 2D electrical resistivity survey profile was carried out in the north to south direction. About 332 collected data points were used for this inversion. Figure (17) shows the measured inverse model resistivity cross-section of profile one.

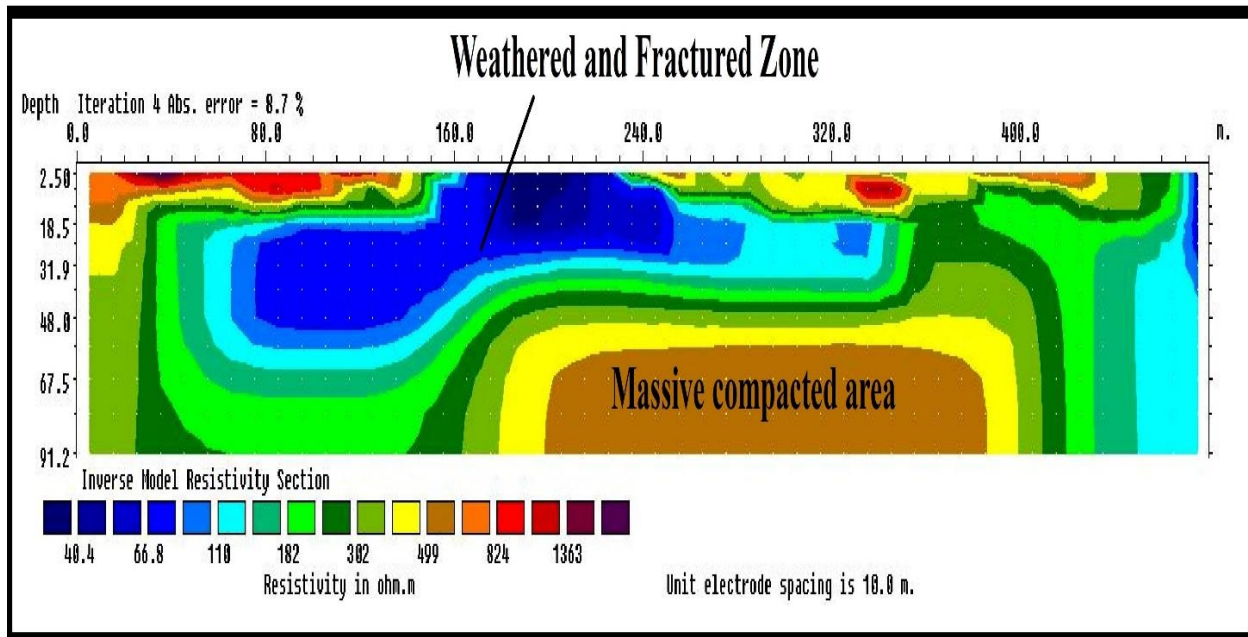


Figure 16. 2D Inverse Model Cross-Section of Profile One

The inversion utilized 252 data points, with resistivity values ranging from 40.4 Ωm to 1363 Ωm and depths up to 91.2 m. Results show varying subsurface resistivity, with low-resistivity zones (40.4 Ωm to 66.8 Ωm) indicating weathered and fractured rock, high-resistivity zones (824 Ωm to

1363 Ωm) corresponding to Massive, and unfractured rock, and medium resistivity values slightly weathered and fractured rock.

The main aquifer zone, consisting of schist, gneiss fractured and weathered metamorphic rock, is located in the northern part to center of the profile at depths up to 50 m.

4.1.1.2 Inverse Model Cross-Section of Profile Two

Profile Two's inverse model cross-section shows a similar pattern to Profile One but with some distinct features. Figure (18) shows the 2D inverse model cross-section of Profile Two, highlighting subsurface resistivity variations

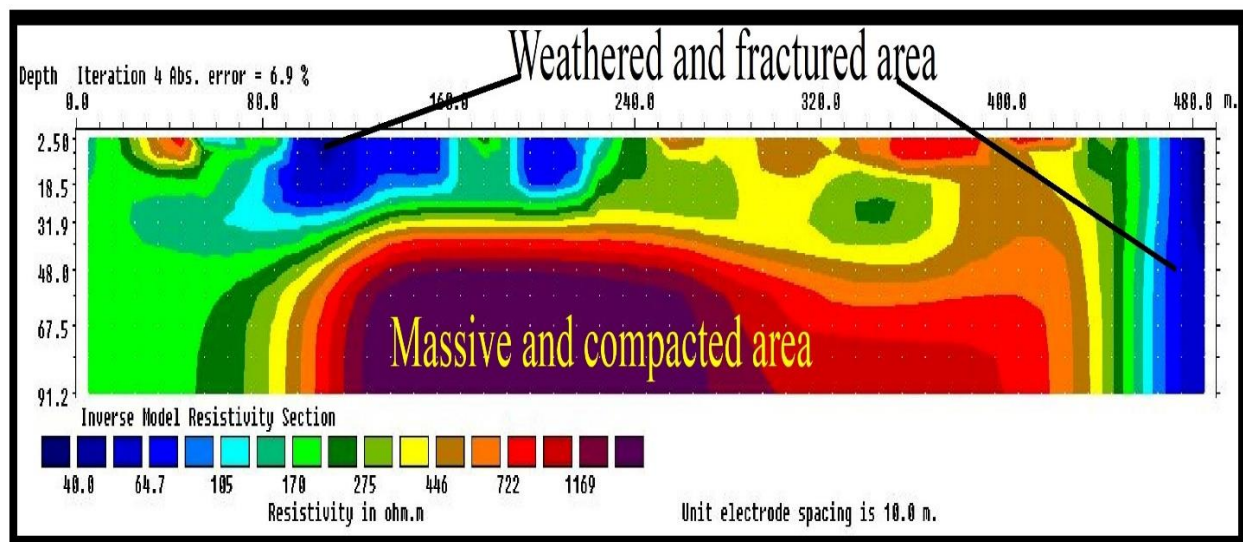


Figure 17. 2D Inverse Model Cross-Section of Profile Two

The inversion process used 194 data points, with resistivity values spanning from 40.8 Ωm to 1169 Ωm . The results show high resistivity values (446 Ωm to 1169 Ωm) extending from the south to the center and part of north of the survey area. These zones are interpreted as compacted unwelded that are impermeable and have very low permeability. Above this layer lies the water-bearing aquifer zone, consisting of fractured or weathered with resistivity values from 40.8 Ωm to 105 Ωm .

4.1.1.3 Inverse Model Cross-Section of Profile three

The inverse model cross-section of Profile three highlights a complex subsurface structure. This 2D electrical resistivity survey profile was conducted along Profile two, with a spacing of 125 m between measurements in the north to south direction.

A total of 500 data points were collected, and the results are presented as an inverse model resistivity section, shown in Figure (19).

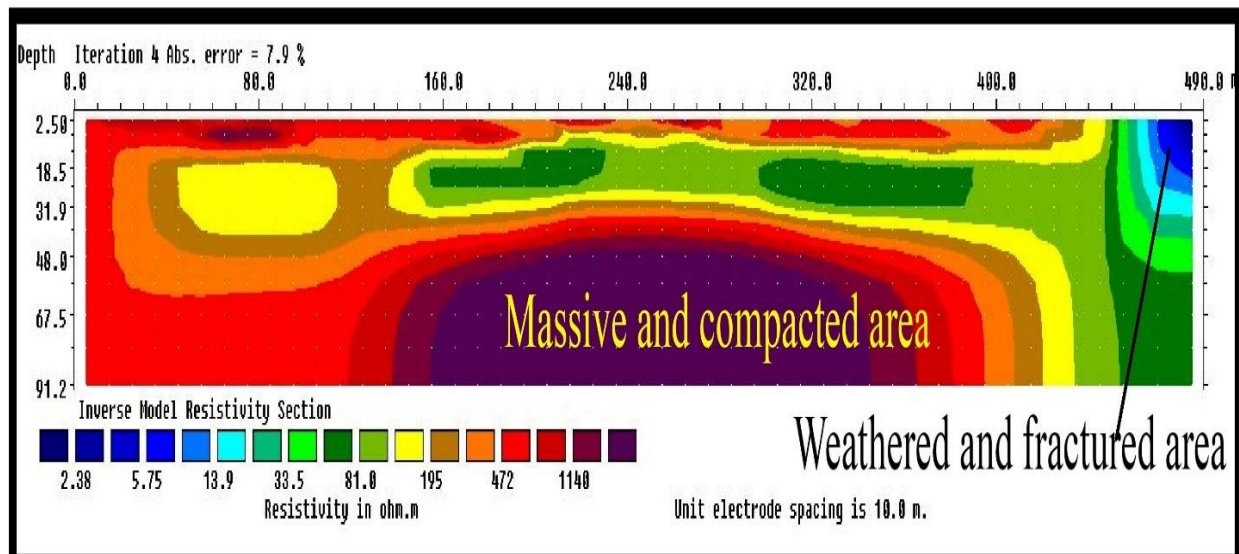


Figure 18. 2D Inverse Model Cross-Section of Profile three

The profile shows a top layer of dry soil with high resistivity values between 195 Ωm and 1148 Ωm , extending from 2.58 m to 91.20 m in the west and south, and at shallow depths in the north. In the eastern part, a zone of highly weathered and fractured, representing the main aquifer, is observed at depths of 2.58 m to 35 m, with low resistivity values ranging from 2.38 Ωm to 13.9 Ωm .

4.1.1.4 Inverse Model Cross-Section of Profile Four

This is the fourth line over which electrical resistivity tomography surveys was done and the line runs cross over to profile 1, profile 2, profile 3, and profile 5 with opposite direction to line . In this profile 500 data point were recorded along 500m long. According to the result obtained through the inversion process, resistivity range from (19.3 Ωm to 1001 Ωm) through penetrating depths of 91.2m were produced. Figure (20) indications the inverse model cross-section of 2D electrical resistivity of profile 4.

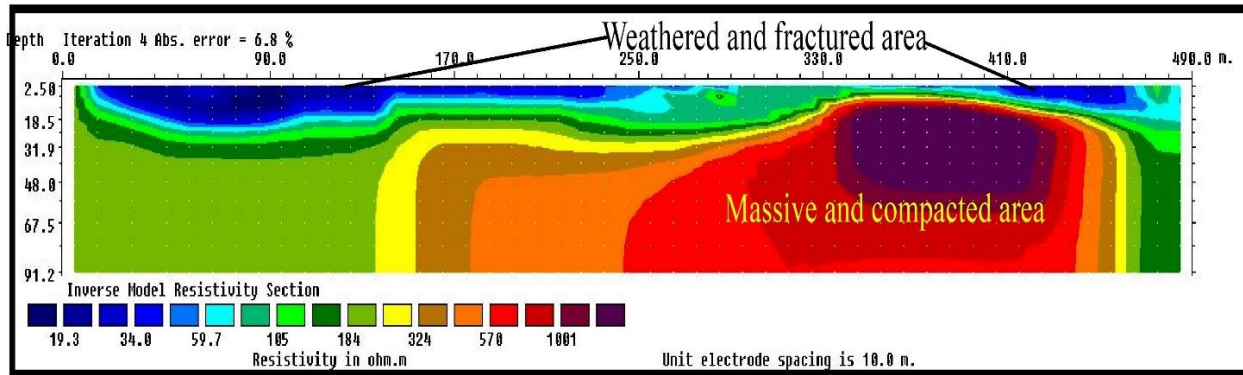


Figure 19. 2D Inverse Model Cross-Section of Profile Four

The profile shows a moderate resistivity zone with values between 105 Ωm and 324 Ωm , extending from the surface to depths of 10 m to 91.2 m in the central and southern sections. Below, a highly fractured and weathered aquifer zone is found at depths between 2.5 m and 18 m, with resistivity values from 19.3 Ωm to 59.7 Ωm . Beneath this layer, massive and unfractured rock is detected at 18.5 m depth from center to south with a resistivity of 184 Ωm to 1001 Ωm .

4.1.1.5 Inverse Model Cross-Section of Profile Five

The inverse model cross-section of Profile Five, the final segment of the 2D electrical resistivity tomography survey, was conducted along a North-to-South direction. With parallel to Profiles 1, 2, 3 and it intersects Profile 4 and uses 500 m of cable with 500 data points collected for the model. The resulting resistivity distribution is illustrated in Figure (21).

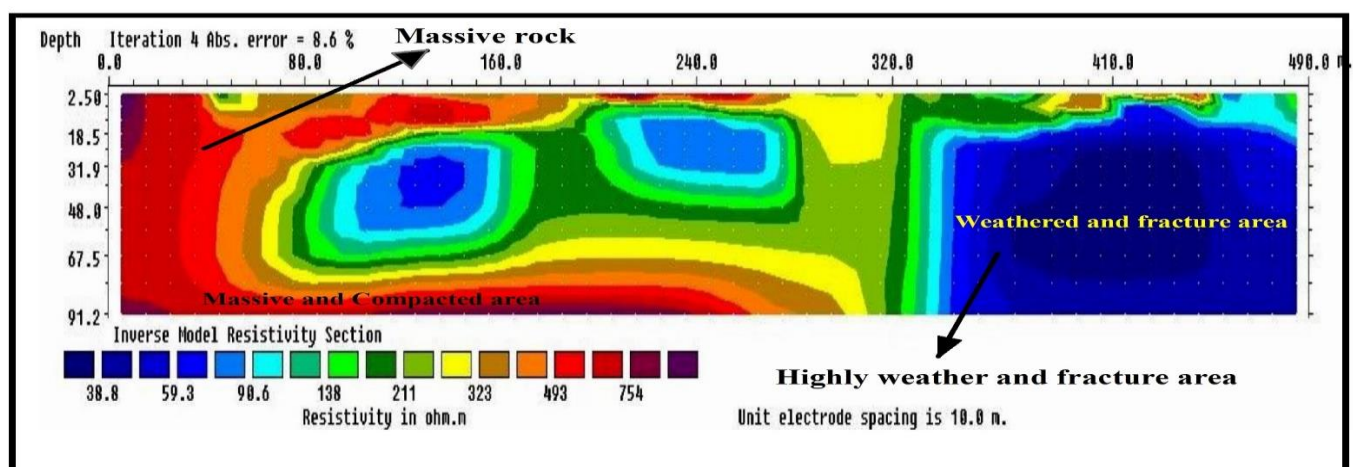


Figure 20. 2D Inverse Model Cross-Section of Profile Five

The resistivity section reveals clear vertical stratification of subsurface materials, important for assessing groundwater potential. The low resistivity zone (38.8–90.6 Ωm) indicates highly weathered and fractured materials, favorable for shallow groundwater storage. The main aquifer lies within the highly weathered and fractured zone, making it the most productive. This interpretation provides a reliable framework for groundwater development. Combining resistivity data with geological zonation enhances understanding of subsurface conditions and supports effective water resource management.

Above it, a moderately resistive zone (138–323 Ωm) represents partially weathered rock with moderate groundwater potential, depending on fracture density. A moderately weathered and fractured layer, extends from the north to the center, sloping southward, further influencing groundwater distribution. At greater depths, a high resistivity zone (323–754 Ωm) is interpreted as compact, unweathered bedrock with limited groundwater potential except in deep fractures. Regionally, high resistivity values are found from the surface to about 15 m in the north, extending west and south to 91.2 m depth, suggesting compact quartzite and marble. Below, the main aquifer extends from 2.5–91.2 m in the east and 10–67.5 m in the center.

4.1.2 Results of Magnetic Data

4.1.2.1 Total Magnetic Intensity (TMI)

Total Magnetic Intensity (TMI) measures the Earth's magnetic field at a specific location, including regional and local geological influences. Use for identify regional geological structure and lithological variation.

In study areas, high TMI values indicate magnetically susceptible rocks, while low values suggest potential groundwater zones due to fractured rock formations. By identifying geological structures such as faults or fractures, TMI helps locate areas where groundwater may accumulate, offering valuable insights for further investigations and drilling efforts. Figure (22) displays the Total Magnetic Intensity (TMI) map, revealing broad magnetic anomalies across the region.

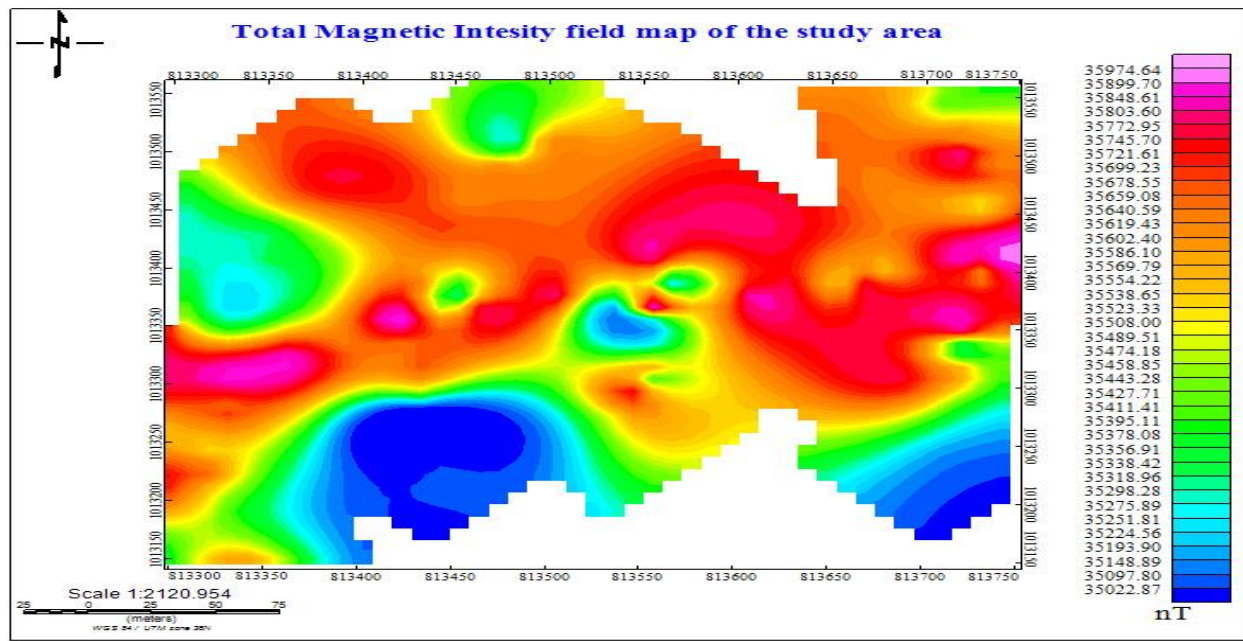


Figure 21 Total Magnetic Intensity Map of the study area

In the study area, the Total Magnetic Intensity (TMI) ranges from 35022.870 nT to 35974.64 nT, reflecting variations in magnetic susceptibility and groundwater content across different rock types, specifically focusing on metamorphic rocks. High magnetic anomalies, represented by red regions with values ranging from 35508 nT to above 35974.64 nT, are primarily found in the Central, North, West, and East. Rocks with significant magnetite, pyrrhotite, or other ferromagnetic minerals. Dense, compact, and less porous rocks.

These areas are typically associated with magnetically susceptible metamorphic rocks, which tend to have lower porosity and permeability, limiting water storage and flow. As a result, these regions may indicate less favorable conditions for groundwater potential.

Low magnetic anomalies, shown as blue regions with values ranging from 35022.870 nT to 35298.28 nT, are located in the South part of area. These areas likely contain rocks that have undergone weathering or fracturing, which can enhance their porosity and permeability, making them more conducive to water storage. These zones more favorable for water accumulation, particularly in fractured and weathered rock formations associated with quartz, calcite, or graphite-rich compositions.

Intermediate magnetic anomalies, represented by green regions with values ranging from 35318.96 nT to 35489.51 nT in the part of West, Center, North, South and East, indicate regions where

rocks may be mixed with other geological materials, influencing water storage and flow in varying ways. Rocks with moderate amounts of magnetic minerals like biotite, muscovite, or minor magnetite. Transitional between high and low anomalies.

4.1.2.2 Residual Magnetic Field

Extract local geological anomalies by removing regional trends. Enhance detection of shallow subsurface features. The Residual Magnetic Field map of the Ganja catchment area revealed several localized magnetic anomalies, indicating the presence of shallow fractured and weathered basement zones. These anomalies, extracted from the regional background and highlighted through advanced processing techniques, suggest potential groundwater-bearing structures. The most prominent residual area correspond to known fault lines and align with zones of increased groundwater yield verified by previous subsurface investigations, confirming their relevance for targeted groundwater exploration. Figure (23) illustrates the Residual Magnetic Map, enhancing shallow magnetic features by removing regional trends

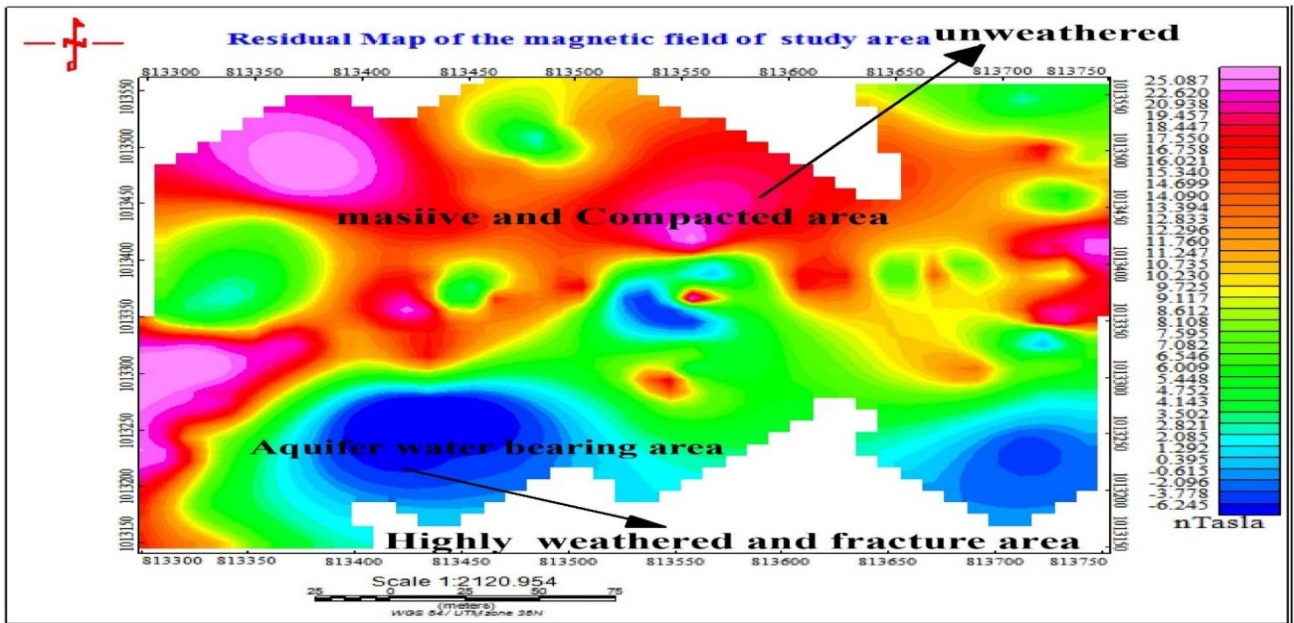


Figure 22 Residual Map of the study area

The residual magnetic map of the study area reveals clear hydrogeological patterns. Low magnetic anomalies (-6.245 nT to 2.821 nT), mostly in the southern part of area, indicate weathered and fractured bedrock, ideal for groundwater storage due to higher porosity and permeability. In contrast, high magnetic anomalies (9.725 nT to 25.087 nT), found in the eastern, central, northern,

and western area, suggest massive, compacted rocks (gneiss, amphibolite) with low groundwater potential. Transitional zones (3.502 nT to 9.117 nT), mainly in the central-eastern part, reflect mixed lithology or structural influence and offer moderate potential. The northeast-southwest trending fractures align with magnetic trends, guiding groundwater flow and storage.

4.1.2.3 Analytic signal Magnetic Field

Analytic signal mapping is a geophysical technique that interprets magnetic data to reveal subsurface geological structures without needing information on magnetization direction.

It combines gradients of the magnetic field in three directions, producing a positive signal that peaks over magnetic sources. This method simplifies magnetic anomaly interpretation by focusing on shape and location rather than magnetic properties, making it ideal for complex geological settings. It effectively identifies faults, fractures, and intrusions, encouraging groundwater assessment.

By focusing on rapid magnetic changes, it improves the accuracy of subsurface mapping, especially for groundwater potential and recharge zones. Figure (24) presents the Analytic Signal Map, which delineates edges and boundaries of magnetic source bodies.

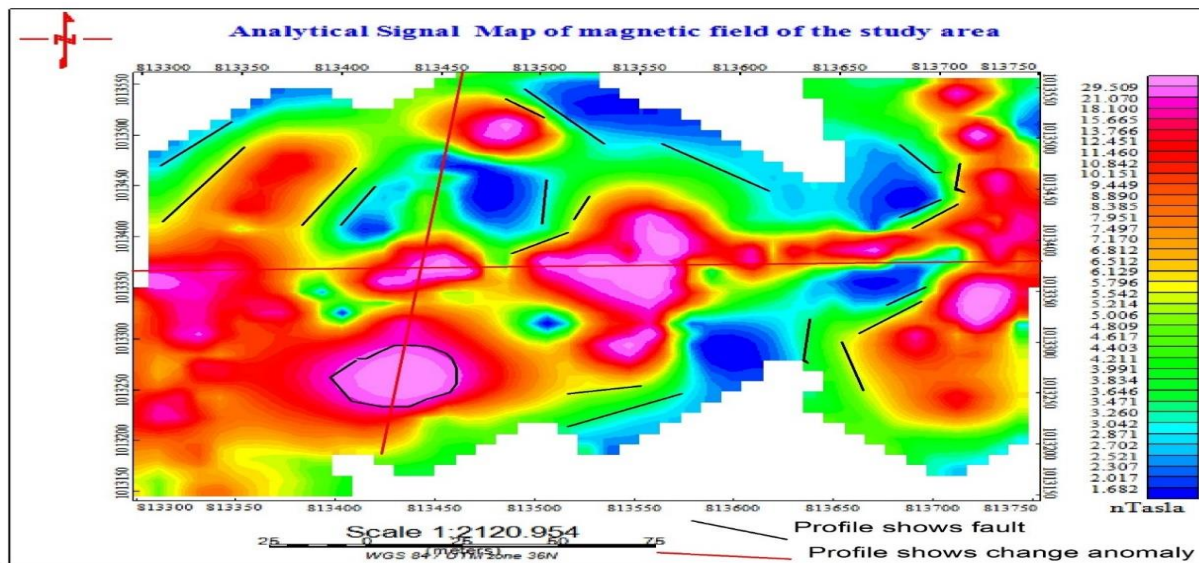


Figure 23 Analytic signal Map of the study area

High Analytical Signal Anomalies (Pink to Red Regions) these indicate strongly magnetized bodies and are associated with iron-rich rocks such as magnetite-bearing schist, amphibolite, or

gneiss. The largest high anomaly in the south western part correspond to a massive, compacted rock unit or an intrusive body. Some high-intensity zones align with mapped faults, suggesting localized mineralization or hydrothermal alteration along structural features.

Low Analytical Signal Anomalies (Blue to Green Regions) these represent less magnetic or demagnetized zones, possibly due to weathering, hydrothermal alteration, or highly fractured rocks. The low-anomaly zones along faults suggest that these areas have undergone significant deformation, leading to magnetic mineral destruction or dilution. The presence of groundwater-bearing weathered zones (as inferred from previous residual magnetic maps) might contribute to the reduction in magnetic intensity.

Structural Features (Faults and Contact Zones) the black lines indicate faults, which act as conduits for fluid flow, rock alteration, and mineralization. The red profiles mark change anomalies, suggesting a transition between different lithological units or altered zones. The cross-cutting structures in the central part of the map suggest complex tectonic deformation, possibly related to shear zones or deep-seated faulting.

4.1.2.4 Tilt Derivative Magnetic Field

The tilt derivative of the magnetic field plays a crucial role in groundwater potential assessment, particularly in identifying subsurface structures that influence water flow and storage. This technique enhances the edges of magnetic anomalies, making it easier to delineate geological features such as faults, fractures, and lithological boundaries, which often serve as conduits or barriers for groundwater movement. By calculating the arctangent of the ratio between the vertical derivative and the total horizontal derivative, the tilt derivative highlights both shallow and deep structures while minimizing the effects of amplitude variations. In groundwater studies, this method is used to map structural lineaments, which can indicate zones of increased permeability and potential aquifer locations. When combined with electrical resistivity surveys and hydrogeological data, tilt derivative analysis provides a more comprehensive understanding of subsurface conditions, helping researchers identify optimal drilling sites and assess groundwater sustainability. Studies have shown that integrating tilt derivative maps with other geophysical techniques improves the accuracy of groundwater exploration, particularly in regions with complex geological settings. Figure (25) depicts the Tilt-Derivative Map, enhancing structural edges and shallow magnetic source locations

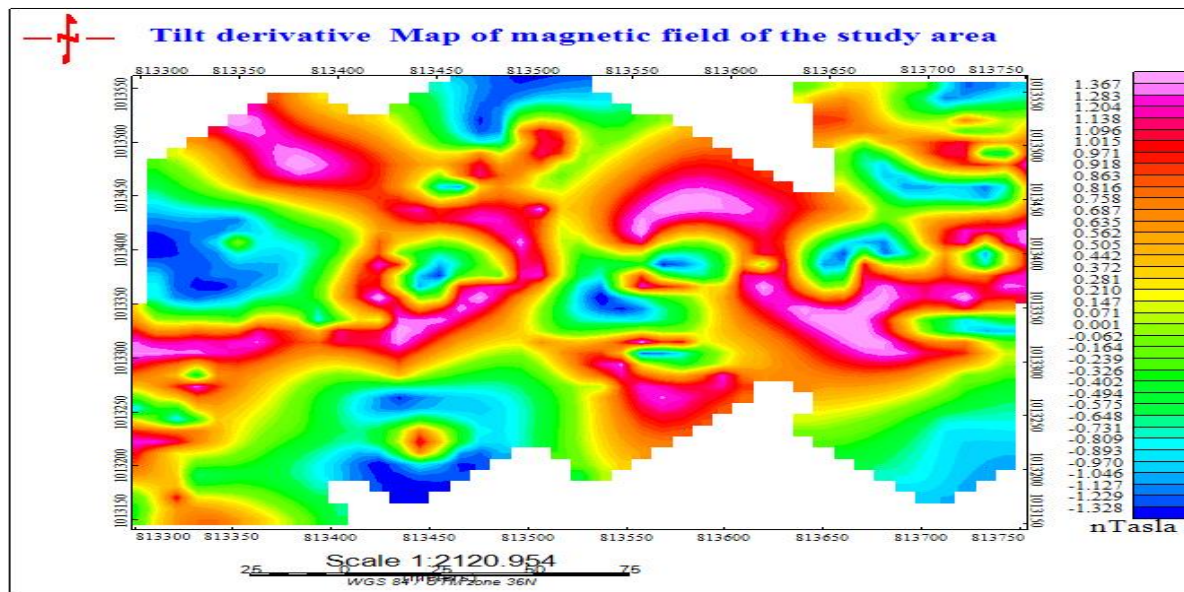


Figure 24 Tilt-Derivative Map of the study area

Low Magnetic Anomaly (Blue zones from -1.328 nT to -0.809 nT): These areas, likely composed of highly weathered rocks, are concentrated in the west, central and southeastern sections of the map. They represent fractured zones and fault-controlled aquifers, making them favorable locations for groundwater storage and movement.

Medium Magnetic Anomaly (Green zones from -0.731 nT to 0.147 nT): Found mostly along transitional boundaries between blue and red zones, these areas consist of moderately weathered rocks. They indicate potential fault zones and partially saturated aquifers, improving secondary porosity and groundwater storage.

High Magnetic Anomaly (Red zones from 0.210 nT to 1.367 nT): Concentrated in the northwestern and southwestern parts of the map, these zones correspond to unaltered metamorphic or igneous rocks rich in magnetite and pyrrhotite. While generally low in permeability, faults intersecting these zones may allow limited groundwater accumulation along fracture networks..

4.1.2.5 Vertical Derivative Magnetic Field

Vertical derivatives are powerful tools in geophysics, bringing clarity to the hidden structures beneath the Earth's surface. Uses for Enhancing weak anomaly. They sharpen our ability to detect geological features by analyzing how the geophysical field changes with depth (Mussett & Khan, 2000).

Surface Vertical Derivative: This map paints the big picture, capturing large-scale geological formations like basement rocks and regional faults. Broad, smooth anomalies here indicate deep-seated structures that shape the overall framework of an area. First Vertical Derivative: If the surface map gives the overview, the first derivative zooms in. Shallow sources (filters out much of the deep regional field). It enhances edges and transitions between rock units, making faults, shear zones, and lithological contacts stand out. This level of detail helps pinpoint structures that are neither too deep nor too shallow. Second Vertical Derivative: The second derivative highlights the smallest-scale features right near the surface fractures, dikes, joints, and fine structural details. Very shallow, ultra-near-surface sources (further short-wavelength enhancement), 2VD is more sensitive to noise and data errors. Each derivative plays a role, building a layered understanding of the subsurface. Together, they provide a comprehensive geological picture, from deep regional trends to shallow, intricate details. This method is invaluable for resource exploration, geotechnical work, and structural geology studies.

A well-rounded approach like this ensures no detail gets overlooked. Figure (26) presents the Vertical Derivative Map, emphasizing high-frequency magnetic anomalies from near-surface features.

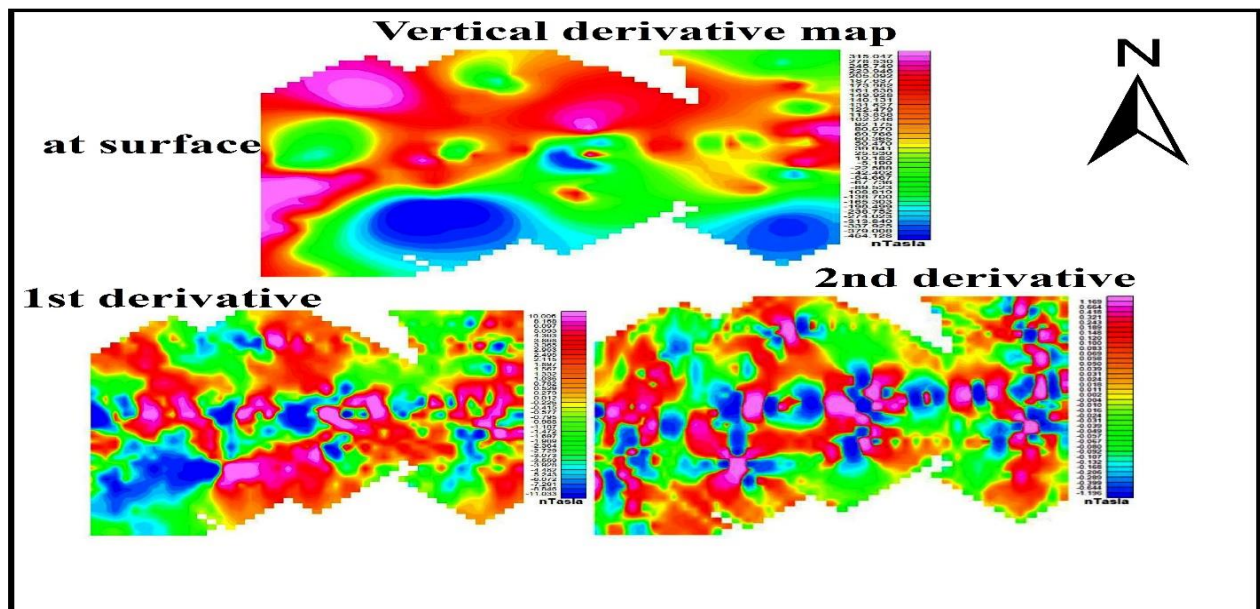


Figure 25 Vertical Derivatives Map of the study area

4.1.3.6 Upward Continuation Magnetic Field

Upward continuation is a powerful technique in geophysical surveys, particularly for magnetic studies, as it projects measured data to higher elevations, smoothing high-frequency noise while highlighting deeper structures. Higher elevation filters out shallow features, enhancing deeper regional patterns. If an anomaly is at 50 meters depth and data is continued upward to 100 meters, the shallow feature's signal weakens, making it less visible. $\text{Depth (d)} = 0.5 \times \text{Upward Continuation Height (h)}$ (Ruff et al., 2021). This method helps distinguish overlapping anomalies, allowing geoscientists to focus on shallow or deep-seated structures based on their study's goals. While lower continuation heights preserve near-surface details like mineral deposits, higher levels enhance deep basement features and large geological structures. Imagine standing on the ground, looking at a detailed landscape filled with hills, valleys, and scattered rocks. Everything is sharp and clear, allowing you to see even the smallest details. This is similar to a surface-level upward continuation map; it provides the highest resolution, capturing both deep and shallow sources, including fine-scale geological features like mineral deposits or localized intrusions.

Now, slowly rising in a hot air balloon. As ascend to 50 meters, the view starts to smooth out some of the smallest details unclear, but broader features like fault lines and rock contacts become easier to identify. This is how upward continuation helps highlight intermediate-depth structures by suppressing shallow noise. At 100 meters, individual trees disappear from view, but large geological formations like igneous bodies and basement structures start to stand out. The noisy surface variations fade, allowing us to see the broader subsurface framework more clearly. By the time reach 150 meters or 200 meters, only the most dominant features remain visible—massive tectonic boundaries, basin structures, and deep-seated geological formations. These maps now reflect crustal-scale anomalies, offering insights into major regional trends rather than small, localized variations. This progressive filtering is like adjusting focus when looking at a layered painting—it allows geoscientists to separate overlapping anomalies, distinguish between shallow and deep structures, and prioritize targets based on their persistence across different depths. Figure (27) shows the Upward Continuation Map, suppressing shallow effects to focus on deeper magnetic sources.

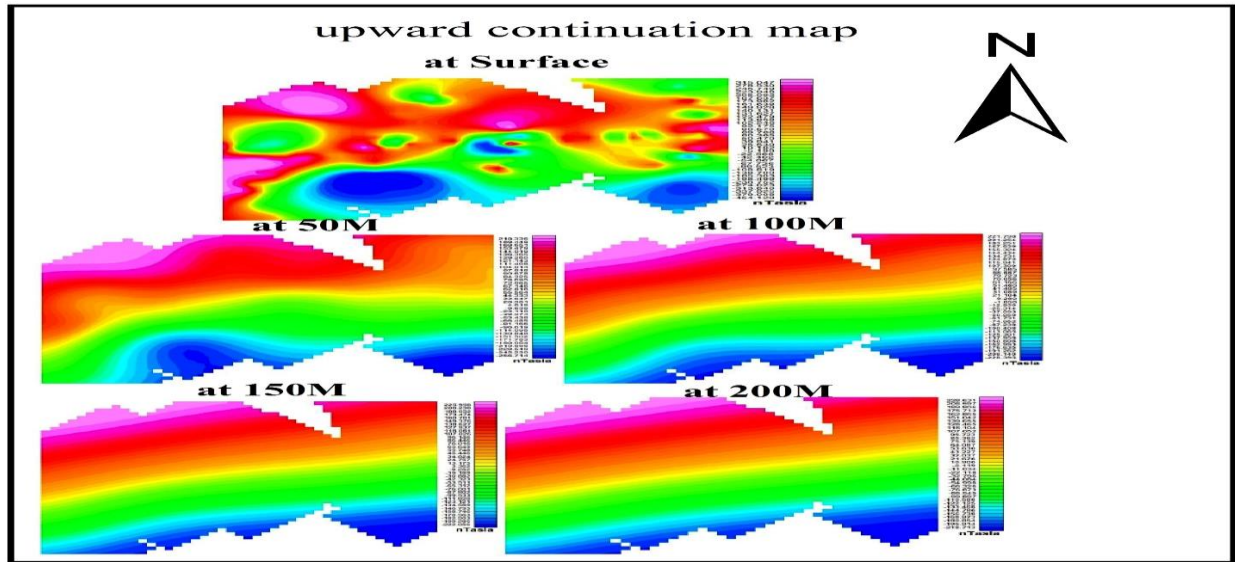


Figure 26 Up-ward Continuation Map of the study area

4.1.3.7 Euler deconvolutions Magnetic Field

Euler deconvolution is efficient and automated but requires careful data processing and selection of the appropriate structural index. It is often used alongside other methods, like Electrical Resistivity Tomography, for more accurate groundwater mapping, especially in complex geological settings. Euler's homogeneity equation is expressed as:

$N \cdot B = (x - x_0) \frac{\partial F}{\partial x} + (y - y_0) \frac{\partial F}{\partial y} + (z - z_0) \frac{\partial F}{\partial z}$. Where:-

- (X_0, y_0, z_0) represents the position coordinates of the magnetic source.
- F :- the magnetic field at a specific point (x, y, z)
- $\frac{\partial F}{\partial x}$, $\frac{\partial F}{\partial y}$, and $\frac{\partial F}{\partial z}$ are the partial derivatives of the field with respect to x , y , and z , indicating how the field changes in space respectively.
- N :- the structural index, which characterizes the type of source geometry (point, line, or plane) responsible for the anomaly.
- B :- the regional field (background level of the field) which may be zero if the regional trend is removed from the data..

From the map as depth increases, depth 13-22 m shallow aquifers, typically suitable for hand-dug wells or small-scale extraction. Depth 22 - 32 m moderate-depth aquifers, often with good yield potential for domestic and agricultural use. Depth 32 - 44 m deeper aquifers, likely confined or

semi-confined, requiring boreholes. Depth 44 - 60 m high-yield aquifers, possibly in fractured bedrock or sedimentary basins. Depth 60 - 89 m deep aquifers, usually confined and under artesian pressure. High Potential Zones between 32-44 and 60 - 89 m these depths often correspond to productive aquifers in sedimentary or fractured rock systems. The 60 - 89 m range is particularly promising because it balances depth (reducing contamination risk) and yield (sufficient recharge). Moderate Potential Zones 32- 44 m are accessible but may be susceptible to seasonal fluctuations. Figure (28) illustrates the Euler Deconvolution results, identifying the depth and location of magnetic sources and faults

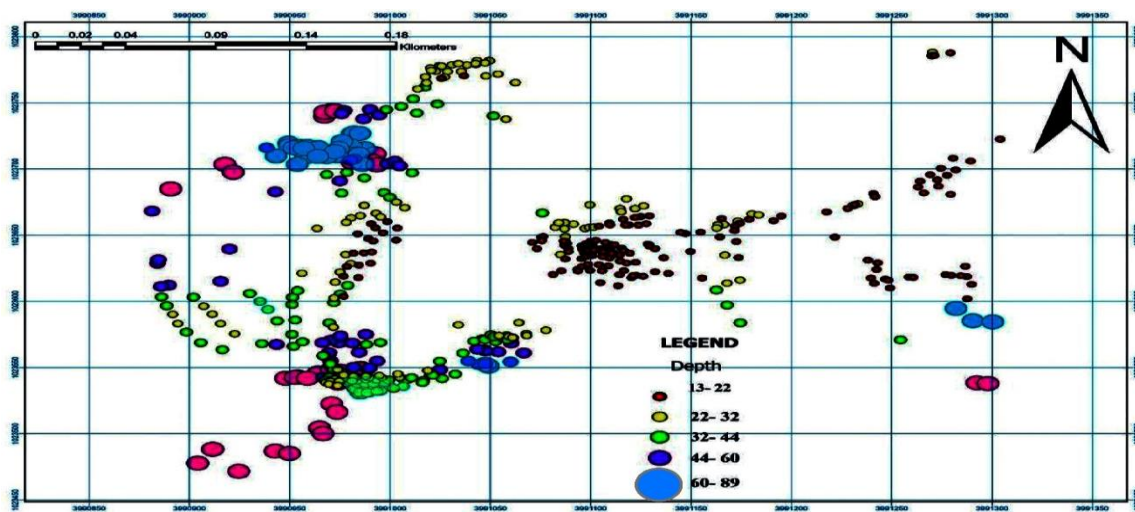


Figure 27 Euler deconvolutions with $SI = 0$: (Indicates a contact or fault).

4.2 Discussion

4.2.1 Integrated ERT and Magnetic Data Interpretation

The comprehensive integration of Electrical Resistivity Tomography and magnetic survey data strongly indicates that the southern and northeastern regions of the study area present the highest potential for groundwater development. The residual magnetic anomaly map reveals that low magnetic values -6.245 to 2.821 nT, predominantly in the southern sector, correspond to weathered and fractured bedrock—conditions highly favorable for groundwater accumulation due to enhanced porosity and permeability. Conversely, elevated magnetic anomalies 9.725 to 25.087 nT, observed in the central, northern, eastern, and western zones, are attributed to compact, magnetically active formations such as gneiss and amphibolite, which exhibit limited groundwater

potential. Complementary ERT analysis identifies low-resistivity zones 38.8–90.6 Ωm , particularly in the eastern and central portions, as weathered, fractured aquifers with high transmissivity. Moderately resistive formations 138–323 Ωm represent partially weathered rocks with intermediate groundwater potential, while high-resistivity zones 493–754 Ωm , associated with unfractured, exhibit minimal potential for water storage.

The inverse resistivity models, derived from five ERT profiles, delineate vertical stratification and lithological boundaries, correlating effectively with the magnetic data. The magnetic interpretation utilized transformation-based techniques to evaluate anomaly source characteristics, revealing that transitional zones marked by moderate anomalies may represent geological interfaces or fault zones, offering secondary potential for groundwater. Overall, the synthesis of ERT and magnetic results confirms that low-resistivity and low magnetic anomaly zones, typically composed of highly weathered and fractured metamorphic rocks such as schist or gneiss, are the most favorable targets for groundwater exploration and well development, while compact and magnetically intense formations represent the least favorable zones.

CHAPTER FIVE

Conclusions and Recommendations

5.1 Conclusions

The groundwater potential assessment of the Ganja Catchment in the West Wallaga Zone, particularly the Gimbi area, was carried out using an integrated geophysical approach combining Electrical Resistivity Tomography and magnetic methods. The study employed with the ERT survey, which systematically identified several low-resistivity zones at varying depths. The study area indicated the presence of water-saturated formations, suggesting the existence of potential aquifers with relatively high permeability and groundwater storage capacity. Most of these zones were associated with fractured or weathered bedrock, enhancing their capability to transmit groundwater.

The magnetic investigation also conducted to further explore the subsurface geological structures. The analysis of regional and residual magnetic anomalies revealed the presence of significant structural features such as faults and fractures, which play a crucial role in groundwater movement and accumulation. Areas of low magnetic intensity were found to correspond with the previously identified low-resistivity zones, implying a strong correlation between structural geology and groundwater potential.

Subsequently, the integration of ERT and magnetic data enabled a comprehensive interpretation of the subsurface environment. This integrated approach provided a strong framework for delineating groundwater-rich zones and understanding the complex hydrogeological system of the study area. Specifically, ERT Profiles One to Five consistently demonstrated alignment between low resistivity zones and magnetic anomalies, further validating the presence of structurally controlled aquifers.

The spatial analysis of magnetic anomalies across the study area revealed geological variability. The Northern and Central regions, characterized by high magnetic values, are likely underlain by dense rock formations or structural discontinuities that may restrict groundwater flow. In contrast, the Southern regions, with lower magnetic anomalies, are associated with more porous and permeable geological materials, suggesting higher potential for groundwater accumulation.

In conclusion, this ground water potential assessment demonstrated that the combined use of ERT and magnetic methods provides reliable and complementary information for identifying groundwater potential zones. The study successfully pinpointed several areas with high groundwater potential, at depth of 60m to 90m particularly where aquifers coincide with structural features like faults and fractures. These findings are consistent with earlier research and contribute valuable insights for the sustainable potential of groundwater resources in the Ganja Catchment area.

5.2 Recommendations

Given the increasing water demand and the inadequate surface water supply in the Ganja Catchment area, it is strongly recommended that local authorities and water resource planners prioritize the development of groundwater resources, particularly in the southern and northeastern regions identified as high-potential zones through geophysical surveys. The study highlights the effectiveness of integrated Electrical Resistivity Tomography (ERT) and magnetic methods in locating productive aquifers, and thus, future groundwater exploration and well-drilling activities should adopt similar integrated approaches for more accurate and cost-effective site selection. Additionally, sustainable groundwater management practices including controlled abstraction, community awareness programs, and periodic monitoring should be implemented to ensure long-term water security and support the socio-economic development of the Gimbi area.

To ensure the reliability of the study results, it is advisable to conduct Vertical Electrical sound along the same profiles used for the ERT and magnetic surveys. This will enhance depth resolution and provide a more detailed understanding of the subsurface geology and groundwater potential zones. To address the limitations of resolution and depth of investigation in geophysical techniques, it is recommended to conduct further validation through drilling and well logging. This will help confirm the geophysical findings and provide more precise data on the aquifers' characteristics, ensuring a more accurate subsurface assessment. Additionally, integrating three Dimension (3D) modeling of ERT and magnetic data will help define the geometric relationships between lithological units concerning depth, shape, resistivity, and magnetic properties. Developing a comprehensive geophysical model from these datasets will serve as a crucial guide for geologists, complementing their geological models in exploratory drilling programs. This integrated approach will enhance confidence in drill target selection, improving the success rate of

groundwater exploration. Moreover, incorporating joint inversion techniques for ERT and magnetic data can further refine subsurface interpretations by reducing ambiguity and increasing accuracy in identifying geological structures. It is also recommended to estimate fracture-zone permeability influenced by geological structures using a combination of geophysical methods. This will aid in optimizing regions with high groundwater potential and ensuring the long-term sustainability of aquifers within the study area. Additionally, comparing ERT resistivity anomalies with corresponding magnetic variations will help distinguish between water-filled fractures and compact lithologies, thereby improving the efficiency of groundwater exploration and resource management.

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APPENDIX

Magnetic Data:

The Table-2 below presents magnetic data processed and corrected using Oasis Montaj to map residual, regional, and total magnetic anomalies for subsurface analysis.

Table 2 Magnetic data mapped subsurface anomalies.

Easting	Northing	CTMI	Longitudes	Latitudes	Regional	Residual	IGRF	Inclination	Declination	Distance
813342	1013369	35192	35.8509	9.156258	35278.42	-136.982	35286.57	0.799841	1.794079	0
813376	1013475	35753.5	35.85122	9.157214	35288.36	414.7305	35286.84	0.802353	1.794161	111.3194
813363	1013460	35651.2	35.8511	9.157079	35298.2	302.1704	35286.8	0.801975	1.794152	131.1688
813360	1013444	35462.9	35.85107	9.156935	35307.91	104.331	35286.76	0.801601	1.794139	147.4476
813353	1013425	35296.6	35.85101	9.156763	35317.51	-71.8921	35286.71	0.801148	1.794125	167.6961
813349	1013414	35350.3	35.85097	9.156664	35326.97	-27.076	35286.68	0.800886	1.794117	179.4008
813343	1013395	35260	35.85091	9.156493	35336.3	-125.667	35286.63	0.800436	1.794102	199.3256
813335	1013381	35254.8	35.85084	9.156367	35345.49	-138.075	35286.59	0.800095	1.794093	215.4501
813331	1013367	35218.5	35.8508	9.156241	35354.53	-181.834	35286.56	0.799764	1.794082	230.0104
813326	1013347	35306.2	35.85076	9.156061	35363.43	-101.166	35286.51	0.799294	1.794066	250.6259
813325	1013330	35565.6	35.85074	9.155907	35372.16	151.7178	35286.46	0.798904	1.794051	267.6553
813325	1013329	35791.3	35.85074	9.155898	35380.74	372.0416	35286.46	0.798881	1.79405	268.6553
813326	1013303	35892.4	35.85075	9.155663	35389.16	466.5089	35286.4	0.798291	1.794026	294.6745
813329	1013288	35652.1	35.85078	9.155528	35397.41	220.3676	35286.37	0.797958	1.794011	309.9716
813333	1013272	35736.8	35.85081	9.155383	35405.49	299.5627	35286.33	0.797604	1.793995	326.464
813329	1013258	35590.5	35.85078	9.155257	35413.4	148.3886	35286.3	0.797274	1.793984	341.0242
813321	1013242	35494.9	35.8507	9.155113	35421.13	47.34359	35286.25	0.796887	1.793973	358.9127
813314	1013229	35783.6	35.85064	9.154996	35428.69	331.2486	35286.22	0.796571	1.793964	373.6776
813322	1013216	35553	35.85071	9.154878	35436.08	95.93096	35286.19	0.796297	1.793949	388.9419
813321	1013196	35507.4	35.8507	9.154697	35443.29	45.89461	35286.14	0.795838	1.793932	408.9669
813328	1013188	35401.8	35.85076	9.154624	35450.32	-63.4707	35286.13	0.795676	1.793922	419.597
813334	1013165	35473.6	35.85081	9.154416	35457.17	4.855257	35286.08	0.795168	1.793899	443.3668
813335	1013149	35568.8	35.85082	9.154271	35463.84	96.32044	35286.04	0.794806	1.793884	459.398
813443	1013237	34986.9	35.85181	9.155059	35470.34	-489.029	35286.31	0.797118	1.79392	598.7106
813433	1013263	34153.4	35.85172	9.155294	35476.66	-1325.95	35286.37	0.797682	1.793947	626.5674
813433	1013282	35178.1	35.85172	9.155466	35482.8	-303.643	35286.41	0.798115	1.793964	645.5674
813432	1013312	35667.9	35.85172	9.155737	35488.77	183.5288	35286.49	0.798796	1.793992	675.584
813426	1013321	35646.6	35.85166	9.155819	35494.57	160.2493	35286.5	0.798984	1.794002	686.4007
813424	1013342	35641.3	35.85165	9.156009	35500.19	153.2304	35286.55	0.799457	1.794022	707.4957
813433	1013358	35703	35.85173	9.156152	35505.65	212.3328	35286.6	0.799847	1.794033	725.8533
813434	1013385	35642.9	35.85174	9.156396	35510.94	149.8982	35286.66	0.800466	1.794057	752.8718
813435	1013397	35558	35.85175	9.156505	35516.07	62.65215	35286.69	0.800742	1.794067	764.9134

813438	1013413	35626.4	35.85178	9.156649	35521.03	128.5838	35286.73	0.801115	1.79408	781.1922
813444	1013426	35673.1	35.85183	9.156766	35525.83	173.6598	35286.76	0.801429	1.794089	795.51
813446	1013440	35689.2	35.85185	9.156892	35530.48	187.3359	35286.8	0.801753	1.794101	809.6521
813457	1013457	35606.3	35.85195	9.157045	35534.97	102.3004	35286.85	0.802172	1.794112	829.9006
813469	1013473	35631.7	35.85206	9.157189	35539.31	125.3452	35286.89	0.802571	1.794122	849.9006
813468	1013487	35596.1	35.85206	9.157315	35543.5	86.99399	35286.92	0.802887	1.794135	863.9363
813473	1013495	35636.8	35.8521	9.157387	35547.55	124.8852	35286.95	0.803083	1.79414	873.3703
813478	1013503	35292.5	35.85215	9.157459	35551.45	-222.708	35286.97	0.80328	1.794145	882.8042
813486	1013511	35301	35.85222	9.157531	35555.22	-216.922	35286.99	0.803485	1.794149	894.1179
813491	1013515	35586.7	35.85227	9.157567	35558.85	67.00452	35287	0.80359	1.794151	900.5211
813450	1013373	35192	35.85188	9.156287	35562.35	-329.526	35286.64	0.800237	1.794039	1048.322
813450	1013373	35223	35.85188	9.156287	35565.71	-301.388	35286.64	0.800237	1.794039	1048.322
813570	1013447	35770.7	35.85298	9.156947	35568.95	244.1569	35286.89	0.802263	1.794058	1189.304
813566	1013432	35776.6	35.85294	9.156811	35572.06	247.5618	35286.85	0.80191	1.794046	1204.828
813556	1013414	35895.5	35.85285	9.15665	35575.05	364.3989	35286.8	0.801472	1.794034	1225.419
813562	1013393	35090.3	35.8529	9.156459	35577.93	-444.26	35286.76	0.80101	1.794012	1247.26
813556	1013368	35921.8	35.85285	9.156234	35580.68	384.6786	35286.69	0.800423	1.793992	1272.97
813555	1013353	35049.6	35.85284	9.156099	35583.32	-489.903	35286.66	0.800078	1.793979	1288.003
813559	1013339	35234.5	35.85287	9.155972	35585.85	-308.721	35286.63	0.79977	1.793965	1302.563
813554	1013321	35625.3	35.85283	9.15581	35588.27	79.06371	35286.58	0.799346	1.793951	1321.245
813556	1013307	35371.8	35.85284	9.155683	35590.57	-177.271	35286.55	0.799033	1.793938	1335.387
813543	1013293	35819.2	35.85272	9.155557	35592.77	267.1319	35286.51	0.798677	1.79393	1354.492
813530	1013280	35470.6	35.8526	9.155441	35594.87	-84.6497	35286.47	0.798344	1.793924	1372.877
813534	1013262	35467.4	35.85264	9.155278	35596.86	-91.1009	35286.43	0.797945	1.793906	1391.316
813711	1013241	35135.1	35.85425	9.155076	35598.75	-427.321	35286.48	0.797966	1.793816	1569.557
813720	1013283	35369.8	35.85433	9.155454	35600.53	-195.705	35286.59	0.798949	1.79385	1612.51
813721	1013303	35539.3	35.85434	9.155635	35602.22	-29.7431	35286.64	0.799408	1.793868	1632.535
813723	1013316	35610.1	35.85436	9.155752	35603.8	37.53816	35286.67	0.79971	1.793879	1645.688
813721	1013333	35061.6	35.85434	9.155906	35605.29	-514.161	35286.71	0.800092	1.793895	1662.806
813724	1013348	35949	35.85437	9.156041	35606.67	370.617	35286.74	0.800442	1.793907	1678.103
813727	1013366	35751.4	35.8544	9.156204	35607.96	170.97	35286.79	0.800861	1.793922	1696.351
813732	1013380	35747.9	35.85445	9.15633	35609.15	164.8749	35286.83	0.801194	1.793933	1711.217
813729	1013394	35509.7	35.85442	9.156457	35610.23	-76.1398	35286.86	0.801505	1.793947	1725.535
813738	1013405	35892.2	35.8545	9.156555	35611.22	303.387	35286.89	0.801781	1.793953	1739.748
813735	1013413	35797	35.85448	9.156628	35612.11	205.4456	35286.91	0.801955	1.793961	1748.292
813734	1013432	35815.9	35.85447	9.156799	35612.89	222.2301	35286.95	0.802385	1.793979	1767.318
813732	1013440	35695.3	35.85445	9.156872	35613.58	99.36933	35286.97	0.802562	1.793987	1775.564
813730	1013453	35508.7	35.85444	9.156989	35614.17	-89.7143	35287	0.802852	1.793999	1788.717
813729	1013464	35500	35.85443	9.157089	35614.65	-100.64	35287.02	0.8031	1.794009	1799.762
813734	1013476	35751.9	35.85447	9.157197	35615.03	149.4485	35287.06	0.803388	1.794018	1812.762
813734	1013491	35588.3	35.85447	9.157332	35615.3	-15.7227	35287.09	0.80373	1.794032	1827.762

813719	1013502	35846.8	35.85434	9.157433	35615.47	240.6159	35287.11	0.803938	1.794048	1846.363
813719	1013515	35559.6	35.85434	9.15755	35615.54	-50.2176	35287.14	0.804235	1.794059	1859.363
813716	1013525	35638.1	35.85431	9.157641	35615.5	26.91445	35287.16	0.804454	1.79407	1869.804
813709	1013543	35404.5	35.85425	9.157804	35615.35	-207.022	35287.2	0.804844	1.794089	1889.117
813697	1013559	35568.9	35.85414	9.157949	35615.09	-42.9722	35287.23	0.805175	1.794108	1909.117
813742	1013419	35931.1	35.85454	9.156681	35614.72	319.037	35286.92	0.802111	1.793964	2056.171
813718	1013410	35870.5	35.85432	9.156602	35614.25	259.0763	35286.89	0.801838	1.793965	2081.803
813706	1013406	35780.9	35.85421	9.156567	35613.66	169.7125	35286.87	0.801713	1.793967	2094.452
813689	1013303	35755.4	35.85405	9.155637	35612.96	144.6425	35286.62	0.799317	1.793881	2198.846
813681	1013396	35522.8	35.85399	9.156478	35612.15	-87.2949	35286.83	0.801415	1.793968	2292.189
813669	1013392	35826.8	35.85388	9.156443	35611.22	217.9765	35286.82	0.80129	1.793969	2304.839
813655	1013391	35480.2	35.85375	9.156435	35610.18	-126.914	35286.81	0.801227	1.793973	2318.874
813647	1013386	35569.7	35.85368	9.15639	35609.03	-35.8779	35286.79	0.801091	1.793972	2328.308
813629	1013386	35786.1	35.85351	9.156391	35607.77	182.4036	35286.78	0.80104	1.793979	2346.308
813617	1013384	35744.5	35.8534	9.156374	35606.39	143.0973	35286.77	0.80096	1.793982	2358.474
813606	1013383	35836.9	35.8533	9.156366	35604.89	238.2719	35286.76	0.800906	1.793986	2369.519
813593	1013379	35573.4	35.85318	9.156331	35603.29	-22.8817	35286.74	0.800778	1.793987	2383.121
813544	1013358	35163.7	35.85274	9.156145	35601.57	-430.011	35286.66	0.800161	1.793988	2436.431
813530	1013371	35086.1	35.85261	9.156263	35599.74	-504.38	35286.68	0.800418	1.794006	2455.536
813505	1013375	35798.5	35.85238	9.156301	35597.8	211.047	35286.68	0.800438	1.794019	2480.854
813480	1013377	35659	35.85216	9.156321	35595.75	74.63289	35286.67	0.800413	1.794031	2505.934
813461	1013368	35743.4	35.85198	9.156241	35593.59	163.3282	35286.64	0.800155	1.79403	2526.958
813443	1013366	35447.8	35.85182	9.156224	35591.33	-127.703	35286.62	0.800058	1.794036	2545.068
813426	1013357	35927.3	35.85166	9.156144	35588.95	356.631	35286.59	0.799805	1.794035	2564.304
813414	1013344	35735.7	35.85155	9.156027	35586.48	168.5771	35286.55	0.799475	1.794028	2581.996
813395	1013334	35618.1	35.85138	9.155938	35583.9	56.10504	35286.52	0.799193	1.794026	2603.466
813384	1013328	35713.6	35.85128	9.155885	35581.23	155.2065	35286.49	0.799025	1.794025	2615.996
813365	1013330	35855	35.85111	9.155904	35578.45	300.9002	35286.49	0.799017	1.794035	2635.101
813349	1013337	35616	35.85096	9.155969	35575.59	67.00991	35286.5	0.799131	1.794047	2652.566
813327	1013345	35479.4	35.85076	9.156043	35572.63	-65.0051	35286.5	0.799251	1.794063	2675.975
813316	1013356	35379.8	35.85066	9.156143	35569.58	-158.898	35286.52	0.799471	1.794078	2691.531
813305	1013359	35444.3	35.85057	9.156171	35566.45	-89.2445	35286.52	0.799508	1.794085	2702.933
813301	1013361	35690.7	35.85053	9.156189	35563.24	162.5738	35286.52	0.799543	1.794088	2707.405
813341	1013370	35223	35.85089	9.156267	35559.95	-300.267	35286.57	0.799861	1.79408	2748.405