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Hydrogeophysical Characterization of Volcanic Aquifers Using Integrated Resistivity and Induced Polarization in Mount Tumpa, Manado

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ABSTRACT

This study investigates the aquifer system in the Mount Tumpa area, North Sulawesi, Indonesia, using integrated electrical resistivity and induced polarization (IP) methods. Data were acquired with a dipole–dipole array, enabling high lateral resolution of subsurface heterogeneity. Resistivity inversion was used to delineate aquifer geometry, while IP data were analyzed to identify zones of enhanced electrochemical polarization related to lithological and mineralogical variations. Aquifer zones are characterized by low resistivity values (< 9.17 Ωm). On Line 1, an aquifer is identified at 100–130 m and depths of 15–25 m; on Line 2, at 215–230 m and depths of 10–20 m. On Line 3, three distinct aquifer units are resolved: (1) 150–175 m at depths ≥ 75 m, (2) 220–235 m at 30–40 m, and (3) 285–305 m at 35–45 m. These findings indicate a multi-layered groundwater system with variable depth distribution. Chargeability responses are high on Lines 1 and 3 and moderate on Line 2, suggesting the presence of polarizable materials such as volcanic clay, iron oxides, and organic-rich layers. These materials may influence groundwater geochemical behavior through adsorption and redox processes; however, IP responses do not directly indicate groundwater quality in the absence of hydrochemical data. The subsurface is interpreted as a layered volcanic aquifer system, where groundwater is primarily hosted in permeable lapilli and volcanic ash deposits overlying compact lava, with additional storage in fractured lava zones. The identified aquifers are interpreted as shallow to intermediate systems based on geophysical evidence, although further hydrogeological validation is required.

Keywords: aquifer characterization; chargeability; induced polarization; Mount Tumpa; resistivity method

Karakterisasi Hidrogeofisika Akuifer Vulkanik Menggunakan Metode Resistivitas dan Polarisasi Terinduksi Terintegrasi Di Gunung Tumpa, Manado

ABSTRAK

Penelitian ini mengkaji sistem akuifer di wilayah Gunung Tumpa, Sulawesi Utara, menggunakan integrasi metode geolistrik resistivitas dan polarisasi terinduksi (IP). Akuisisi data dilakukan dengan konfigurasi elektroda dipole–dipole yang sensitif terhadap variasi lateral bawah permukaan. Data resistivitas digunakan untuk mendelineasi geometri akuifer, sedangkan data IP dimanfaatkan untuk mengidentifikasi zona dengan respons polarisasi elektrokimia yang berkaitan dengan variasi litologi dan mineralogi. Zona akuifer dicirikan oleh nilai resistivitas rendah (< 9,17 Ωm). Pada Lintasan 1, akuifer teridentifikasi pada jarak 100–130 m dengan kedalaman 15–25 m; pada Lintasan 2 pada jarak 215–230 m dengan kedalaman 10–20 m. Pada Lintasan 3, teridentifikasi tiga unit akuifer, yaitu: (1) jarak 150–175 m pada kedalaman ≥ 75 m, (2) jarak 220–235 m pada kedalaman 30–40 m, dan (3) jarak 285–305 m pada kedalaman 35–45 m. Hasil ini menunjukkan sistem airtanah berlapis dengan distribusi kedalaman yang bervariasi. Respons chargeability menunjukkan nilai tinggi pada Lintasan 1 dan 3 serta nilai sedang pada Lintasan 2, yang mengindikasikan keberadaan material terpolarisasi seperti lempung vulkanik, oksida besi, dan lapisan kaya bahan organik. Material ini berpotensi memengaruhi kondisi geokimia airtanah melalui proses adsorpsi dan reaksi redoks; namun demikian, data IP tidak secara langsung merepresentasikan kualitas airtanah tanpa dukungan analisis hidrogeokimia. Sistem bawah permukaan diinterpretasikan sebagai akuifer vulkanik berlapis, dengan zona penyimpanan utama berada pada endapan lapili dan abu vulkanik yang permeabel di atas batuan lava yang lebih kompak, serta potensi tambahan pada zona lava terfraktur. Berdasarkan data geofisika, akuifer yang teridentifikasi diklasifikasikan sebagai sistem airtanah dangkal hingga menengah, meskipun validasi hidrogeologi lebih lanjut masih diperlukan.

Kata kunci: metode resistivitas; polarisasi terinduksi; chargebilitas; Gunung Tumpa; karakteristik akuifer.

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INTRODUCTION

The Province of North Sulawesi is an archipelagic region located on the margin of the Pacific Ocean, within the subduction zone between the Pacific and Eurasian Plates. Geographically, the area consists of mountains, hills, highlands, lowlands, and coastal zones. This complex topographic setting results in diverse climatic conditions and uneven rainfall distribution across the region.

Rainfall is a key climatic element that plays an important role in sustaining water availability, particularly in rainfed and dryland areas (Herlina & Prasetyorini, 2020; Sunarmi *et al*., 2022). Groundwater availability is strongly influenced by factors such as rainfall intensity, vegetation type, geographic setting, lithological composition, and the level of water resource exploitation. In Manado and North Sulawesi, increasing population growth and urban expansion have led to rising water demand, with groundwater serving as a primary source for domestic and small-scale industrial use. Regional statistics indicate a continuous increase in water demand in urban areas, while piped water supply coverage remains limited, leading to higher dependence on groundwater extraction (KLHK, 2022; BPS, 2023). Unsustainable groundwater use can reduce both its quality and quantity, and may even lead to aquifer depletion due to the reduction of recharge zones (Bhalla *et al*., 2025; Cao *et al*., 2025; Jasechko *et al*., 2024).

According to Law of the Republic of Indonesia No. 24 of 2007 on Disaster Management, mitigation refers to a series of efforts aimed at reducing disaster risk through both structural (physical) and non-structural (capacity-building) approaches. In the context of groundwater resources, mitigation includes the protection of recharge areas and the sustainable management of groundwater extraction in accordance with aquifer capacity and environmental conditions.

The Mount Tumpa sub-region is part of the Wallacea conservation area, characterized by high biodiversity in both flora and fauna (Tallei & Nangoy, 2016). This area also includes the H. V. Worang Grand Forest Park (Tahura), which functions as critical green infrastructure for maintaining ecosystem balance, reducing urban heat, and sustaining groundwater reserves. To preserve these functions, a comprehensive understanding of aquifer characteristics, recharge zones, and subsurface layer connectivity is required.

Groundwater availability is uneven and typically separated based on local aquifer systems (Zuhdi *et al.,* 2023), which are further influenced by the geological conditions of the subsurface layers that affect groundwater chemistry (Saparun *et al*., 2022).

The geoelectrical resistivity method is widely used to delineate aquifer geometry and thickness based on variations in subsurface electrical properties. In contrast, the induced polarization (IP) method provides complementary information related to the electrochemical properties of subsurface materials, which are influenced by lithological characteristics such as clay content, grain size, and pore structure (Ammar *et al.*, 2023; Lebogo *et al*., 2025; McLachlan *et al.*, 2020). The volcanic rocks composing Mount Tumpa exhibit complex lithological characteristics distinct from lowland deposits, while topographic variations from flat to steep slopes further influence groundwater distribution (Irawan *et al*., 2022). However, previous hydrogeophysical studies in volcanic environments often rely solely on resistivity data, which may lead to ambiguities in distinguishing lithological variations and fluid-related properties. Pure groundwater typically exhibits chargeability values close to 0 ms (Telford *et al*., 2004). The rocks composing Mount Tumpa possess unique characteristics that differ from those of the lowland region. Topographic variations from flat to very steep slopes also influence the occurrence and distribution of groundwater (Irawan *et al*., 2022). However, to date, no study has specifically examined the characteristics and lithological thickness of aquifers in Mount Tumpa using a combined resistivity and induced polarization approach. In North Sulawesi, groundwater investigations have predominantly used resistivity methods alone, as reported by Antareza *et al*. (2021) and Vienastra *et al*. (2022), without integrating additional geophysical parameters. The integration of resistivity and IP methods therefore provides a more comprehensive approach to characterizing aquifer systems by combining electrical and electrochemical responses. Moreover, the volcanic geology and steep topography of the Mount Tumpa area have never been investigated hydrogeophysically using an integrated resistivity and induced polarization method. Therefore, this study provides added value by combining both geophysical techniques to obtain a more comprehensive understanding of aquifer characteristics and subsurface conditions in the Mount Tumpa region.

This study aims to delineate the geometry, thickness, and lithological control of volcanic aquifers in Mount Tumpa using an integrated resistivity and induced polarization approach.

RESEARCH METHOD

The study was conducted in the H. V. Worang Grand Forest Park (Tahura) of Mount Tumpa, Manado City, from July to October 2025. Data were acquired using geophysical exploration techniques, specifically the dipole–dipole resistivity configuration (Figure 1) and the induced polarization (IP) method.

The dipole–dipole array was selected due to its high sensitivity to lateral resistivity variations and its ability to resolve subsurface heterogeneity. This characteristic is particularly important in volcanic environments, where aquifer systems are often controlled by complex lithological variations, weathered zones, and fracture networks. Compared to other electrode configurations, the dipole–dipole array provides better horizontal resolution, making it suitable for delineating aquifer boundaries and identifying structural features.

Although the depth of investigation of the dipole–dipole array is relatively lower than that of some other configurations (e.g., Schlumberger), it remains effective for imaging shallow to intermediate subsurface structures, which are relevant for groundwater exploration in volcanic terrains. Therefore, this configuration is well suited for characterizing aquifer geometry and lithological variations in the Mount Tumpa area.

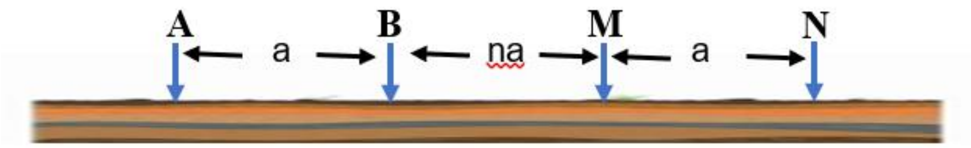

Figure 1. Electrode position in a dipole-dipole configuration

Measurements were carried out along three survey lines, each consisting of 48 electrodes with an electrode spacing (a) of 10 m and a total length of 480 m (Figure 2). As shown in Figure 2, the survey lines are not perfectly linear due to terrain and accessibility constraints. Line 1 exhibits moderate curvature, Line 2 shows slight deviation in its upper segment, while Line 3 is relatively linear.

To accommodate this condition, electrode positions were recorded in the field and subsequently projected onto a straight reference line prior to 2D inversion processing. Although 2D inversion assumes linear electrode geometry, the degree of deviation in this study is considered moderate and acceptable.

It is recognized that such non-linearity may introduce minor spatial distortions, particularly in the horizontal positioning of subsurface features. However, these effects are not expected to significantly influence the overall interpretation of resistivity and chargeability distributions. The non-linear survey design reflects realistic field conditions in volcanic terrains, where ideal linear layouts are often impractical.

Data acquisition employed the MAE X612EM multichannel and multielectrode resistivity and IP meter. Resistivity and chargeability data were processed using Res2Dinv software (version 4.03.36). The inversion was carried out using a smoothness-constrained least-squares algorithm to obtain two-dimensional models of subsurface resistivity and chargeability. The resistivity and induced polarization datasets were inverted simultaneously to ensure consistency between the models.

Relatively high resistivity values are typically associated with dry rocks, igneous rocks, bedrock, or similarly resistive materials, whereas relatively low resistivity values are associated with wet rocks, moist overburden layers, water-filled channels/fractures, or metallic materials. By integrating these resistivity values with local geology and lithological information, the subsurface rock types, soil characteristics, and structural features can be interpreted accordingly. Chargeability values derived from induced polarization (IP) measurements reflect electrochemical polarization processes occurring at the grain–fluid interface, including membrane polarization in clay-rich materials and electrode polarization associated with metallic particles (Pelton *et al.*, 1978; Slater & Lesmes, 2002). Elevated chargeability does not directly indicate contamination; however, under certain geological and geochemical conditions—such as increased ionic concentration in groundwater due to saline intrusion or contaminant plumes—enhanced polarization effects may occur (Revil &

Florsch, 2012). Therefore, chargeability anomalies can be used as an indirect indicator of potential groundwater contamination when interpreted jointly with resistivity data and subsurface lithology (Ward, 2004).

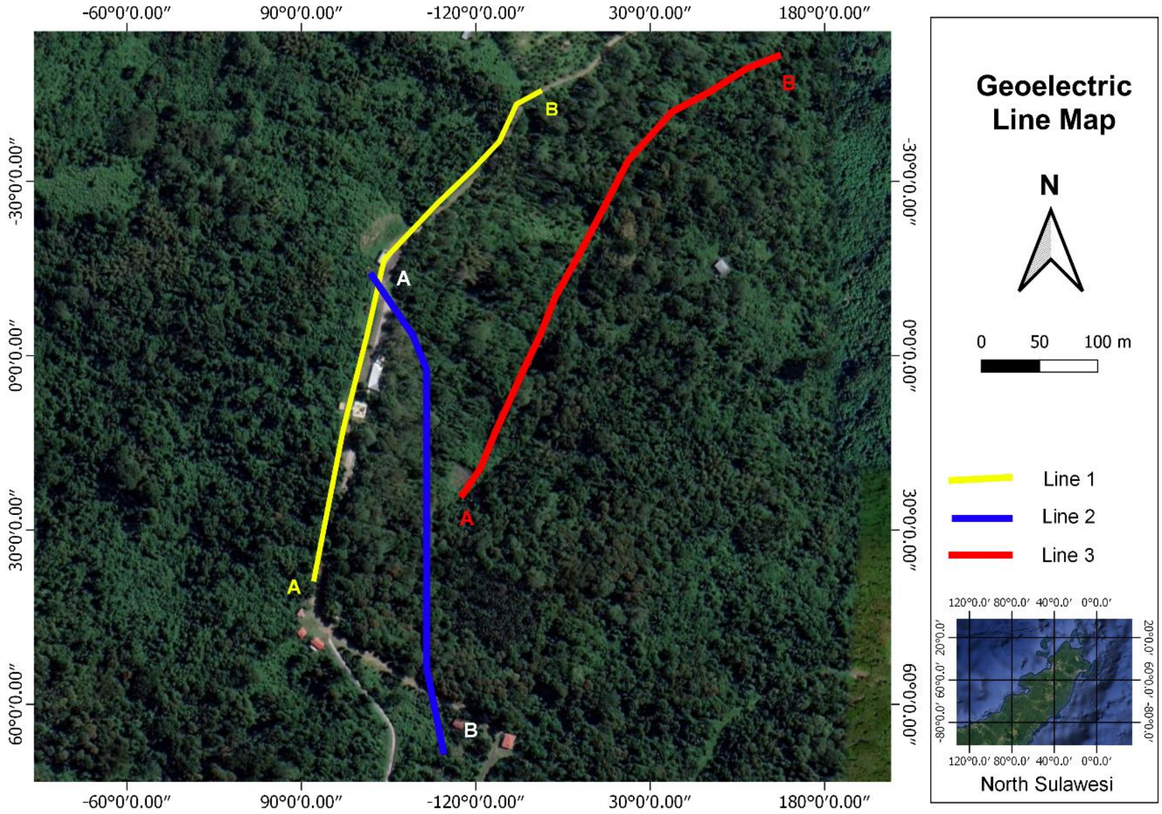

Figure 2. Geoelectrical Survey Line Map

RESULTS AND DISCUSSION

Subsurface Cross-Section of Resistivity at the Research Site

The resistivity measurement data in DAT format were processed using Res2Dinv software to produce subsurface resistivity cross-sections. In general, aquifers are porous geological formations capable of storing and transmitting groundwater; however, their resistivity values vary significantly depending on lithology, porosity, and groundwater salinity. While previous studies have reported aquifer resistivity ranges of 17–111 Ωm (Mohamaden *et al*., 2016), 10–800 Ωm (Sulaiman *et al*., 2022), and 34–3017 Ωm in limestone formations (Dayani *et al*., 2023), much lower resistivity values can occur in environments with high ionic concentrations or significant clay content. Increased salinity enhances electrolytic conduction, while clay minerals contribute to surface conduction, both resulting in reduced resistivity values (Archie, 2003; Revil, 2012). In this study area, which is characterized by coastal deposits and potential seawater intrusion, aquifers were identified at resistivity values of < 9.17 Ωm, reflecting groundwater-bearing zones influenced by saline conditions and/or fine-grained sediments rather than typical freshwater aquifers.

Line 1

Figure 3 shows the subsurface resistivity cross-section for Line 1. Aquifer potential is identified between electrodes 10 (at 100 m) and 13 (at 130 m), at depths of 15–25 m. Only one aquifer zone is detected along this line.

Line 2

Figure 4 presents the subsurface resistivity cross-section for Line 2. Aquifer potential is identified between 215 m and 230 m, at depths of 12–22 m. Only one aquifer zone is found along this line.

Line 3

Figure 5 displays the subsurface resistivity cross-section for Line 3. Three aquifer zones are identified:

1. Aquifer 1, located between 150 m and 175 m, at depths of ≥ 75 m.
2. Aquifer 2, located between 285 m and 305 m, at depths of 30–40 m.
3. Aquifer 3, located between 220 m and 235 m, at depths of 30–40 m, which is relatively small and less productive.

Chargeability Cross-Sections of the Study Area

Line 1 (aquifer at ~15–25 m)

A medium–high chargeability zone appears in the shallow to intermediate layers, close to the shallow aquifer zone identified from resistivity (Figure 3). This high-IP zone likely reflects clay-rich layers, fine volcanic ash, organic material, or accumulated iron oxides, which may act as adsorption media for contaminants (nutrients, metals). Contamination risk: *moderate*. If surface contamination sources exist, fine-grained materials may enhance adsorption and release of contaminants into the shallow aquifer.

Line 2 (aquifer at ~12–22 m)

The IP pattern shows medium and vertically distributed values, with no dominant shallow anomaly (Figure 4). The lithological environment appears more graded (mixed ash and lapilli), and medium IP suggests the presence of clay or iron oxides. Contamination risk: *low to moderate*. Since IP anomalies are not extreme near the primary aquifer, dissolved contaminants (e.g., salinity) would be reflected more strongly in resistivity; however, IP-active layers may adsorb trace metals if present.

Line 3 (Aquifer I ≥ 75 m; Aquifer II 30–40 m)

A high chargeability zone is observed beneath Aquifer II (the main aquifer) at intermediate depths (Figure 5). Elevated chargeability values in induced polarization (IP) data generally reflect electrochemical polarization processes associated with lithological and mineralogical properties, such as the presence of clay-rich layers, iron oxides, or disseminated sulfide minerals. These materials can influence groundwater geochemistry through surface adsorption and redox reactions; however, high chargeability does not directly indicate groundwater contamination.

In this study, the identified high chargeability zone is therefore interpreted as a layer with enhanced polarizable materials that may interact with groundwater, potentially affecting its chemical characteristics. In the absence of supporting hydrochemical data (e.g., Fe, Mn, or TDS concentrations), this anomaly should be considered as indicative of subsurface geochemical reactivity rather than confirmed contamination risk.

Groundwater Recharge Zones

Groundwater recharge zones, which serve as pathways for water infiltration into subsurface layers, are identified by resistivity values ≤ 173 Ωm (Figures 3–5). These low-resistivity anomalies fall within the range typically associated with saturated fine-grained lithologies in ERT/VES studies (Hussein & Ali, 2023; Sangawi *et al*., 2023; Wahab *et al*., 2021). Infiltration experiments show that saturation leads to resistivity decreases to ~120–130 Ωm, supporting the ≤ 173 Ωm threshold as an indicator of recharge under non-saline conditions (Papadopoulos *et al*., 2024). Recent integrated studies validating recharge mapping with ERT also show consistent low–medium resistivity values in confirmed recharge zones (Mohammed *et al*., 2025).

Recharge zones identified:

1. Line 1: at 110–125 m, 170–230 m, 310–330 m, and 380–440 m.
2. Line 2: throughout the line except 20–40 m, which represents an impermeable zone.
3. Line 3: generally along the entire survey except at 35–80 m.

Groundwater Aquifers and Chargeability

Groundwater purity in aquifers varies depending on the presence of contaminants within surrounding rock layers. Fine particles, oxides, or organic materials may affect groundwater quality, including color and taste.

Line 1

High chargeability values in this zone indicate the presence of polarizable materials such as volcanic clay, iron oxides, or organic-rich layers. These materials are known to influence groundwater geochemistry through adsorption and redox processes (Pelton *et al*., 1978; Revil, 2012; Slater & Lesmes, 2002). While such conditions may be associated with elevated Fe, Mn, or organic content, chargeability alone does not directly indicate groundwater contamination. Therefore, this zone is interpreted as having potential geochemical influence rather than reduced water quality.

Line 2

Moderate chargeability values within the aquifer zone suggest a mixed lithological composition, consisting of relatively clean granular materials interbedded with finer sediments. This condition may locally influence groundwater chemistry; however, no direct inference on contamination can be made without supporting hydrogeochemical data.

Line 3

Elevated chargeability values in Aquifer II (depth 30–40 m), interpreted as the main groundwater-bearing zone, indicate the presence of significant polarizable materials such as fine-grained sediments, iron oxides, or organic matter. These materials may affect groundwater geochemical characteristics (e.g., Fe and Mn concentrations) through surface and redox processes, but do not directly imply contamination. In the shallow aquifer (Aquifer I), potential vulnerability to surface influence exists; however, given the forested setting, anthropogenic impact is likely limited. Overall, these interpretations reflect lithological and geochemical controls rather than confirmed groundwater quality conditions.

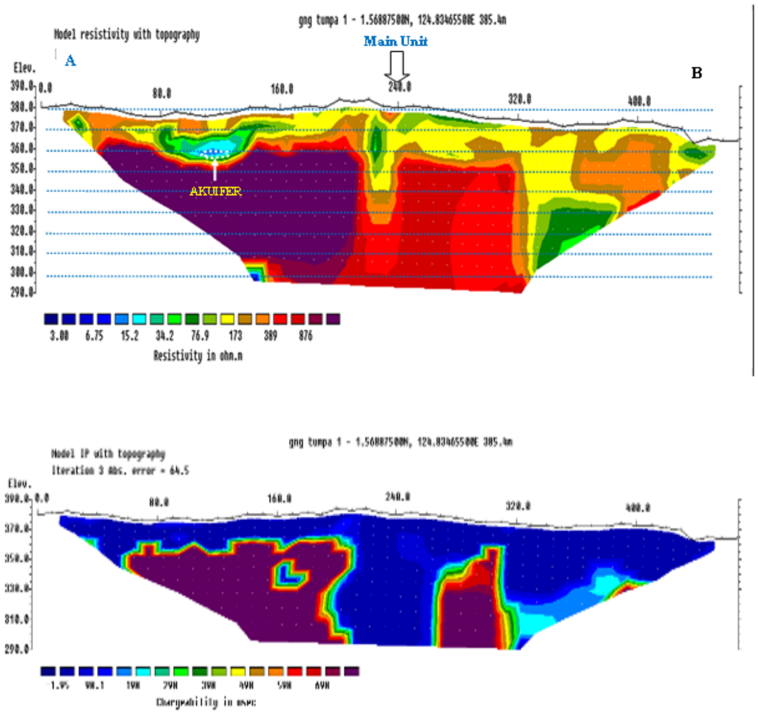

Figure 3. Subsurface resistivity and chargeability cross-section of Line 1

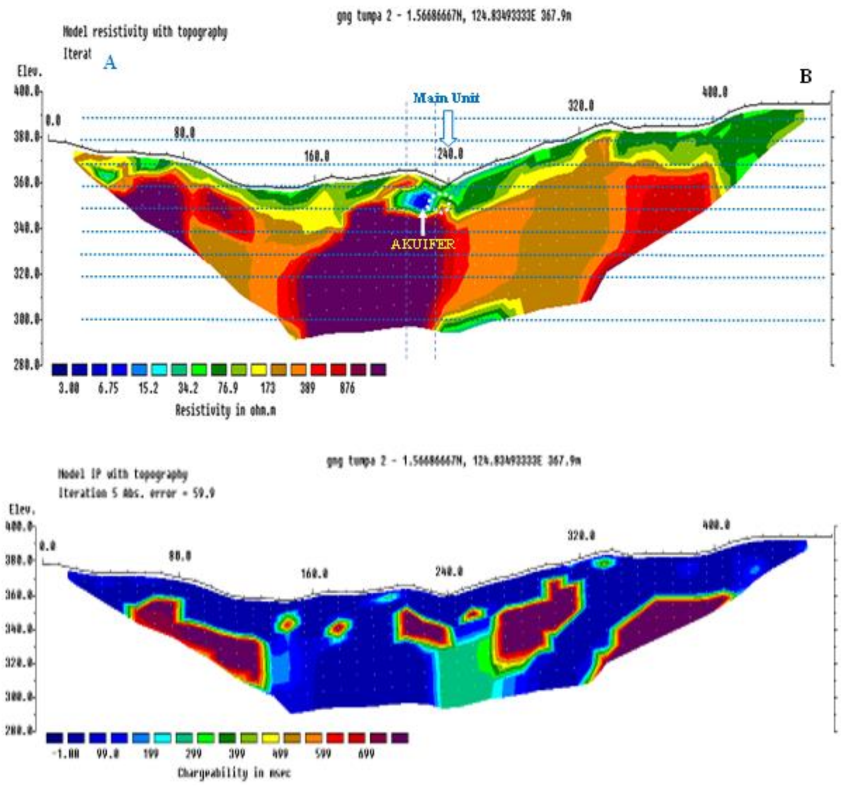

Figure 4. Subsurface resistivity and chargeability cross-section of Line 2

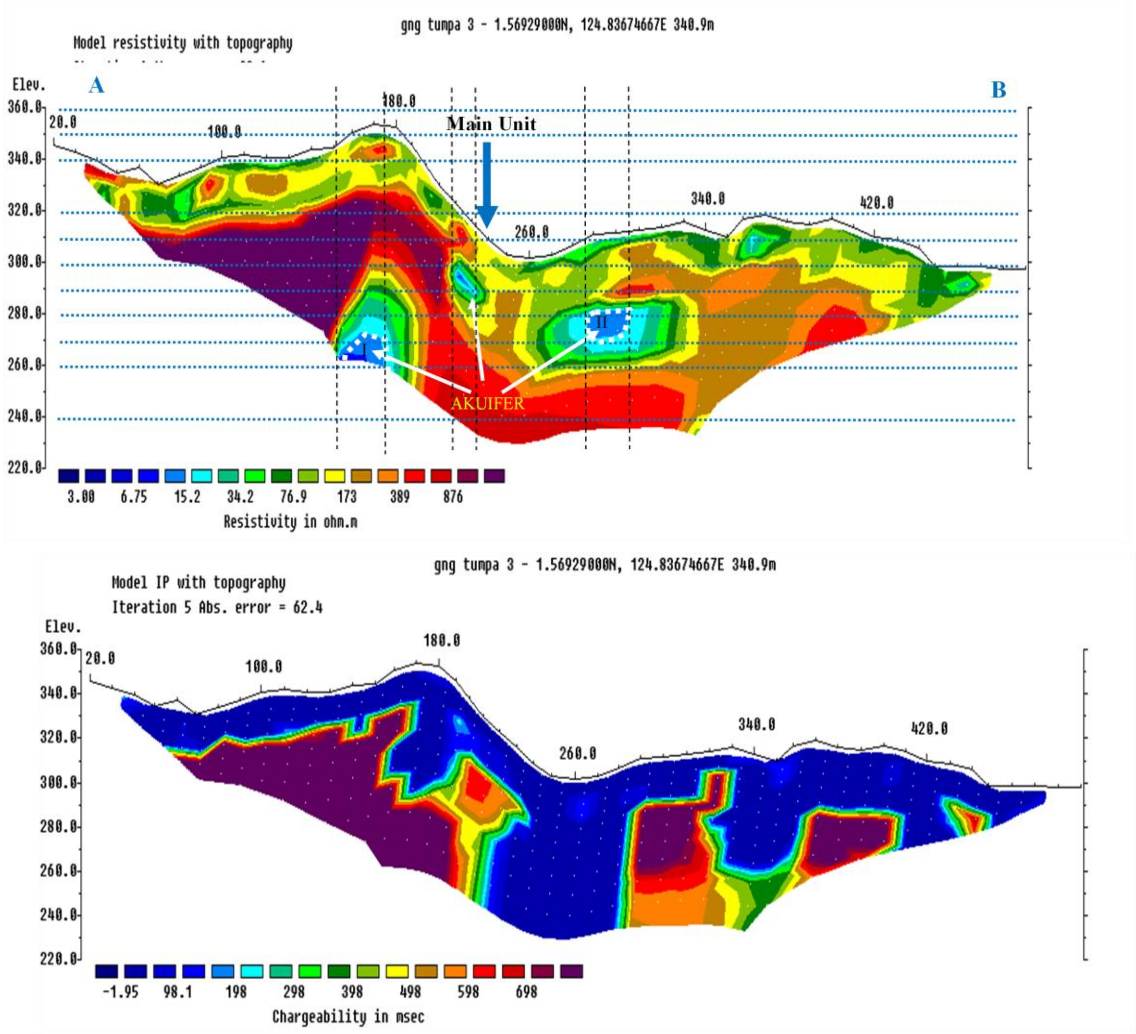

Figure 5. Subsurface resistivity and chargeability cross-section of Line 3

Aquifer Characteristics

Based on the local geological setting and aquifer depth, the aquifers in the study area can be grouped into unconfined aquifers, perched aquifers, and fractured aquifers. The aquifers identified in the study area are predominantly unconfined and shallow aquifers, except for Aquifer II on Line 3. Shallow aquifers are generally more vulnerable to contaminants from the surrounding environment; natural contaminants such as volcanic clay, iron oxides, or dissolved organic carbon (DOC) from slope humus may cause groundwater discoloration, slight odor, or elevated Fe and Mn concentrations.

Aquifer II on Line 3, which represents the main aquifer, is more protected due to its depth. Aquifer depth is one of the key factors determining aquifer vulnerability to contamination; deeper aquifers typically possess a thicker vadose zone and/or impermeable layers that reduce the likelihood of rapid contaminant infiltration from the surface (Barbulescu, 2020). Aquifer II exhibits high chargeability values, suggesting the presence of intercalated fine particles, oxides, or organic materials. Laboratory and field studies have identified characteristic IP responses in materials containing modified iron or sulfur (oxides or sulfides), supporting the interpretation that high chargeability anomalies may reflect oxide-rich or alteration products (Emerson *et al*., 2024).

Overall, the three survey lines indicate a multi-layered volcanic aquifer system, consisting of unconfined to semi-confined aquifers deposited above impermeable massive lava. Rapti (2025) conducted a study on multi-aquifer systems in volcanic–sedimentary deposits and described a stratified aquifer system (unconfined–confined) controlled by lithology and structural features that influence groundwater flow and aquifer protection.

Shallow low-resistivity layers (< 9.17 Ωm) at depths of approximately 12–30 m represent fine- to medium-grained volcanic materials (ash, lapilli, volcanic sand) functioning as productive aquifers, particularly in Lines 1 and 3. Volcanic deposits (including ash and lapilli) commonly form aquifers, with depth and hydraulic conductivity linked to surface water systems (Esquivel-Hernández *et al.*, 2024; Nugraha *et al*., 2023). Low-resistivity layers are frequently associated with saturated pyroclastic materials that act as productive groundwater reservoirs (Caesario *et al*., 2024; Nugraha *et al*., 2025; Sendrós *et al*., 2021).

High-resistivity layers (> 587 Ωm) indicate massive lava or large volcanic blocks that function as impermeable layers or hydraulic barriers, although they may act as local fractured aquifers when structural discontinuities are present. This aligns with studies of lava-flow reservoirs and ERT modelling, which consistently identify massive volcanic rocks as highly resistive domains. However, where fractures or structural discontinuities occur, such rocks may provide secondary porosity and permeability, functioning as local fractured aquifers (Carrasco-García *et al.*, 2025; Millett *et al*., 2024). Numerous ERT/MT and field investigations also highlight that fracturing can enhance secondary porosity and conductivity, enabling parts of massive lava flows to act as local fractured aquifers (Nugraha *et al*., 2025; Sopan *et al.*, 2024).

Line 3 exhibits two aquifer zones (shallow and deeper) with high productivity and characteristics consistent with a semi-confined system, making it the most promising line for groundwater storage. The shallow aquifer is more susceptible to contamination, whereas the deeper aquifer is better protected and has a greater storage capacity.

CONCLUSION

This study delineates the geometry, thickness, and lithological control of volcanic aquifers in the Mount Tumpa area through the integration of resistivity and induced polarization (IP) methods. Aquifer zones are consistently characterized by low resistivity values (< 9.17 Ωm), with distinct spatial distributions across the survey lines, including three aquifer units identified on Line 3 at varying depths (≥ 30 m, 30–40 m, and 35–45 m). Chargeability responses reveal the presence of polarizable materials such as volcanic clay, iron oxides, and organic-rich layers, which indicate subsurface lithological and geochemical heterogeneity rather than direct groundwater contamination. The subsurface system is interpreted as a layered volcanic aquifer, where groundwater is primarily stored in permeable lapilli and volcanic ash deposits overlying compact lava, with additional storage potential in fractured lava zones. The main contribution of this study lies in demonstrating that the integration of resistivity and IP data enhances the resolution of aquifer characterization in complex volcanic environments, particularly in distinguishing conductive groundwater zones from lithologically controlled polarization effects. This integrated approach reduces ambiguity in interpreting low-resistivity zones and provides a more robust framework for identifying groundwater-bearing formations. Practically, the results contribute to improving groundwater exploration strategies and support sustainable water resource management in volcanic regions with increasing water demand and environmental pressures.

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