ZIBELINE INTERNATIONAL™ PUBLISHING

ISSN: 2523-5664 (Print)
ISSN: 2523-5672 (Online)
CODEN: WCMABD

Water Conservation & Management (WCM)

DOI: http://doi.org/10.26480/wcm.03.2025.603.610

CrossMark

RESEARCH ARTICLE

AQUIFER POTENTIAL DETECTION USING ELECTRICAL RESISTIVITY TOMOGRAPHY (ERT) TO PROVIDE WATER NEEDS IN PROBOLINGGO, INDONESIA

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Article History:

Received 11 July 2025
Revised 21 August 2025
Accepted 17 September 2025
Available online 1 October 2025

ABSTRACT

Groundwater is vital for socio-economic development worldwide, as it sustains communities and supports various industries. Indonesia, especially the island of Java, has a unique geological setting, characterized by a volcanic aquifer associated with andesitic stratovolcanoes, which contributes to the availability of high-quality groundwater. However, groundwater in volcanic terrains is often complex and unidentified due to heterogeneous subsurface conditions, particularly in regions experiencing water scarcity and environmental degradation. This study employed Electrical Resistivity Tomography (ERT) using the ADMT 300HT2 to characterize aquifers in seven villages of Probolinggo Regency, East Java. The research encompasses seven villages: Maron Kidul, Wonorejo, Sumberan, Brumbungan Kidul, Jangur, Tegasan Kidul, and Alas Tengah. The results revealed resistivity values ranging from 0.3 to 60 Ωm, with low values (<5 Ωm) indicating clay-rich impermeable layers and higher values (>30 Ωm) corresponding to productive aquifers such as volcanic sandstone, sandy breccia, and silt sand. Aquifers were identified at depths of 20–50 m (unconfined) and >100 m (confined), with the highest potential observed in Wonorejo, Sumberan, and Tegasan Kidul villages. These findings provide crucial insights for local government authorities, offering hydrogeologically based recommendations for optimal drilling sites and facilitating the development of sustainable groundwater management strategies in Probolinggo Regency.

KEYWORDS

Aquifer characterization, groundwater, Electrical Resistivity Tomography (ERT), Water resource management.

1. INTRODUCTION

Access to reliable groundwater is fundamental to socio-economic development and human well-being worldwide (Velis et al., 2017). In Indonesia, groundwater plays a particularly crucial role, with much of the population relying on volcanic aquifers generated by the subduction area of the Indo-Australian Plate to the bottom of the Eurasian Plate. Eastern Java, the focus of this study, hosts several large stratovolcanoes that supply high-quality groundwater through springs, artesian wells, and pumping wells. Among these, the aquifer systems on the northeastern slope of the Bromo-Tengger volcano are of growing importance due to increasing water demand from local communities and industries.

Despite their importance, andesitic volcanic aquifers remain poorly characterized. These aquifers are highly heterogeneous because stratovolcanoes exhibit substantial lateral and vertical variability in their geological facies, which directly control aquifer structure and groundwater flow, depending on their distance from central volcanic vents (Velis et al., 2017; Millett et al., 2024; Vessell and Davies, 1981). This complexity makes predicting aquifer geometry and groundwater availability challenging, requiring a multidisciplinary approach that combines geology, hydrogeology, and geophysics (Baud et al., 2024; Vittecoq et al., 2019).

Electrical resistivity tomography (ERT) is widely used in volcanic settings because it is sensitive to resistivity contrasts and can reveal subsurface stratigraphy and aquifer zones (Belle et al., 2019; Fadillah et al., 2023). However, the application of ERT in an andesitic volcanic context is still limited by the method itself, namely the depth of investigation and the need for well logs to be calibrated. For example, detailed characterization cannot delineate the aquifer's boundaries (Toulier et al., 2019).

ERT operates by utilizing variations in the electrical properties of subsurface materials, enabling the mapping of stratigraphic structure and the identification of underground aquifers (Yin et al., 2020; Hsu et al., 2010; Zhu et al., 2017). ERT concludes the result in resistivity values, whereas the relationship between resistivity values and geology is complex. Various rocks may exhibit different responses or wide resistivity ranges from site to site, depending on factors such as grain size, porosity,

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Cite The Article: Listyo Yudha Irawan, Rizal Sulaiman, Damar Panoto, Widodo Eko Prasetyo, Abdullah Alfarabi, Denisa Aulia Pratiwi, Mohammad Tah ir Mapa (2025). Aquifer Potential Detection Using Electrical Resistivity Tomography (Ert) To Provide Water Needs In Probolinggo, Indonesia. Water Conservation & Management, 9(3): 603-610.

water saturation, and even secondary porosity. Therefore, an ERT survey must first be conducted in areas where the geology and/or hydrogeology settings are locally known to correctly calibrate resistivity values on outcrops or borehole logs, for instance. Subsequently, additional profiles can be extended from this initial point to the identified objects of interest. This methodical technique must be subject to review based on the daily data collection analysis to adapt to the next-line acquisition.

This study addresses this gap by refining the link between resistivity and lithology in an andesitic volcanic aquifer. Specifically, it (i) examines the geological facies of the research area, (ii) identifies the relationships between geological facies and aquifers/aquicludes, and (iii) discusses the resistivity ranges and the geological facies, intending to improve hydrogeological interpretation in complex volcanic terrains. In line with previous findings, the aquifer potential in Probolinggo also varies depending on lithological conditions, topography, soil type, and land use (Irawan et al., 2024).

2. Materials And Methods

2.1 Study Area

The research area for surface water watersheds is located within the Pekalen watershed. The general methodology employed is ERT surveys, which have been conducted on known geological and hydrogeological settings, including outcrops, boreholes, and springs. These surveys aim to determine the resistivity value and interpret the subsurface geological and hydrogeological units (aquifers/aquicludes). The picture below represents the distribution of survey locations based on Geological Formation.

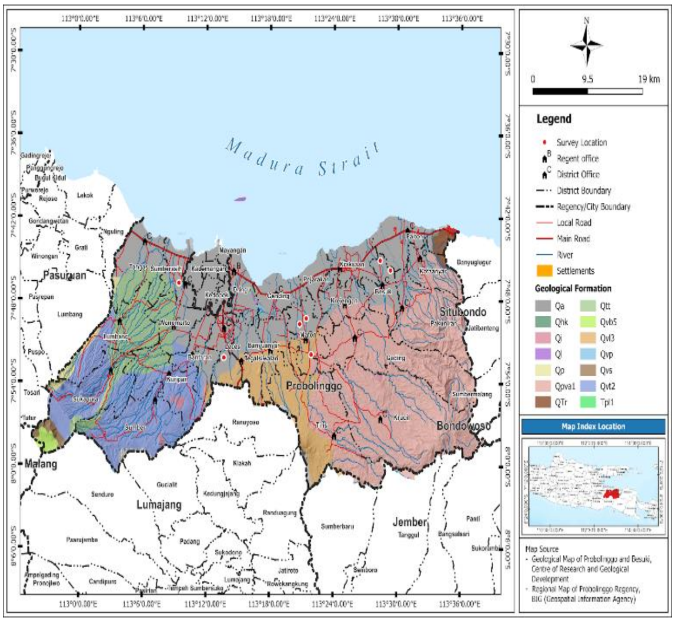


Figure 1: Localization of the study area based on regional geology sketches and Google photographs.

The research location is characterized by alluvial geological formations (Qa) with a morphology consisting of lowlands. A total of six survey locations are included in alluvium geology, and one is located in the Argopuro volcanic geological formation (QVA). Alluvium geological formations generally have higher groundwater availability than Argopuro geological formations. Geological conditions greatly affect the characteristics, availability, and quality of groundwater in an area. First of all, the type of rock and geological structure greatly determines whether an area has a good aquifer or not. Permeable rocks such as sand, gravel, and weathered rocks have pores that allow water to seep in. In contrast, solid rocks such as clay can become a layer that is almost impermeable to water, affecting the ability of water to flow into the aquifer.

The geological structure, such as folds, faults, or cracks in the rock, also has an effect. They can be water flow paths or restrict water flow in rocks. Topography also plays a role: the slope of the slope can affect the direction and speed of groundwater flow. Areas with steep slopes tend to have faster and larger water flows than flat areas. Additionally, geology also influences hydrogeological conditions, including groundwater recharge areas. For example, rainwater can quickly seep into the soil and fill the aquifer in karst formations. This condition is important in water resources management to ensure sustainability.

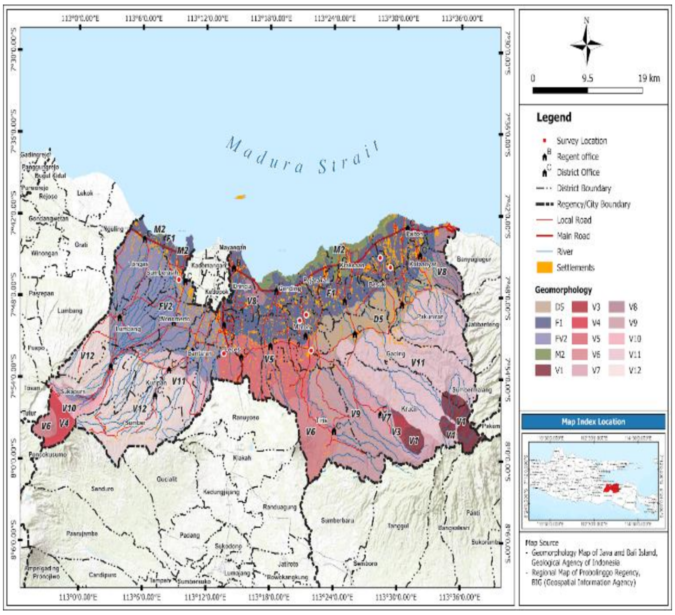


Figure 2: Localization of the study area based on the regional geomorphology sketch and Google photographs.

The geomorphology of Probolinggo Regency consists of 15 geomorphological units. There are five origins of landforms in Probolinggo Regency, namely: Formations of volcanic origin, denudational, fluvial, volcanic fluvial, and marine. In the southern region, volcanoes dominate several mountains that play an active role in this process, such as Mount Bromo, Mount Lamongan, and Mount Argopuro. The central and northern regions have a mix of landforms, including fluvial, volcanic fluvial, and denudational. The land formation is still affected by the original material of the volcanic formation in the southern region. Meanwhile, in the coastal area, the formations that emerged were formations of marine origin as a result of the existence of the Java Sea in the north of Banyuwangi Regency.

Most survey locations are in areas with fluvial origins, including Brumbungan Kidul Village, Wonorejo Village, Sumberan Village, Alas Tengah Village, and Jangur Village. Meanwhile, the area includes two villages of volcanic origin: Maron Kidul Village and Tigasan Kulon Village. Sloping to flat topography dominates in areas with fluvial base formations. The slopes on this slope are almost invisible and can be difficult to identify visually. Areas with sloping topography are often found in lowlands, vast river basins, or flat coastal areas, such as the Probolinggo Regency's northern region. Alluvial soils dominate this area. Alluvial soils are formed by sedimentation resulting from the deposition of materials such as soil, sand, mud, and gravel that are transported and deposited by river or flood water.

The youngest deposits in the study area are Aluvium deposits, consisting of clay containing silt and blackish fresh sand, brownish-weathered color, medium clay-sand grain size, angular grain shape, closed-medium container, poor-medium sorting, poor-medium permeability, soft hardness, and can be squeezed. This deposit is a sediment that occupies the largest area in the research area, a flood runoff flatbed from the main river in the form of a swamp. The determination of the age and deposition environment of this unit was carried out by comparing previous research based on lithological characteristics. This unit can be compared to Alluvium Deposits.

2.2 Data Collection, Processing, and Analysis

The ADMT (Audio Magneto Scanner) is a geophysical exploration tool that utilizes high-frequency electromagnetic (EM) signals to investigate various underground cavities, ranging from shallow to deep [14-15]. The data obtained are electric field signals (E) and magnetic field signals (H). Both data sets can produce a series of frequencies to get the pseudo-type ground curve and the angle of the impedance phase. ADMT can provide deeper and broader data in a relatively short time.

ERT measurements have been very successful in detecting and describing subsurface cavities in a variety of geological conditions that can cause engineering and construction problems (Chambers et al., 2007; Torgashov et al., 2016). The ERT technique aims to identify electrical resistivity variations in the depth of underground formations by using resistivity meters to measure several parameters, including apparent resistivity, conductivity, and depth.

Based on the results of interviews and map interpretation, the location determination was spread across seven points of the area, namely the villages of Maron Kidul, Brumbungan Kidul, Wonorejo, Sumberan, Jangur, Tigasan Kulon, and Alas Tengah. This area is located on moorlands, rice fields, and settlements. Based on the interviews and observations, data were obtained indicating that most people use dug wells with depths ranging from 4 to 23 meters. The groundwater used by the community is in the free aquifer layer. This is known based on the characteristics of the water found to have a mixture of sand and dust materials in groundwater. Then, in the dry season, discharge is decreased until there is no water at all.

When viewed from topographic and geological conditions, Maron Kidul village is situated in a hilly topographic area with volcanic rock formations, which poses a potential risk of contaminated water. Meanwhile, other measurements have plain topographic conditions with the dominance of alluvium formations. Hence, this area has a higher potential for groundwater because it is composed of axial rocks. After initial identification, ADMT measurements were carried out using ADMT 300 HT2, which uses the magnetotelluric working principle. This principle is based on the process of wave propagation and electromagnetic induction that occurs in subsurface anomalies. The electromagnetic field that penetrates below the surface generates a secondary electric and magnetic field (Eddy current/telluric current) in the conductive material inside the earth, which is then recorded by the sensor. The value of material resistivity in magnetotellic data can be obtained by solving Maxwell's equations. This equation describes the behavior of the electromagnetic field in the synthesis of laws applicable to electromagnetic phenomena.

The magnetotelluric method investigates the electrical structures below the surface using artificial (controlled) or natural sources of electromagnetic fields. In artificial or controlled magnetotellic methods, electromagnetic signals are generated by EM transmitters. In natural magnetotelluric exploration, electromagnetic fields originate from global lightning or spherics (short-period signals) and solar wind activity in the ionosphere (long-period signals). The measured field value on the surface contains information about the conductivity of subsurface rocks, so that by measuring the electric field and magnetic field simultaneously in the exact location using a comparison of the magnetic field values at various frequencies, the conductivity value of the rock for each depth can be determined.

In the magnetotelluric method, if the frequency is larger or the period is lower, the depth measurement power will be lower, the attenuation will be faster, and vice versa. The impedance value, which is the ratio between the electric field and the magnetic field, affects the resistivity structure of the measured place. The results of the ADMT measurement are then sent wirelessly using Bluetooth to the AIDU Prospecting software using the AIDU Golden Rod (AGR) instrument.

The electrode method recorded resistivity using AGR-300 HT2 with a track length of 2m. Furthermore, the results were interpreted and visualized using AIDU Prospecting software to determine the position of the underground aquifer and the type of material that exists.

3. Results And Discussion

3.1 Results

The ADMT line in the research area has a variable line length. The data collection process is carried out at every 2-meter interval, consisting of various measurement points with a cross-sectional depth of up to 300 meters. Data collection consists of seven locations: Maron Kidul Village, Wonorejo Village, Sumberan, Alas Tengah, Brumbungan Kidul, Jangur, and Tegasan Kidul Village.

Subsurface Characterization

a) Lithology and Resistivity:

The study identifies various lithological formations (volcanic sandstone, silt sand, gravel clay, breccias, etc.) with resistivity values ranging from 0.3–60 Ωm across seven locations.

Higher resistivity (>30 Ωm) corresponds to productive aquifers like sandy breccia and volcanic sandstone, while lower resistivity (<5 Ωm) is associated with impermeable layers such as clay.

b) Aquifer Depths and Types:

Unconfined aquifers are found at shallow depths (20–50 m) in most locations, ideal for dug wells and springs.

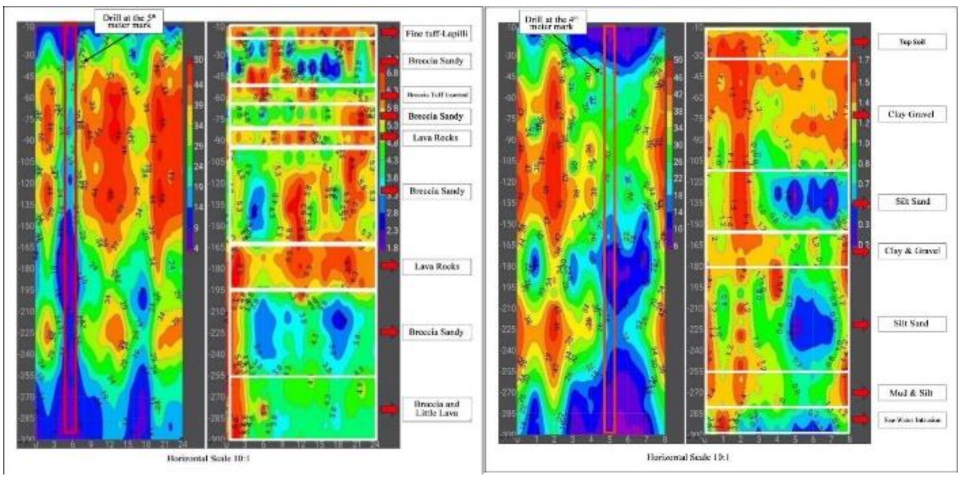
Confined aquifers are identified in deeper layers (>100 m), requiring drilling for access.

Aquifer Potential by Location:

Table 1: Aquifer Potential by Location, Along with Lithology, Resistivity Range, and Recommended Drilling Depth

Location	Aquifer Potential	Lithology	Resistivity Range (Ωm)	Recommended Drilling Depth (m)
Maron Kidul	Moderate	Volcanic sandstone	2.3–7.2	37
Brumbungan Kidul	Low	Clay gravel	0.3–1.7	45
Wonorejo	High	Silt, sand, gravel, and clay	7–60	37
Sumberan	High	Volcanic sandstone	22–54	40
Jangur	Moderate	Silt, sand, gravel, and clay	16–45	38
Tegasan Kulon	High	Sandy breccia	43–48	47
Alas Tengah	Moderate	Silt, sand, gravel, and clay	14–49	37

The following are visualization results from ADMT:



(a) **(b)**

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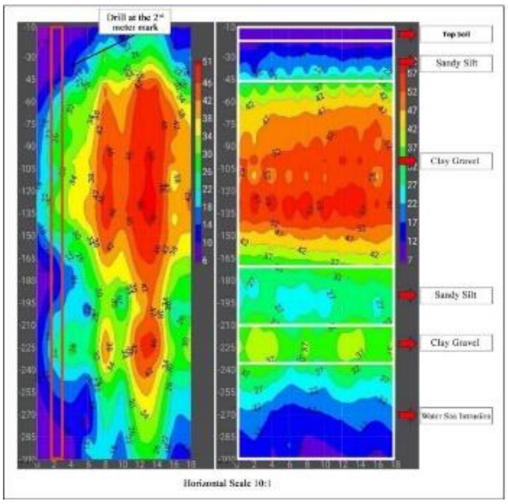

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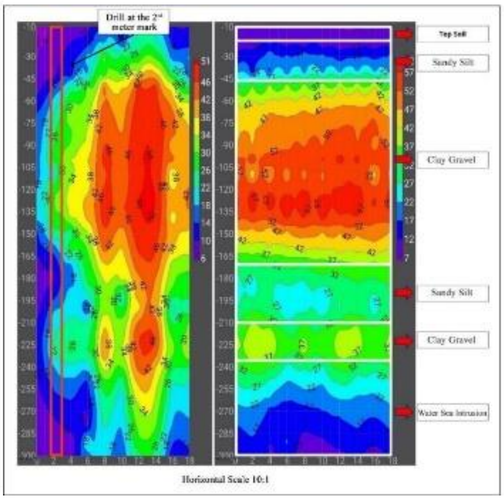

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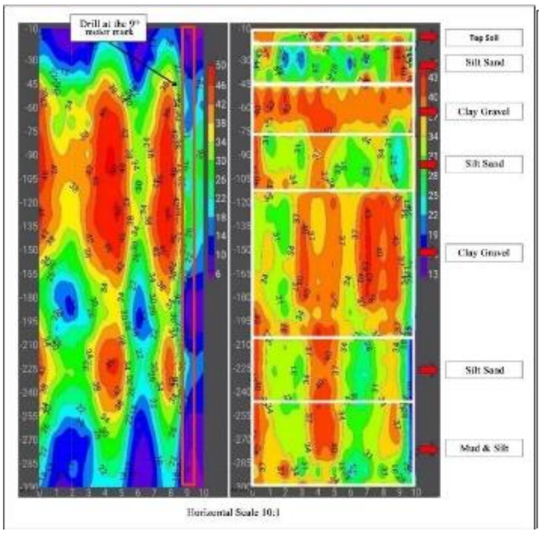

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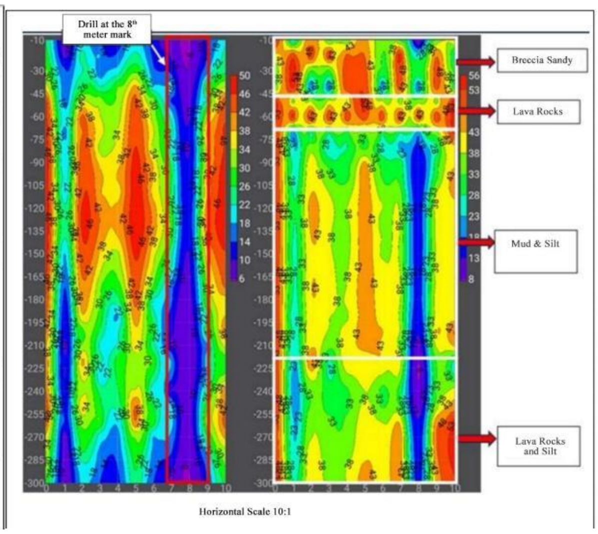

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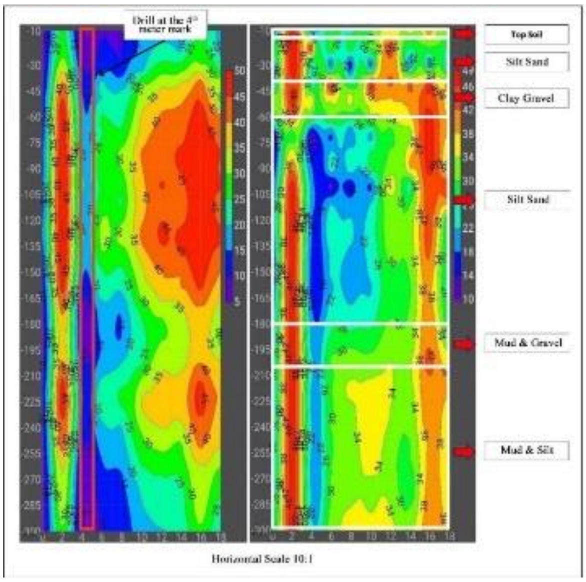

(g)

Figure 3: Inverted ERT Model (a) Maron Kudul Village (b) Brumbungan Kidul Village (c) Wonorejo Village (d) Sumberan Village (e) Jangur Village (f) Tigasan Kulon Village (g) Alas Tengah Village.

3.1.1 Maron Kidul Village

The ADMT line in Maron Kidul Village has a line length of 24 meters, and data collection is carried out at every 2-meter interval, consisting of 12 measurement points. This line's range of resistivity values is 1.8 - 7.2 Ωm. In the subsurface cross-section of this line, it is interpreted to be composed of volcanic sandstone lithology, fine tuff, tuff intercalated breccia, and andesite lava. The recommended drilling point is in an unconfined aquifer in the form of volcanic sandstone in the 5th meter of the line with a depth of 37 meters. Maron Kidul Village features volcanic rock formations composed of young Argopuro volcanic rocks (Qva) from the early and late Pleistocene, characterized by breccia and tuff. The characteristic of groundwater quality in volcanic lithology is that it easily absorbs and passes water, which causes areas with volcanic rock lithology to have poor water because it is very easy to pass surface water. Free aquifers can be found at a depth of 20-50 meters in the form of sand breccia, in which the Argopuro Breccia is the last result of the activity of Mount Argopuro. Judging from the topographic and geological conditions, terrain with hilly topography and volcanic rock formations has poor groundwater potential. The details of the data interpretation can be seen in the following table:

Table 2: Results of Interpretation of ADMT of Maron Kidul Village

Lithology	Deep (m)	Resistivity (Ohm.m)
Lapilli end dive	0 - 20	6.3 - 7.2
Breccia Sandy (unconfined aquifer)	20 - 50	2.3 - 3.8
Breccia Tuff Inserted	50 - 65	4.5 - 6.8
Breccia Sandy (semi-confined aquifer)	65 - 80	2.3 - 3.8
Lava Rocks	80 - 95	6.3 - 7.2
Breccia Sandy (first confined aquifer)	95 - 165	2.3 - 3.8
Lava Rocks	165 - 195	6.3 - 7.2
Breccia Sandy (Second confined aquifer)	195 - 255	2.3 – 3.8
Breccia and little lava	255 - 300	3.8 - 6.3

3.1.2 Brumbungan Kidul Village

The ADMT line in Brumbungan Kidul Village has a line length of 8 meters, and data collection is carried out at every 2-meter interval consisting of 4 measurement points. This line's range of resistivity values is 0.8 - 6.8 Ohm.m. In the subsurface cross-section of this line, it is interpreted as topsoil, volcanic sandstone, weathered lava, gravel, clay, and gravel mud. The recommended drilling point is at the 5th meter with a depth of 45 meters. The lithology of the rocks around the measurement point in Brumbungan Kidul Village is influenced by alluvium formations (Qa), which comprise the following constituent rocks: clay, mud, sand, gravel, shells, blocks, and plant residues. Based on identification with ADMT measurements, the rocks at the measurement point include: topsoil layer, gravel, clay, silt, sand, and seawater intrusion. The surface layer is dominated by a clay layer extending up to a 30-meter depth. The surface layer is used as agricultural land in the form of fields. The complete details can be seen in the following table.

Table 3: Results of ADMT Interpretation of Brumbungan Kidul Village

Lithology	Deep (m)	Resistivity (Ohm.m)
Top Soil	10 - 30	1 – 1.5
Clay Gravel	30 - 110	1.2 - 1.7
Sand Silt (First Confined Aquifer)	110 - 153	0.3 - 0.7
Clay Gravel	153 - 180	1.2 - 1.7
Sand Silt (Second Confined Aquifer)	180 - 225	0.3 - 0.7
Mud and Silt	255 - 280	0. 7 - 1.4
Water Sea Intrusion	280 - 300	0.2 - 0.7

3.1.3 Wonorejo Village

The ADMT line in Wonorejo Village has a line length of 18 meters, and data collection is carried out at every 2-meter interval consisting of 9 measurement points. This line's range of resistivity values is 7 - 60 Ohm.m. The subsurface cross-section of this line is interpreted as topsoil, volcanic sandstone, gravel, clay, gravel mud, and weathered lava. The recommended drilling point is located in the unconfined aquifer, which consists of volcanic sandstone, at 37-meter depth, within the 2nd meter of the line. Alluvium (Qa) formations influence the lithology of the rocks around the measurement point of Wonorejo Village; the constituent rocks include Clay, mud, sand, gravel, blocks, and plant residues. Based on identification with ADMT measurements, the rocks at the measurement point include the topsoil layer, gravel, clay, silt, sand, mud, and seawater intrusion. The surface layer is dominated by a dispute of silt and sand layers up to 20-meter depth. The surface layer is used as agricultural land in the form of fields. The complete details of the data can be seen in the following table.

Table 4: Results of Interpretation of the Wonorejo Village ADMT

Lithology	Deep (m)	Resistivity (Ohm.m)
Top Soil	0 - 20	7 - 12
Silt Sand (Free Aquifer)	20 - 45	12 - 27
Gravel Clay	45 - 170	42 - 60
Silt Sand (Depressed Aquifer 1)	170 - 210	22 - 27
Mud Gravel	210 - 238	27 - 42
Seawater Intrusion	238 - 300	7 -27

3.1.4 Sumberan Village

The ADMT line in Sumberan Village has a line length of 8 meters; data collection is carried out at every 2-meter interval consisting of 4 measurement points. This line's range of resistivity values is 18-58 $\Omega \cdot m$. In the subsurface cross-section, this line is interpreted as topsoil, volcanic sandstone, gravel, clay, and gravel mud. The recommended drilling point is in the unconfined aquifer in the form of volcanic sandstone in the 3rd meter of the track with a depth of 40 meters. Alluvium (Qa) formations influence the lithology of the rocks around the measurement point of Wonorejo Village; the constituent rocks include: Clay, mud, sand, gravel, blocks, and plant residues. Based on identification with ADMT measurements, the rocks at the measurement point include topsoil layers, silt, sand, gravel, clay, and seawater intrusion. The surface layer is dominated by silt sand disputes up to 12-meter depth. The surface layer is used as agricultural land in the form of fields and settlements. The complete details of the data can be seen in the following table.

Table 5: Results of Interpretation of ADMT Sumberan Village

Lithology	Deep (m)	Resistivity (Ohm.m)
Top Soil	0 - 12	46 - 58
Silt Sand (Free Aquifer)	12 - 50	22 - 34
Gravel Clay	50 - 62	38 - 54
Silt Sand (Semi-Depressed Aquifer)	62 - 115	22 - 34
Clay, Pebbles, and Mud	115 - 164	34 - 54
Silt Sand (Depressed Aquifer)	164 - 239	22 - 34
Clay, Pebbles, and Mud	238 -300	34 - 54

3.1.5 Jangur Village

The ADMT track in Jangur Village has a line length of 10 meters, and data collection is carried out at every 2-meter interval, consisting of 5 measurement points. This line's range of resistivity values is 13 - 45 Ohm.m. In the subsurface cross-section, this line is interpreted as topsoil, volcanic sandstone, gravel, clay, and gravel mud. The recommended drilling point is in the unconfined aquifer in the form of volcanic sandstone in the 9th meter of the line with a depth of 38 meters. Alluvium (Qa) formations influence the lithology of the rocks around the measurement point of Wonorejo Village; the constituent rocks include: Clay, mud, sand, gravel, blocks, and plant residues. Based on identification with ADMT measurements, the rocks at the measurement point include topsoil layer, silt, sand, gravel, clay, mud, and silt. The surface layer is dominated by a dispute of silt and sand layers up to 15 meters in depth. The surface layer is used as agricultural land in the form of highways. The complete details of the data can be seen in the following table.

Table 6: Results of Interpretation of ADMT Sumberan Village		
Lithology	**Deep (m)**	**Resistivity (Ohm.m)**
Top Soil	0 – 15	34 – 40
Silt Sand (Free Aquifer)	15 – 44	16 – 25
Gravel Clay	44 – 75	34 – 45
Silt Sand (Depressed Aquifer 1)	75 - 110	16 – 25
Gravel Clay	110 - 250	34 – 45
Silt Sand (Depressed Aquifer 2)	250 - 245	16 – 25
Mud and Silt	245 - 300	28 – 43

3.1.6 Tigasan Kulon Village

The ADMT line in Tigasan Kulon Village has a line length of meters; data collection is carried out at every 2-meter interval, consisting of 5 measurement points. This line's range of resistivity values is 8 - 56 Ohm.m. The subsurface cross-section of this track is interpreted as tuffaceous breccia, weathered lava, mud, and silt. The recommended drilling point is in the confined aquifer in the form of tuffaceous breccia at a 8th meters and at a depth of 30 meters. Alluvium (Qa) formations influence the lithology of the rocks around the measurement point of Wonorejo Village; the constituent rocks include: Clay, mud, sand, gravel, blocks, and plant residues. Based on identification with ADMT measurements, the rocks at the measurement points include Sandy breccia, lava rocks, mud and silt, and lava and silt rocks. Breccia disputes and silt sand dominate the surface layer at 47-meter depth. The surface layer is used as agricultural land in the form of fields. The complete details of the data can be seen in the following table.

Table 7: Results of ADMT Interpretation of Tigasan Kulon Village		
Lithology	**Deep (m)**	**Resistivity (Ohm.m)**
Sandy Breccia (Depressed Aquifer)	10 – 47	43 – 48
Lava Rocks	47 – 68	48 – 53
Mud and silt (Stressed Aquifer)	68 - 220	18 – 43
Lava and Siltstone	220 - 300	7 – 38

3.1.7 Alas Tengah Village

The ADMT line in Alas Tengah Village has a line length of 18 meters, and data collection is carried out at every 2-meter interval, consisting of 9 measurement points. This line's range of resistivity values is 10-49 Ω · m. In the subsurface cross-section, this line is interpreted as topsoil, volcanic sandstone, gravel, clay, and gravel mud. The recommended drilling point is in the unconfined aquifer as volcanic sandstone in the 4th meter of the line, with a depth of 37 meters. Alluvium (Qa) formations influence the lithology of the rocks around the measurement point of Wonorejo Village; the constituent rocks include: Clay, mud, sand, gravel, blocks, and plant residues. Based on identification with ADMT measurements, the rocks at the measurement points include Topsoil, silt, sand, gravel, clay, silt, sand, gravel, wells, and silt mud. The surface layer is dominated by silt sand at a depth of 12 meters. The surface layer is used as agricultural land in the form of fields. The complete details of the data can be seen in the following table.

Table 8: Results of ADMT Interpretation of Alas Tengah Village		
Lithology	**Deep (m)**	**Resistivity (Ohm.m)**
Top Soil	0 – 12	34 - 38
Silt Sand (Free Aquifer)	12 – 40	14 - 26
Gravel Clay	40 – 60	34 - 49
Silt Sand (Depressed Aquifer)	60 - 180	14 - 26
Mud and Gravel	180 - 205	26 - 38
Mud and Silt	164 – 239	30 - 42

4. Discussion

The findings from this study have enabled the development of a preliminary hydrogeologic conceptual model for the Probolinggo district. The model shows that the main recharge areas are on the northeast slope of Mount Bromo-Tengger and the northwest slope of Mount Iyang-Argopuro (Figure 5). These areas are essential for understanding groundwater dynamics and aquifer recharge mechanisms. The model enables the interpretation of multiple-layered aquifers with diverse productivity potential. The results also indicate that aquifers occur at different depths, ranging from unconfined to confined systems, and are strongly influenced by lithology and geomorphology.

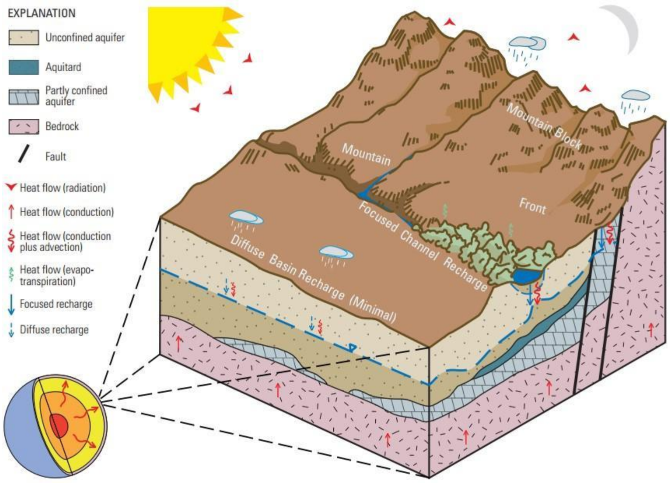

Figure 4: A generic conceptual model of natural recharge processes within the atmospheric circulation features (Blasch et al., 2007).

Figure 5: It can be estimated that the natural recharge processes are derived from the northeast slope of the Bromo-Tengger volcano and the northwest slope of the Iyang-Argopuro volcano, which consist mainly of lava flow complexes with middle-high permeability (modified from (Hendrayana et al., 2024).

However, at this stage, the model is not mature enough to serve as a basis for formulating sustainable water management policies. The study discussed that such conceptual models still contain a high degree of uncertainty due to data limitations, especially in the central region, which is the largest water extraction zone (Enemark et al., 2019). Therefore, additional data collection is strategically required to refine the model. Although not fully complete, the model provides a clear framework for further research and an initial direction for more sustainable management of groundwater resources in the region.

A crucial step forward involves obtaining detailed geological data, particularly in the "midstream" areas where water extraction is most intensive. These areas encompass springs, dug wells, borewells, and artesian wells. The geological structure of the aquifer plays a pivotal role in determining water availability and quality, as shown in studies such as those by (Fadillah et al., 2023; Belle et al., 2019). Understanding the geological heterogeneity will aid in pinpointing high-potential zones for groundwater extraction.

Piezometric level measurements are another essential component for building a robust hydrogeological model. These measurements help create a piezometric map to better understand water fluxes, underground sub-watersheds, and aquifer interconnections. This aligns with methodologies discussed, who emphasized the role of electrical resistivity tomography (ERT) in characterizing groundwater storage heterogeneity and supporting hydrogeological interpretations by (González et al., 2021).

Quantifying water outflows, both natural and anthropogenic, is critical. Field surveys, database analyses, and remote sensing techniques can provide comprehensive estimates of water usage. Such efforts have been successfully demonstrated, who combined electrical sounding and tomography to understand the hydrogeological dynamics of artesian springs by (Dumont et al., 2021).

The interaction between rivers and groundwater remains an area of uncertainty. Conducting gauging and electrical conductivity measurements during dry seasons will enhance our understanding of these interactions. Such investigations are critical for accurate water budget estimations and identifying pollutant transfer pathways, as noted in their characterization of surface and subsurface interactions using ERT and geophysical methods (Sauret et al., 2015).

Geophysical campaigns, particularly those utilizing ERT, are indispensable for calibrating local geological and hydrogeological parameters. This analysis demonstrated the value of 3D resistivity data modeling in identifying aquifer potential in volcanic breccia formations, emphasizing the importance of calibration with existing wells and outcrops (Fatahillah et al., 2023).

Another priority is acquiring comprehensive meteorological datasets. These datasets should include measurements of rainfall, temperature, humidity, and river discharge. Remote sensing and climate models can complement in situ data collection, as So recommended in their work on hydrogeological complexities in volcanic regions (nkamble et al., 2022).

The findings from this study emphasize the importance of understanding subsurface characteristics in volcanic regions to ensure sustainable groundwater management, particularly in areas such as Probolinggo Regency, East Java, which rely on aquifers for their water supply. Electrical Resistivity Tomography (ERT) has proven effective for detecting subsurface resistivity anomalies, allowing researchers to identify key aquifer structures. The results demonstrated that the primary aquifers are located at varying depths across the different study sites and are influenced by the region's lithology and geomorphology. The existence of multiple aquifers at various depths (ranging from unconfined to confined aquifers) demonstrates the complexity of the local hydrogeological system. Probolinggo's unique challenges, including ecotourism development, deforestation, and uncontrolled groundwater pumping, necessitate an integrated management approach.

The results from Maron Kidul, Wonorejo, Sumberan, Brumbungan Kidul, Tigasan Kulon, Jangur, and Alas Tengah villages highlight the variability of subsurface materials and the importance of lithological and structural controls on aquifer potential. For example, volcanic sandstones, breccias, and silt sands represent favorable aquifer materials, whereas compact clay and lava rock act as aquicludes or barriers to water flow. This aligns with the findings of previous studies who also emphasized the role of geological facies in aquifer characterization within volcanic settings (Belle et al., 2019; Fadillah et al., 2023).

Seasonal variability significantly impacts aquifer recharge. Resistivity variations and lithological differences indicate that recharge occurs preferentially in permeable layers. This reinforces the observations of who noted the spatial and temporal heterogeneity of recharge in volcanic aquifers. Understanding groundwater–surface water interactions is vital. Rivers and springs suggest a bidirectional relationship, where groundwater extraction may influence surface water bodies (Vittecoq et al., 2019). This is consistent with findings, who highlighted the importance of these interactions in maintaining aquifer sustainability by (Toulier et al., 2019).

The interaction between groundwater and surface water systems remains an area requiring further investigation. The presence of rivers and springs within the study area suggests that surface water bodies might play a role in the recharge of shallow aquifers, and vice versa, they might be affected by groundwater extraction. highlight the significance of such interactions in maintaining aquifer sustainability, especially in volcanic regions where recharge is spatially and temporally heterogeneous (Toulier et al., 2019).

The findings also highlight the need for government involvement in establishing policies for groundwater use, particularly in areas where agriculture and settlements predominate. Uncontrolled groundwater pumping can significantly decline aquifer levels, as observed during the dry season. This highlights the importance of regulating and promoting public awareness campaigns that emphasize sustainable water use practices.

In conclusion, the application of ERT in Probolinggo Regency has provided a clearer picture of the subsurface hydrogeological conditions, aiding in identifying viable aquifer layers. However, the complexity of volcanic aquifer systems necessitates ongoing research, comprehensive monitoring, and well-informed water management policies to prevent overexploitation and ensure a sustainable water supply for future generations.

5. Conclusions

This research highlights the effectiveness of integrating Electrical Resistivity Tomography (ERT) with geological and hydrogeological data to characterize the complex subsurface of Probolinggo Regency. It identified multiple aquifer systems, with productive zones typically associated with volcanic sandstone, sandy breccia, and silt sand at resistivity values above 30 Ωm, while clay and lava serve as aquicludes. Aquifers were found at varying depths, from shallow unconfined to deep confined systems, emphasizing the area's lithological and structural complexity. The findings support the need for sustainable groundwater management, which involves ongoing data collection, borehole calibration, and hydrogeological modeling. This research offers a foundation for informed water resource planning and recommends future studies to expand spatial coverage and assess the impacts of land use and extraction.

Acknowledgment

The authors are grateful to the Lembaga Penelitian dan Pengabdian kepada Masyarakat (LPPM) Universitas Negeri Malang, for funding this research. We also extend our thanks to CV. Fadira Perdana and Dinas Perumahan, Pemukiman dan Pertanahan Kabupaten Probolinggo, for their valuable assistance in data collection and field surveys.

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