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TWO-DIMENSIONAL RESISTIVITY STRUCTURE AND DEEP AQUIFER CHARACTERIZATION IN THE HARUMAN VOLCANIC AREA, WEST JAVA, INDONESIA: AN AUDIO MAGNETOTELLURIC INVESTIGATION

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Abstrak. Groundwater availability in volcanic environments depends heavily on rock diversity, structural breaks, and the hydraulic features of specific deposits. The western slope of Mount Haruman, situated in the critical southern recharge zone of the Bandung Soreang Groundwater Basin, serves as a vital water catchment area in West Java, Indonesia. Earlier electrical resistivity studies only detected shallow, unconfined aquifers located at depths above forty meters. Consequently, the geometry and overall continuity of the deeper groundwater systems remained largely unknown. To address this knowledge gap, this specific study utilized the Audio Magnetotelluric method to accurately map deep aquifers situated beneath the Haruman volcanic complex. Researchers successfully collected data from six stations using specialized Phoenix equipment. After processing the time series data with advanced remote reference techniques, the information was inverted into highly detailed one dimensional and two dimensional resistivity models. These resulting models display significant variations directly linked to the complex volcanic sequences. Low and moderate resistivity zones indicate permeable tuffs and fractured, water saturated rocks. Conversely, high resistivity areas represent compact lava flows acting as barriers. Ultimately, the interpreted deep aquifer system proves that the Audio Magnetotelluric method is exceptionally effective for sustainable groundwater exploration and local water resource conservation efforts.

Kata kunci: Audio Magnetotellurics; Deep Aquifer; Groundwater; Volcanic Aquifer; Resistivity Inversion; West Java

Abstract. Ketersediaan air tanah di lingkungan vulkanik sangat bergantung pada keragaman batuan, diskontinuitas struktural, dan karakteristik hidrolik dari endapan tertentu. Lereng barat Gunung Haruman, yang terletak di zona imbuhan selatan yang krusial bagi Cekungan Air Tanah Bandung-Soreang, berfungsi sebagai daerah tangkapan air yang vital di Jawa Barat, Indonesia. Studi resistivitas listrik sebelumnya hanya mendeteksi akuifer dangkal tak tertekan (unconfined) pada kedalaman kurang dari empat puluh meter. Akibatnya, geometri dan kontinuitas keseluruhan sistem air tanah yang lebih dalam sebagian besar masih belum diketahui. Untuk mengatasi kesenjangan informasi ini, studi khusus ini menggunakan metode Audio Magnetotelluric guna memetakan secara akurat akuifer dalam yang terletak di bawah kompleks vulkanik Haruman. Para peneliti berhasil mengumpulkan data dari enam stasiun

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menggunakan peralatan Phoenix khusus. Setelah memproses data deret waktu dengan teknik referensi jarak jauh (remote reference) yang canggih, informasi tersebut diinversi menjadi model resistivitas satu dimensi dan dua dimensi yang sangat rinci. Model-model yang dihasilkan menunjukkan variasi signifikan yang berkaitan erat dengan urutan vulkanik yang kompleks. Zona resistivitas rendah dan sedang mengindikasikan adanya tuf permeabel serta batuan retakan yang jenuh air. Sebaliknya, area dengan resistivitas tinggi merepresentasikan aliran lava padat yang bertindak sebagai penghalang. Pada akhirnya, interpretasi sistem akuifer dalam ini membuktikan bahwa metode Audio Magnetotelluric sangat efektif untuk eksplorasi air tanah berkelanjutan dan upaya konservasi sumber daya air setempat.

Keywords: Magnetotelurik Audio; Akuifer Dalam; Air Tanah; Akuifer Vulkanik; Inversi Resistivitas; Jawa Barat

1. Pendahuluan

Groundwater constitutes one of the most essential freshwater resources supporting domestic, agricultural, and industrial activities worldwide. Increasing population growth, rapid urbanization, and climate variability have substantially intensified groundwater exploitation, particularly in volcanic regions where groundwater represents the primary freshwater source. Volcanic terrains are among the most productive groundwater reservoirs because volcanic deposits commonly exhibit highly heterogeneous hydraulic properties. Pyroclastic deposits, pumice, scoria, and fractured lava flows generally possess high porosity and permeability, whereas massive lava flows and volcanic breccias often behave as impermeable barriers [1]. Consequently, groundwater occurrence in volcanic environments is highly controlled by lithological variations together with tectonic structures such as faults and fracture networks. Identifying these subsurface heterogeneities is therefore fundamental for groundwater exploration and water resource management.

The Haruman volcanic area, situated on the western flank of the Malabar volcanic complex in West Java, Indonesia, represents one of the principal recharge zones of the Bandung–Soreang Groundwater Basin. The region functions as an important groundwater catchment because abundant rainfall infiltrates highly permeable volcanic deposits before flowing toward the Bandung Basin. Previous hydrogeological investigations have demonstrated that groundwater flow generally follows the western slope of Mount Haruman, highlighting the strategic importance of this area in maintaining regional groundwater availability [2]. Several geophysical investigations have previously been conducted in the Haruman area. DC resistivity surveys using Schlumberger and Wenner configurations successfully identified shallow unconfined aquifers occurring at depths generally less than 40 m beneath coarse volcanic tuffs [3,4]. Although these studies significantly improved the understanding of shallow groundwater systems, they provided limited information regarding deeper aquifers because the depth of investigation by the electrical resistivity method [5].

Deep groundwater resources have become increasingly important in volcanic regions because shallow aquifers are vulnerable to seasonal fluctuations, land-use changes, and anthropogenic contamination. Reliable delineation of deep groundwater systems therefore requires geophysical techniques capable of imaging several hundred meters to several kilometers beneath the surface. Among available electromagnetic methods, the Audio Magnetotelluric (AMT) method has emerged as an effective passive technique for investigating subsurface electrical resistivity. Unlike active-source electromagnetic methods, AMT utilizes naturally occurring electromagnetic fields generated primarily by global lightning activity within the frequency range of approximately 1 Hz to 10 kHz [6]. The method offers high vertical resolution while simultaneously providing penetration depths approaching several kilometers, depending on subsurface resistivity conditions [7]. Consequently, AMT has been widely applied to groundwater exploration, geothermal investigations, volcanic studies, and structural mapping [8]. Recent international studies have demonstrated the capability of AMT to characterize groundwater-bearing formations in volcanic and structurally complex environments [9,10,11]. Nevertheless, most published investigations focus either on geothermal systems or sedimentary aquifers, whereas relatively few studies have addressed deep groundwater characterization within tropical Quaternary volcanic terrains. Furthermore, integrated interpretation combining one-dimensional and two-dimensional resistivity inversion remains limited for volcanic aquifer systems in Indonesia.

The principal scientific gap therefore lies in the limited understanding of deep groundwater distribution beneath the Haruman volcanic complex. Existing investigations have concentrated primarily on shallow groundwater using electrical resistivity tomography, while the geometry, continuity, and hydrogeological significance of deeper groundwater systems remain unresolved. This study addresses this knowledge gap by employing Audio Magnetotelluric data to characterize the deep resistivity structure beneath Mount Haruman. Robust processing, impedance analysis, one-dimensional Occam inversion, and two-dimensional inversion are integrated to obtain a comprehensive resistivity model of the subsurface. The resulting resistivity distribution is interpreted together with regional geological and hydrogeological information to identify potential deep aquifers and their controlling lithological units.

The novelty of this research lies in three major aspects. First, it presents one of the first applications of Audio Magnetotelluric investigation specifically designed to characterize deep groundwater systems beneath the Haruman volcanic area. Second, it integrates one-dimensional and two-dimensional inversion for improved hydrogeological interpretation of volcanic deposits. Third, it establishes a conceptual relationship between resistivity distribution, volcanic lithology, and groundwater occurrence that can support sustainable groundwater exploration within the Bandung Groundwater Basin.

The results presented in this study provide new insights into groundwater occurrence beneath Quaternary volcanic terrains and demonstrate the effectiveness of passive electromagnetic methods for deep aquifer exploration [12]. The findings are expected to contribute not only to groundwater resource assessment in West Java but also to future hydrogeophysical investigations in similar volcanic environments worldwide.

2. GEOLOGICAL SETTING

2.1 Regional Geology

The study area is located on the western flank of Mount Haruman, which forms part of the Malabar Volcanic Complex in West Java, Indonesia. Geologically, the area belongs to the southern volcanic belt of Java that has developed as a consequence of the subduction of the Indo-Australian Plate beneath the Eurasian Plate [13]. Continuous volcanic activity since the Late Tertiary has produced thick volcanic successions consisting of lava flows, pyroclastic deposits, volcanic breccias, lahars, and volcanic tuffs. According to the Geological Map of Garut and Pameungpeuk Sheet, the stratigraphy surrounding the investigation area consists of several volcanic formations with different lithological characteristics, Figure 1.

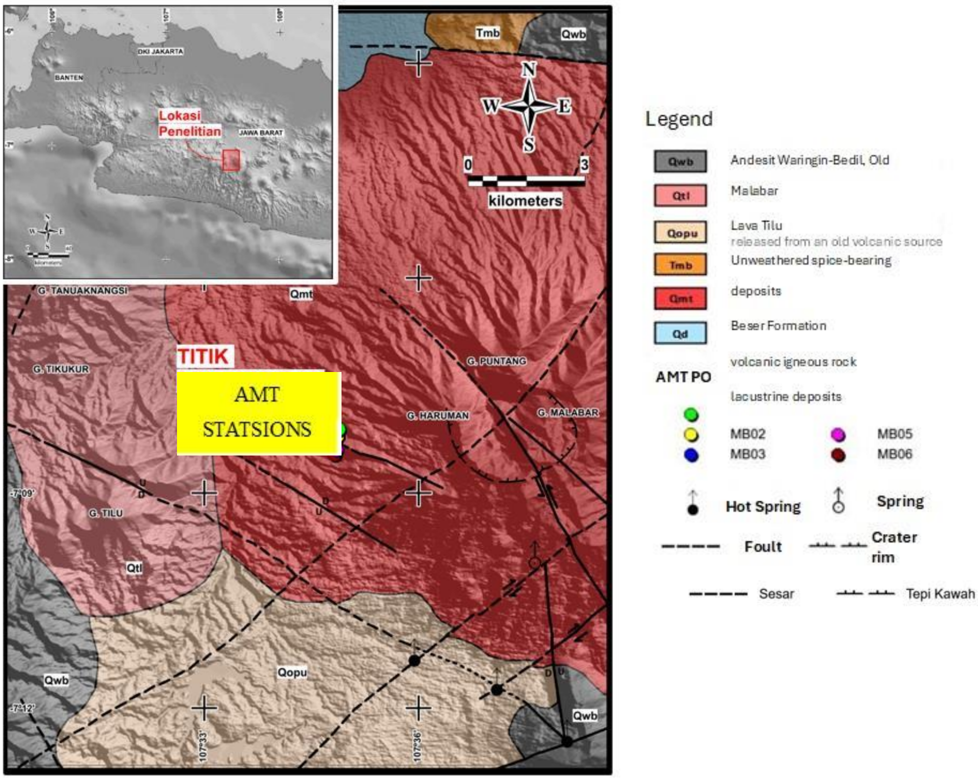

Figure 1. Geologic Map of Research Area (modification of Garut and Pameungpeuk Map, Java [14]

The oldest exposed rocks belong to the Beser Formation (Tmb), composed mainly of volcanic breccia and lava with andesitic to basaltic composition. This formation is unconformably overlain by the Tuffaceous Breccia Formation (Tpv), which consists of volcanic breccia, tuff, and volcaniclastic sandstone. Above these units, Quaternary volcanic products dominate the landscape, including the Old Undifferentiated Volcanic Rocks (Qtv), Waringin Bedil Andesite (Qwb), Old Volcanic Loose Deposits (Qopu), Malabar–Tilu Volcanic Formation (Qmt), and Tilu Lava Formation (Qtl) [15]. These volcanic sequences are finally covered by young alluvial and lacustrine deposits within the Bandung Basin. The regional lithological succession reflects multiple volcanic eruptions and depositional episodes that produced highly heterogeneous volcanic materials with contrasting hydraulic properties [16].

The investigated area is characterized by rugged volcanic topography with elevations exceeding 1,400 m above sea level. The geomorphology is dominated by volcanic cones, lava ridges, and erosional valleys that collectively influence groundwater recharge and subsurface flow. Numerous fractures and joints developed during volcanic emplacement and regional tectonic deformation enhance secondary permeability, providing preferential pathways for deep groundwater circulation [17].

2.2 Hydrogeological Setting

Hydrogeologically, the Haruman volcanic area forms an important recharge zone within the Bandung–Soreang Groundwater Basin. Based on the Hydrogeological Map of

Bandung Regency, groundwater occurs mainly within young volcanic deposits exhibiting moderate to high permeability, [18]. Groundwater flow is primarily controlled by interconnected pore spaces in pyroclastic materials together with fracture systems developed within lava flows [19]. Volcanic aquifers in the study area generally consist of coarse tuffs, pumice-rich deposits, weathered volcanic breccias, fractured lava flows, and vesicular andesitic rocks. These lithologies exhibit relatively high porosity and hydraulic conductivity, enabling significant groundwater storage [20]. In contrast, compact lava flows, massive volcanic breccias, and dense andesitic rocks commonly behave as aquifuges or aquitards that restrict groundwater movement and locally confine groundwater-bearing horizons [21].

Regional groundwater flow is interpreted to follow the western slope of Mount Haruman toward the Bandung Basin [2]. Recharge is mainly supplied by direct rainfall infiltration occurring at higher elevations where permeable volcanic deposits dominate the landscape [22]. Consequently, identifying the geometry of deep groundwater reservoirs beneath the recharge area is essential for sustainable groundwater management within southern Bandung.

3. MATERIALS AND METHODS

3.1 Study Area

The Audio Magnetotelluric (AMT) survey was conducted in Warjabakti Village, Cimaung District, Bandung Regency, West Java, Indonesia Figure 2. The survey area is situated on the western flank of Mount Haruman, approximately within the southern recharge zone of the Bandung-Soreang Groundwater Basin [4].

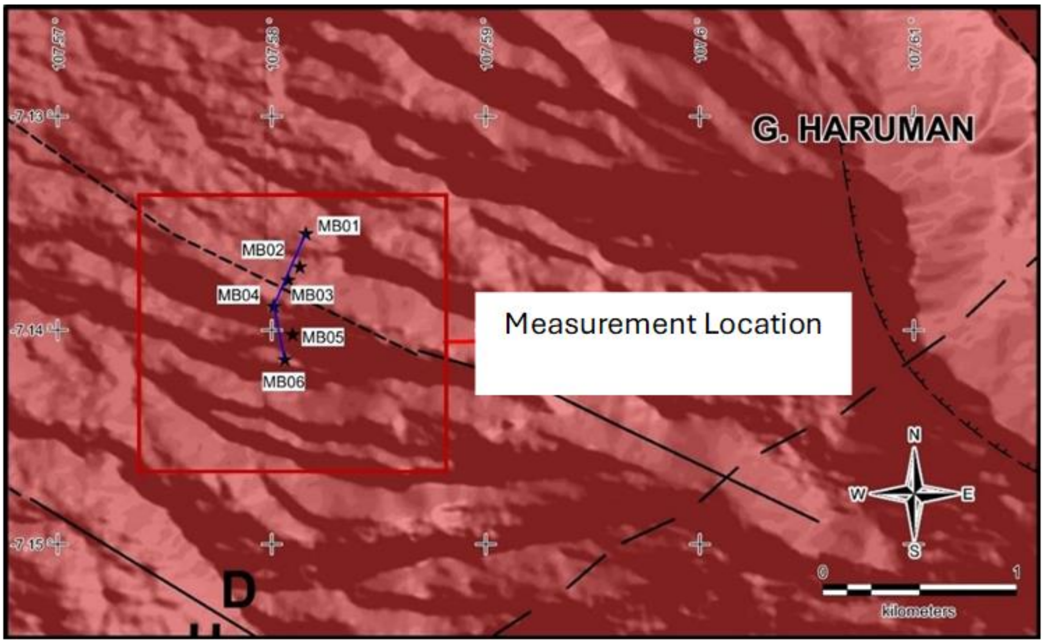

Figure 2. Location of Audio Magnetotelluric Measurement Trajectory (Blue Line)

Field measurements were carried out between May and December 2023. Six AMT stations were established along a profile designed to intersect the major geological structures and volcanic lithological boundaries. The station distribution was selected to maximize sensitivity to both shallow and deep resistivity variations while maintaining sufficient spatial resolution for two-dimensional inversion [1].

3.2 Audio Magnetotelluric Data Acquisition

Data acquisition employed a Phoenix Geophysics MTU-5A recording system equipped with two horizontal electric dipoles (and) and three induction coil magnetometers (, , and). Electric fields were measured using non-polarizable porous-pot electrodes installed with an electrode spacing of approximately 25 m, while magnetic fields were recorded using induction coils oriented orthogonally according to the survey coordinate system [6] Figure 3. $E_x E_y H_x H_y H_z$

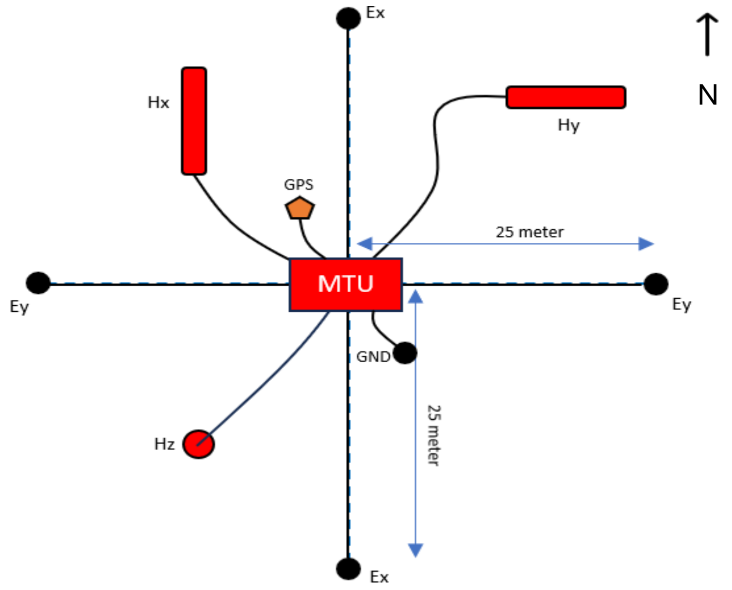

Figure 3. Layout of Acqusition AMT

The AMT method utilizes naturally occurring electromagnetic fields generated primarily by global lightning activity [23]. Consequently, no artificial transmitter is required. Time-series recordings were acquired continuously to ensure adequate signal quality over the frequency band required for imaging shallow to deep subsurface structures [17]. The acquisition parameters were optimized to record frequencies ranging approximately from 1 Hz to 10 kHz, allowing investigation depths from near surface to several kilometers depending on subsurface resistivity conditions [7].

3.3 Data Processing

The acquired time-series data were processed using the Phoenix SSMT2000 software package. Initially, the raw time-domain recordings were transformed into the frequency domain through Fast Fourier Transform (FFT). Robust processing was subsequently applied to suppress random noise and improve impedance estimation [24]. Cross-power spectra were carefully evaluated to identify coherent electromagnetic signals, while noisy frequency bands affected by cultural interference or unstable atmospheric conditions were excluded [25]. Remote-reference and robust statistical procedures were employed whenever possible to enhance impedance estimation and minimize bias associated with correlated noise [26].

Following robust processing, impedance tensors were further examined and edited using MTEditor. Manual smoothing was performed to remove isolated outliers while preserving the overall trend of apparent resistivity and phase curves.

3.4 Dimensionality Analysis

Prior to inversion, impedance tensors were evaluated to determine the dimensional characteristics of the subsurface [27]. Tensor analysis enabled identification of one-dimensional, two-dimensional, and locally three-dimensional responses.

The regional geological setting suggests that the investigated volcanic sequence can reasonably be approximated using a two-dimensional resistivity model because lithological variations predominantly occur perpendicular to the survey profile [28]. Consequently, transverse electric (TE) and transverse magnetic (TM) modes were jointly incorporated during inversion [1].

3.5 Resistivity Inversion

One-dimensional inversion was first performed independently for each sounding using the Occam inversion algorithm. This procedure provided preliminary information regarding vertical resistivity variations and facilitated quality control before two-dimensional inversion. Subsequently, all AMT stations were combined into a two-dimensional inversion using WinGLink software [10]. The inversion iteratively minimized the difference between observed and calculated impedance responses while simultaneously imposing smoothness constraints to stabilize the resulting resistivity model [8].

The inversion process continued until convergence was achieved and the root mean square (RMS) misfit reached an acceptable level, indicating consistency between measured data and the inverted resistivity distribution.

3.6 Hydrogeological Interpretation

The inverted resistivity models were interpreted by integrating regional geological maps, hydrogeological information, previous DC resistivity investigations, and published resistivity ranges for volcanic rocks [29,3]. Low- to moderate-resistivity zones were interpreted as groundwater-bearing volcanic deposits composed mainly of weathered volcanic tuffs, pumice-rich pyroclastic materials, and fractured volcanic rocks exhibiting relatively high porosity and permeability [30]. Conversely, high-resistivity anomalies were interpreted as compact volcanic breccias, massive lava flows, and dense andesitic rocks characterized by limited permeability and acting as aquifuges or aquitards [8]. The final hydrogeological interpretation focused on identifying the geometry, depth, continuity, and lateral extent of deep aquifer systems beneath the Haruman volcanic complex and evaluating their potential contribution to regional groundwater resources.

4. RESULTS

4.1 AMT Data Quality

A total of six Audio Magnetotelluric (AMT) sounding stations (MB01–MB06) were successfully acquired along a southwest–northeast profile on the western slope of Mount Haruman. The survey profile was approximately 700 m long with station spacing ranging from 100 to 175 m, Figure 4. Surface elevations varied between 1,278 and 1,359 m above mean sea level. Each station was recorded for approximately 30 minutes, producing usable electromagnetic signals within a frequency range of 0.35–10,400 Hz.

These acquisition parameters provide sensitivity from shallow subsurface layers to several kilometers depth, depending on subsurface electrical resistivity [12].

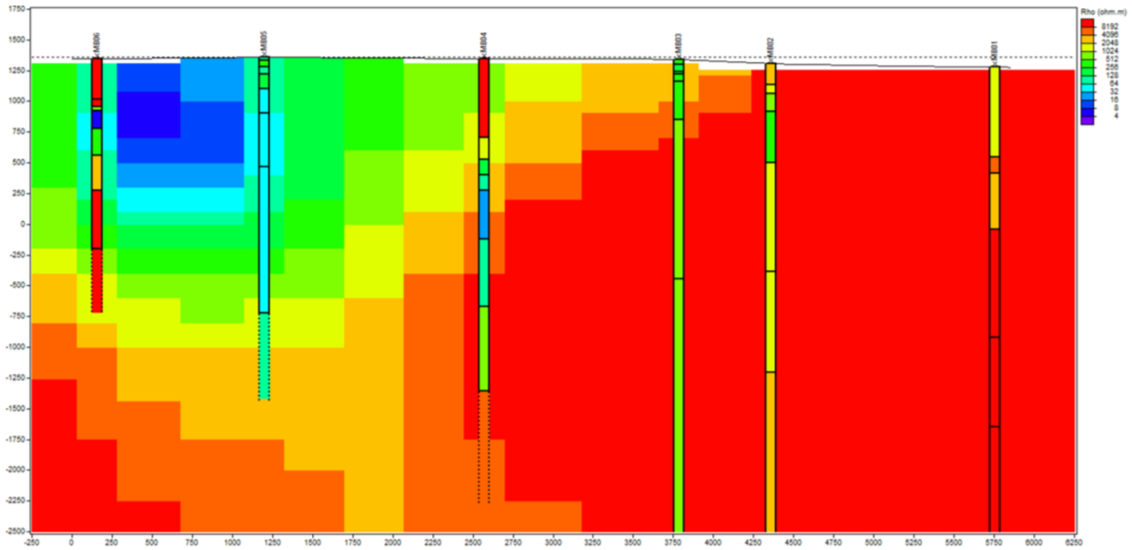

Figure 4. The 1D and Pseudo Section-2D resistivity Structure model of occam scheme inversion

Prior to inversion, the time-series data underwent robust processing and cross-power selection to suppress incoherent noise and improve impedance estimation. The coherence of the raw dataset initially ranged from approximately 54% to 72%. After robust processing and cross-power editing, coherence values increased to approximately 70–79%, indicating a substantial improvement in signal quality and reliability for subsequent inversion [26]. The enhanced coherence demonstrates that the processing workflow effectively removed outliers and cultural noise while preserving the natural electromagnetic response [25].

The apparent resistivity and phase curves exhibit generally smooth frequency-dependent responses with only minor local scatter after editing, suggesting that the impedance estimates are sufficiently stable for quantitative inversion. This data quality is consistent with the relatively low level of anthropogenic electromagnetic interference within the mountainous survey area.

4.2 Dimensionality Analysis

Dimensionality analysis was performed using impedance polar diagrams at representative frequencies of 1500, 159, 22.5, 4.1, and 1.72 Hz. The analysis indicates that the electromagnetic responses exhibit both two-dimensional (2D) and three-dimensional (3D) characteristics. High-frequency responses display mixed 2D–3D behavior, whereas lower frequencies are predominantly characterized by three-dimensional structures. Despite the observed 3D characteristics, previous studies have shown that two-dimensional inversion provides an acceptable first-order approximation for interpreting complex volcanic environments when supported by geological constraints [28].

The dimensionality results suggest that lateral resistivity variations become increasingly significant at greater depths, probably reflecting heterogeneous volcanic stratigraphy together with fracture-controlled groundwater pathways [17]. Consequently, TE and

TM modes were jointly incorporated using the invariant inversion approach to maximize sensitivity to both conductive and resistive subsurface features.

4.3 Two-Dimensional Resistivity Model

The final two-dimensional inversion was performed using fifty nonlinear conjugate-gradient iterations and converged with a root mean square (RMS) misfit of 8.8%, indicating satisfactory agreement between observed and calculated responses, Figure 5. The inversion incorporated both TE and TM modes, allowing simultaneous imaging of conductive and resistive subsurface structures [10].

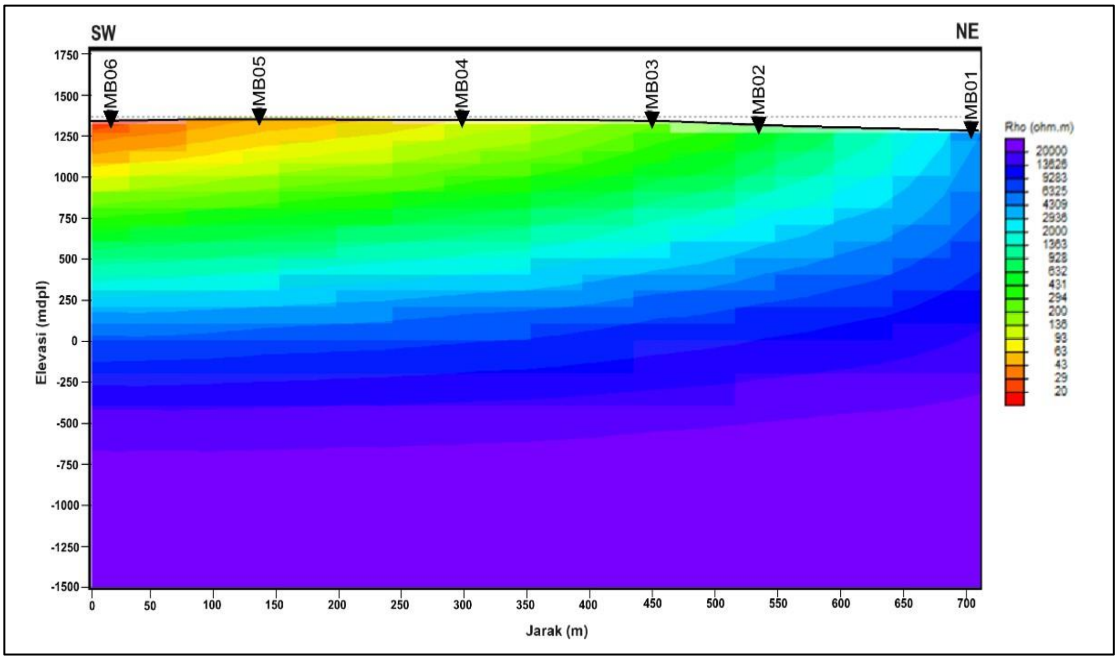

Figure 5. 2D Resistivity result of the final two-dimensional inversion

The resulting resistivity section extends to approximately 1,500 m below the surface and reveals pronounced lateral and vertical heterogeneity. The recovered resistivity values range from approximately 20 to more than 20,000 , reflecting the complex volcanic stratigraphy beneath Mount Haruman [16]. Four principal resistivity domains can be recognized:Ω"m" Ω"m"

- 20 - 43 Ω"m" : very low resistivity
- 43 - 294 Ω"m" : moderate resistivity
- 294 - 4,309 Ω"m" : high resistivity
- 4,309 Ω"m" : very high resistivity

These resistivity domains form laterally continuous but vertically variable layers that correlate well with the regional volcanic stratigraphy.

4.4 Lithological Interpretation

The uppermost conductive layer, characterized by resistivity values of 20–43 Ω."m" , is confined to elevations between approximately 1,359 and 1,130 m above sea level. Based on the regional geological map and published resistivity values of volcanic materials, this conductive horizon is interpreted as weathered soil containing sandy clay with relatively high moisture content. The low resistivity reflects clay minerals, increased water saturation, and weathering processes occurring near the ground surface. Beneath this conductive layer lies a laterally continuous moderate-resistivity zone ranging from 43 to 294 . This unit extends from elevations of approximately 1,130 m to 750 m above sea level and represents the most significant hydrogeological feature identified in the survey. The resistivity values are consistent with permeable volcanic tuffs containing pumice fragments and interconnected pore spaces [1]. These lithologies are capable of storing and transmitting groundwater efficiently and therefore are interpreted as the principal groundwater-bearing formation.Ω."m"

Underlying the interpreted aquifer, resistivity increases to values between 294 and 4,309 . This interval is interpreted as volcanic breccia interbedded with lava flows belonging to the Waringin Bedil Andesite and older Malabar volcanic units. These rocks exhibit relatively low porosity and permeability and therefore function as aquitards or aquifuges that restrict vertical groundwater movement [21]. At greater depths, resistivity exceeds 4,309 , corresponding to massive andesitic lava characterized by extremely low permeability.Ω"m" Ω"m"

4.5 Deep Aquifer Delineation

The most significant result of this investigation is the identification of a laterally continuous deep aquifer within the moderate-resistivity interval (93–294 Ω"m"). The aquifer occupies elevations between approximately 1,325 and 750 m above sea level and extends laterally over the southwestern portion of the survey profile between approximately 0 and 460 m. The interpreted groundwater reservoir is enclosed above and below by relatively impermeable volcanic units, indicating a confined to semi-confined hydrogeological setting.

The interpreted aquifer occurs substantially deeper than the shallow groundwater previously identified using electrical resistivity tomography, confirming that Mount Haruman hosts multiple groundwater-bearing horizons within the Quaternary volcanic succession [5]. The occurrence of permeable pumice-bearing volcanic tuffs surrounded by dense lava and volcanic breccias creates favorable geological conditions for groundwater accumulation.

Because the Bandung Basin lies at elevations of approximately 650–700 m above sea level, the interpreted deep aquifer is hydraulically positioned to contribute groundwater flow toward the basin [16]. The regional topographic gradient and previous hydrogeological studies indicate that groundwater movement likely follows the western slope of the Malabar volcanic complex toward the Bandung Basin [2], suggesting that this deep aquifer may represent an important component of the regional groundwater recharge system.

6. CONCLUSIONS

This study demonstrates the capability of the Audio Magnetotelluric (AMT) method to characterize deep groundwater systems beneath the western flank of Mount Haruman, West Java, Indonesia. By integrating robust data processing, one-dimensional Occam inversion, and two-dimensional resistivity inversion, the subsurface resistivity structure was successfully imaged to depths exceeding one kilometer, providing new insights into the hydrogeological framework of the Haruman volcanic complex [8].

The principal findings of this study are summarized as follows:

1. The AMT resistivity model reveals a highly heterogeneous volcanic subsurface composed of weathered volcanic deposits, pyroclastic materials, volcanic breccias, and massive lava flows. These lithological units exhibit distinct electrical resistivity signatures that closely correspond to their hydrogeological characteristics [16].
2. A laterally continuous deep aquifer was identified within volcanic tuff deposits exhibiting resistivity values between approximately 93 and 294 Ω"m" . The aquifer extends from elevations of approximately 1,325 m to 750 m above sea level and is interpreted as a confined to semi-confined groundwater system enclosed by less permeable volcanic breccias and massive lava flows.
3. The hydrogeological architecture beneath Mount Haruman is considerably more complex than previously recognized from shallow electrical resistivity surveys. Rather than consisting of a single shallow groundwater horizon, the volcanic sequence contains multiple groundwater-bearing layers that may contribute significantly to regional groundwater storage.
4. The interpreted resistivity distribution indicates that groundwater occurrence is primarily controlled by lithological heterogeneity together with fracture-enhanced secondary permeability. Permeable volcanic tuffs and weathered pyroclastic deposits constitute the principal groundwater reservoirs, whereas dense lava flows function as hydraulic barriers [17].
5. The Haruman volcanic area plays an important role as a groundwater recharge zone within the Bandung–Soreang Groundwater Basin. The identified deep aquifer has the potential to contribute substantially to regional groundwater resources, emphasizing the importance of protecting volcanic recharge areas from excessive land-use change and groundwater exploitation.

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