Article

Identification of Aquifer Potential Using Electrical Resistivity Tomography (ERT) Method in the Karst Area of Giritontro, Wonogiri, Central Java

Article Info

Nadia Putri Nur Asri[1*], Rahma Puspa[2], Anggara Putra Prasetya[2], Budy Santoso[1]

[1]Department of Geophysics, Faculty of Mathematics and Natural Science, Universitas Padjadjaran, Indonesia
[2]Geological Agency, Ministry of Energy and Mineral Resources – Center for Groundwater and Environmental Geology

Abstract. Karst regions exhibit unique geological characteristics due to the dissolution of carbonate rocks, lending to the formation of complex underground aquifer systems. This study was conducted in BayemharjoVillage, Giritontro Sub-district, Wonogiri Regency part of the Sewu Karst Zone to identify aquifer potential using the dipole dipole electrical resistivity method. The survey was carried out along three measurement lines ranging from 216 to 710 meters in length, utilizing 72 electrodes with 10 meter spacing. The research involved data acquisition, processing, and interpretation using specialized resistivity software. Interpretation result revealed rock layers with potential as aquifers, particulary those with porous and permeable lithologies such as sandy limestone. Additionally, the presence of aquitard and aquiclude layers was identified, acting as barriers or flow paths for groundwater movement. The resistivity patterns and geological structures indicate the existence of groundwater pockets at various depths, which are crucial for managing clean water resources in this drought-prone region. The resistivity method prove to be effective in delineating aquifers zone within the complex karst environment.

Corresponding Author :
Nadia Putri Nur Asri
Department of Geophysicist, Faculty of Mathematics and Natural Science,
Universitas Padjadjaran, Bandung, Indonesia
Email : putrinadya605@gmail.com

1. Introduction

Karst terrains form through the dissolution of carbonate rocks particularly limestone and dolomite resulting in distinctive exokarst features (such as sinkholes and karren) and endokarst structures (such as caves, underground rivers, and water-filled cavities), Due to the high heterogeneity of karst aquifer systems, accurately characterizing their internal structural features, such as the spatial distribution and dimensions of fractures and conduits, remains a significant challenge [1]. The endokarst system functions as a natural aquifer but exhibits unique characteristics high infiltration rates and limited surface runoff making karst regions especially vulnerable to drought during the dry season. Carbonate rocks are a group of sedimentary rocks composed of carbonate minerals, and they are widely distributed across the planet, covering >15 % of the Earth's surface that is not covered by ice [2].

These rocks form important aquifers, whose high transmissivity is due to the development of the secondary structure of porosity and permeability. The peculiarity of carbonate rocks, especially limestones, is their high solubility. These rocks dissolve along fractures and stratification planes due to the flow of water percolating from the surface, carrying in solution the carbonic acid (CO_2) coming from the atmosphere and the soil [3].This dissolution, which occurs during both infiltration and groundwater flow, can lead to karstification, characterized by the development of highly conductive preferential flow paths and networks, where the direct connection between the surface of the carbonate massif and the saturated zone of the aquifer is favoured. This is due to the rapid infiltration of run-off water through the main conductive structures of the karst, through which water flows at a high velocity. Karst aquifers are often the source of large springs [4].

Groundwater migration in karst systems is primarily controlled by fractures, dissolution-enlarged conduits, and subsurface cave networks, allowing rapid infiltration and flow through highly conductive preferential pathways. The high solubility of carbonate rocks promotes the formation of interconnected underground voids, which can evolve into karst subterranean rivers or dense groundwater channels flowing beneath the surface, reflecting strong hydraulic contrasts between the rock matrix and karst openings [5].
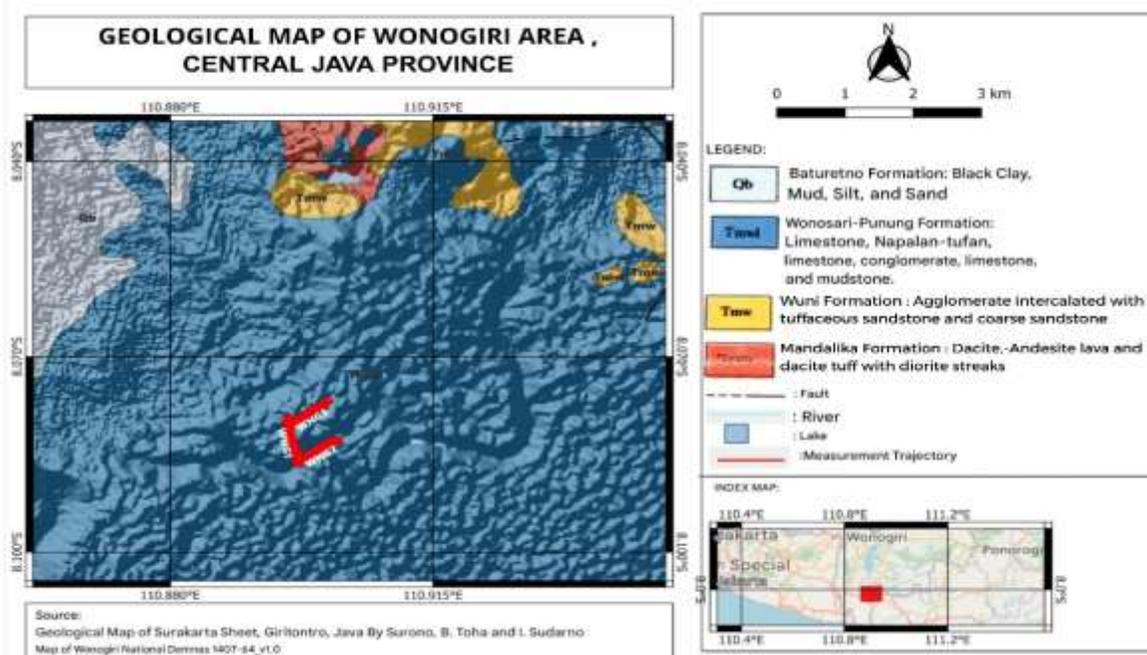

Figure 1. Regional geological map of the research area (modified from the geological map of the Turen sheet, Java)

Geologically (Figure 1), Bayemharjo Village in Giritontro District, Wonogiri Regency, lies within the Sewu Mountain Karst Zone. Its dominant lithology belongs to the Wonosari–Punung Formation (Tmwl), composed of massive limestone, tuffaceous marl, tuffaceous sandstone, and conglomerate. These rocks are porous and permeable, rendering them highly potential secondary aquifers. Meanwhile, the Mandalika Formation (Tmw) and Wuni Red Tuff (Tomm) are impermeable, while the Baturetno Formation (Qb) acts as a flow barrier. According to Ekasara, Geological structures such as faults and fissures enhance infiltration, develop subterranean flow networks, and support karst springs, Based on rainfall map data, the Wonogiri region shows a wide distribution of rainfall intensity, ranging from very low to very high categories. The majority of the area is dominated by very low rainfall intensity, with several parts experiencing low intensity. These persistently low rainfall conditions represent a key environmental issue, contributing to recurrent drought and creating substantial challenges in groundwater availability and access [6].

Hydrogeological data from this region indicate moderate to high groundwater potential, with discharge rates ranging from 5 to 25 L/s. A notable example is the Pace sinkhole (Luweng Pace), which discharges approximately 600 L/s. To systematically map the distribution of aquifer zones, geophysical approaches such as Electrical Resistivity Tomography (ERT) are particularly relevant in complex karst environments.
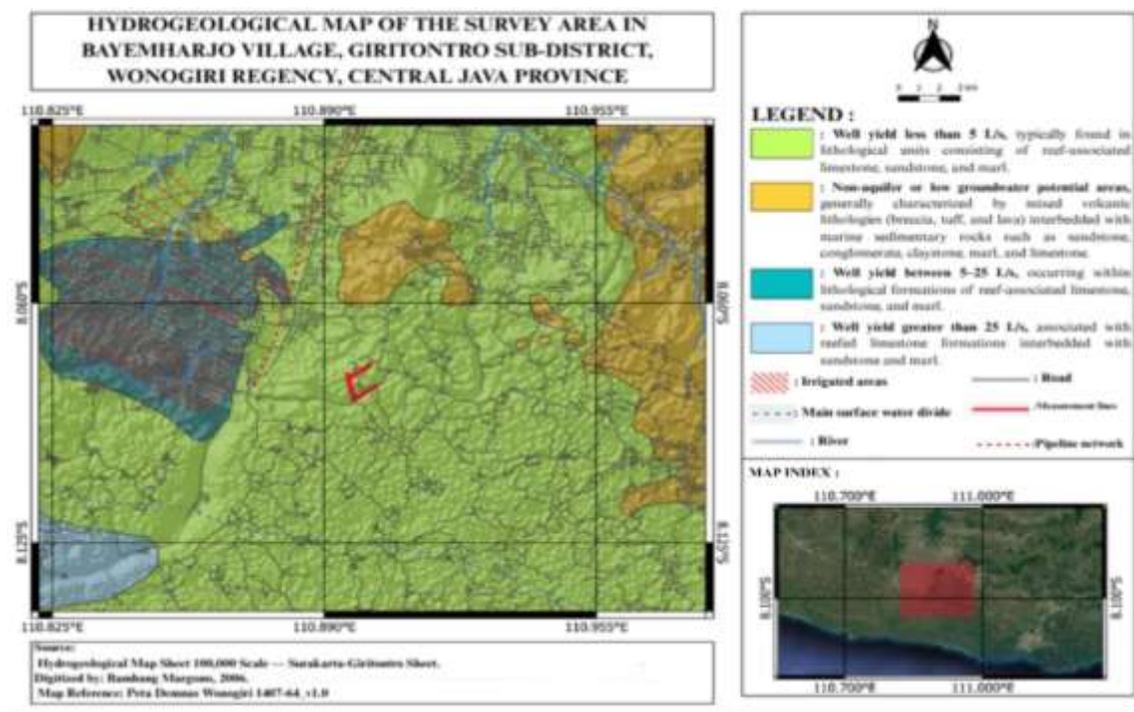

Figure 2. Hidrogeological map of the research area (modified from the geological map of the Turen sheet, Java)

Figure 2 presents the Hydrogeological Map of the Study Area in Bayemharjo Village, Giritontro District, Wonogiri Regency. The groundwater potential in this region varies significantly depending on the underlying lithology. The map shows that areas composed of layered limestone locally containing reef structures along with sandstone and marl, exhibit aquifer potential with well discharges ranging from 5 to over 25 liters per second. This suggests the presence of highly productive aquifers in

certain parts of the region. In karst environments, groundwater is typically stored beneath the surface in the form of underground rivers, indicating that the rock formations in this area have high aquifer potential.

Karst spring discharge is commonly separated into two components: baseflow, which represents the slow contribution from the saturated zone, and fast flow, which is a direct hydrological response to rainfall and reflects the rapid contribution from the infiltration zone. The ratio between these components serves as a key parameter for evaluating karst aquifer vulnerability to contamination, water availability, and drought resilience [7]. Groundwater flow in karst aquifers occurs through two primary pathways: concentrated turbulent flow within conduits (caves or karstic pipes) and diffuse laminar flow through fractures, fissures, and the low-permeability rock matrix [8].

Previous studies in the Gunungkidul karst region demonstrated that Electrical Resistivity Tomography (ERT), using Wenner Schlumberger and Dipole Dipole configurations, is effective in identifying underground rivers and pore fractures within the rock. According Wilopo, also successfully integrated geological mapping and ERT to detect subsidence zones and subsurface cavities in Gunungkidul. Global research has further reinforced the effectiveness of ERT in karst studies [9]. In China, employed a quasi-3D ERT approach to identify cavities and narrow fractures in karst rock with high accuracy [10]. In Morocco, applied a combination of VLF-EM and ERT to detect hidden underground voids [11]. Research conducted in Guangdong, China, successfully identified groundwater zones and cavities based on characteristic resistivity values. In Texas, ERT was used to trace preferential flow paths in karst aquifers. According Bienibuor, in Ghana utilized ERT for groundwater zoning, identifying resistivity values ranging from 5 to 2.200 Ωm [12]. Meanwhile, the U.S. Environmental Protection Agency (EPA) adopted ERT in its controlled aquifer recharge programs [13].

In this study, Electrical Resistivity Tomography (ERT) measurements were conducted using porous pots as potential electrodes instead of conventional copper ones. The application of 2D time-lapse electrical resistivity tomography (ERT) has the major advantage of being non-destructive and minimally invasive when measuring the electrical resistivity targeting the air/soil/rock-filled volumes and water-filled voids in highly heterogeneous aquifers to analyze changes in groundwater characteristics [14]. The novelty of this research lies in the data acquisition system, which employs porous pots still rarely used in ERT applications as potential electrodes. Despite limited usage in previous studies, this method has proven capable of producing high-quality ERT data. Therefore, this research is expected to complement and build upon previous studies in the Gunungkidul and Pacitan areas. Additionally, it aims to develop a localized hydrogeological model and provide technical recommendations to regional authorities regarding well placement and drought mitigation strategies.

The objective of this study is to identify and map the aquifer potential zones in the Bayemharjo karst region through an integrative approach combining Electrical Resistivity Tomography (ERT), local lithological data, and community well discharge information. This approach is expected to yield an accurate and applicable conceptual hydrogeological model. The model will serve as a scientific basis for groundwater management, well planning, and drought mitigation efforts by local governments [15].

2. Research Methodology
2.1. Dipole – Dipole ERT Method
Geophysical technique that allows scientists to determine variations in the electrical resistivity of soils or rocks. Different clustering algorithms can be applied to ERT in order to manage the large quantities of data generated and to better understand how these data are organized [16]. Data acquisition in this study was conducted using the Electrical Resistivity Tomography (ERT) method with a dipole–dipole configuration (Figure 3). In this configuration, current electrodes (C1 and C2) and potential electrodes (P1 and P2) are placed separately. The spacing between electrodes within each pair (C1–C2 and P1–P2) is defined as a, while the distance between the first current electrode (C1) and the first potential

electrode (P1) is represented as *na*, where *n* is the electrode spacing factor. The dipole–dipole configuration was chosen due to its high resolution in detecting lateral resistivity variations, which is crucial for mapping aquifer zones in complex karst environments [17].
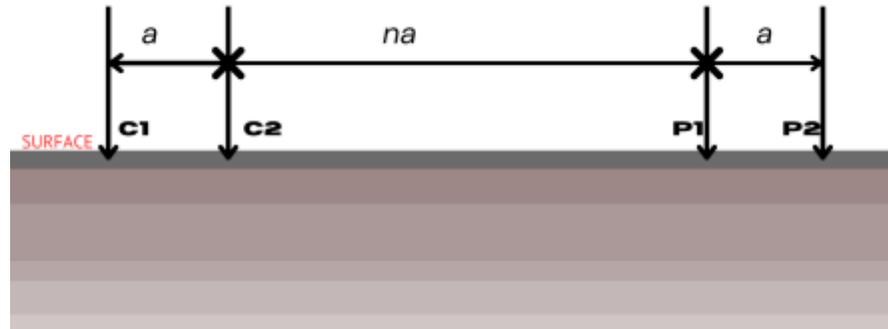

Figure 3. Dipole-Dipole Electrode Configuration

The advantage of the dipole–dipole configuration lies in its high sensitivity in detecting resistivity variations in both horizontal and vertical directions. In addition, this configuration is highly effective in achieving significant depth penetration. The resistivity value measured using this method is referred to as *apparent resistivity* (ρ_a), which is the resistivity calculated based on the assumption that the subsurface consists of homogeneous layers. The value of ρ_a can be expressed by the following equation:

$$\rho = \kappa \frac{\Delta v}{I} \tag{1}$$

Where, ρ = apparent resistivity ($\Omega \cdot$m), κ = geometric factor, Δv potential difference, (v): and I = current (A). For the Dipole-Dipole configuration, the geometric factor (κ) is defined as:

$$\kappa = \pi.\alpha.n\,(n+2)(n+1) \tag{2}$$

The dipole-dipole configuration is widely used in resistivity surveys in karst areas due to its high lateral resolution, making it effective for detecting subsurface cavities and fractures. Although it is susceptible to noise at larger electrode spacings, this configuration remains superior in identifying horizontal resistivity contrasts. The electrical resistivity of surface soil varies with the mineralogical composition of soil and rocks, temperature, the water content, and its solute composition. Electrical resistivity tomography (ERT) is a technique commonly used in geosciences that aims to capture these variations. ERT relies on electrodes, a current injection scheme, and the inversion of an associated resistivity model to map the resistivity of the shallow subsurface, either in two or three dimensions, and derive geological and hydrological interpretations [18].

2.2. Data Acquisition

The research area is located in Bayemharjo Village, Giritontro District, Wonogiri Regency, Central Java Province. Data acquisition was carried out using the IRIS Syscal Jr. Resistivity Meter, covering three survey lines, each with a length of 710 m. The data were collected using 72 electrodes with a spacing of 10 m between each electrode. The ERT survey line map is presented in Figure 4.
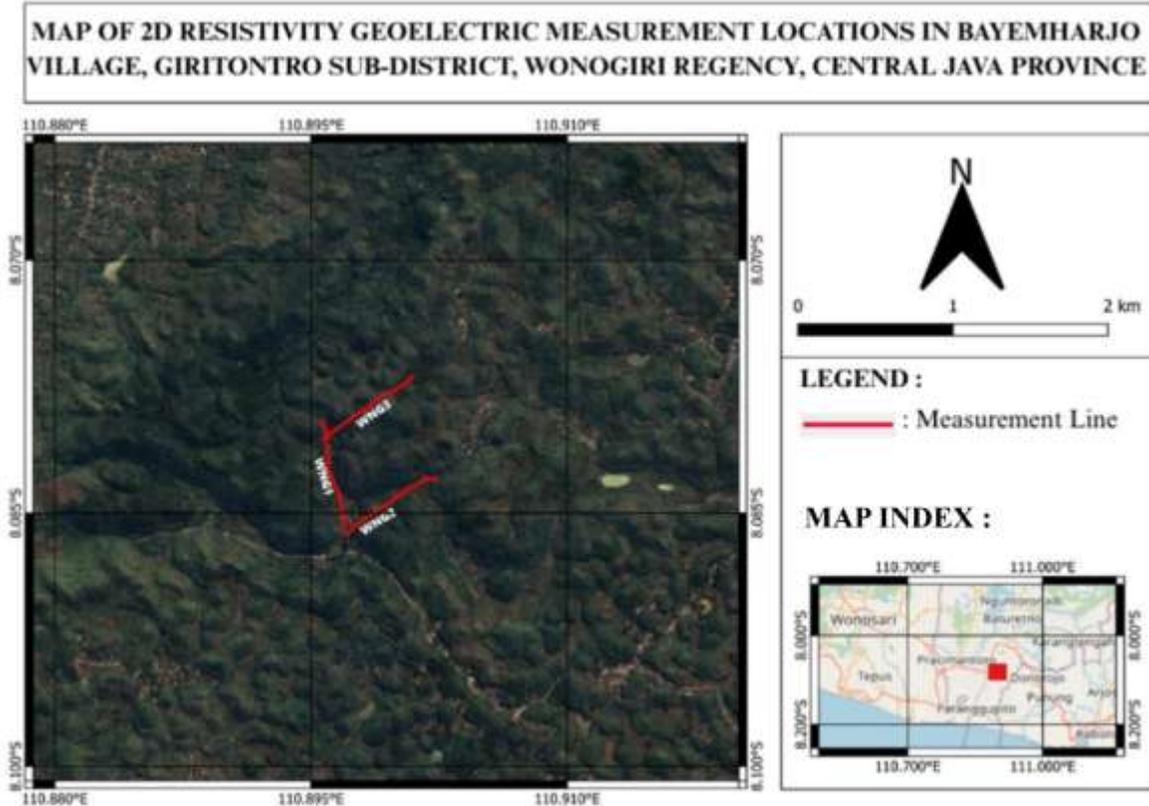
Figure 4. Survey Line Location Map

After the resistivity data were acquired in the field, initial processing was performed using Microsoft Excel for preliminary analysis. The data were then downloaded from the instrument using Prosys II software, which was used to sort and export the data in .dat format for further processing using RES2DINV. This processing step produced 2D subsurface profiles that display resistivity curves and color images representing variations in subsurface resistivity. These colors, ranging from blue to purple, indicate low to high resistivity values associated with different rock types. The inversion results from RES2DINV were exported into Surfer software to construct cross-sections based on lithological data. These sections were then interpreted by considering regional geological conditions and the resistivity values of rock types as outlined by Telford. Based on the interpretation of each survey line, zones with potential aquifers were identified.

This research is supported by previous studies conducted in China, which demonstrate the effectiveness of high-resolution electrical resistivity tomography (ERT) for investigating highly heterogeneous karst aquifers, particularly in resolving air- and water-filled voids and identifying subsurface discontinuities. The ERT data acquisition in this study utilized the Syscal Pro system (IRIS Instruments, France) and was processed using Prosys II and Res2dinv/Res2Dinv software, applying a least-squares smoothness-constrained inversion with a least-squares smoothness-constrained approach, which generated 2D resistivity sections and values for each electrode point [19].

To ensure data quality, quality control was conducted by checking the contact resistance of each electrode prior to acquisition, removing outliers using Prosys II, and cross-validating the results with regional geological data and comparison wells [20]. Data with errors above 15% were eliminated, and the inversion process was iterated until the root mean square (RMS) error dropped below 10% [21]. The data acquisition was conducted using several parameters as shown in Table 1.

Table 1. ERT Data Acquisition Parameters

Line	Length (m)	Electrode Spacing(m)	Configuration	Iteration	Error (%)
WNG-1	710	10	Dipole-Dipole	7	11.4 %
WNG-2	710	10	Dipole-Dipole	7	3.7 %
WNG-3	710	10	Dipole-Dipole	7	11.4 %

This research is supported by previous studies conducted in Europe, which confirm that RMS errors in 2D ERT inversions of highly heterogeneous karst aquifers commonly fall within the 10–15% range and are still considered reliable for subsurface structural interpretation. The ERT profile in this study has an investigation depth of approximately 60 m, and the data were truncated at −40 m to maintain a consistent and comparable scale. Although the inversion quality indicator is relatively high (*relative root mean square/RMS error = 11.77%*) [22].

2.2. Research Workflow

Data processing began by exporting the raw ERT data from the Syscal Jr. Resistivity Meter. The exported data were then imported into Prosys II software for editing, including the removal of outliers or erroneous data. Once editing was completed, the data were exported in .dat format to be processed using RES2DINV. The apparent resistivity data were analyzed using RES2DINV, which applies a least-squares inversion method based on the quasi-Newton optimization technique. This inversion method is a modeling technique used to reconstruct the subsurface layer structure based on the measured data.

In this process, subsurface conditions are visualized as rectangular blocks representing the distribution of apparent resistivity values. To optimize the modeling results, the software reduces the difference between the measured and modeled resistivity values. The analysis results were then integrated with geological and regional stratigraphic studies to interpret subsurface conditions based on field data [23]. The research flowchart is presented in Figure 5.
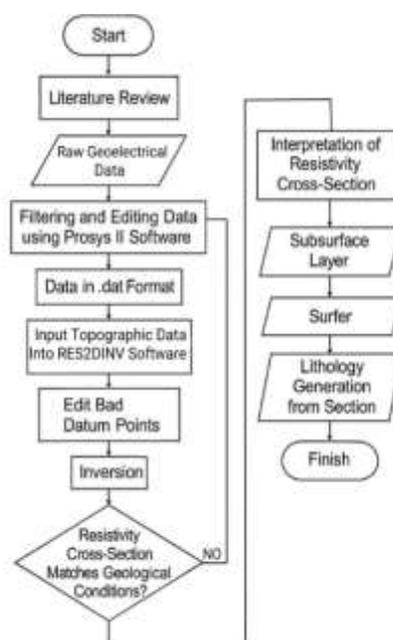
Figure 5. Research Workflow

3. Results and Discussion
3.1 Interpretation of Survey Line WNG 1
The following section presents the interpretation of the 2D Electrical Resistivity Tomography (ERT) model acquired along survey line WNG 1, with an emphasis on interpreting resistivity contrasts to describe the subsurface conditions as illustrated in Figures 6 and 7.
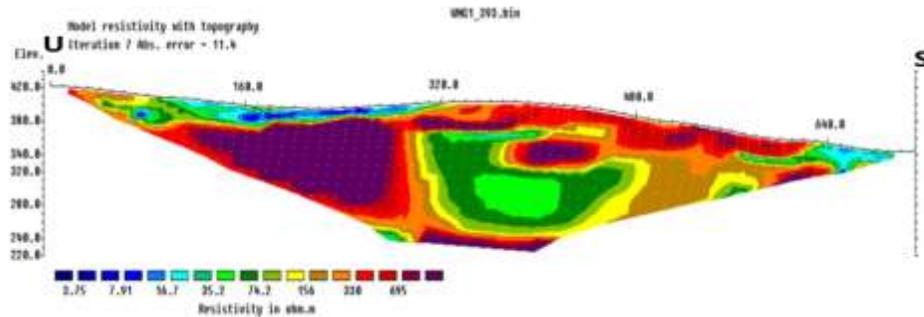

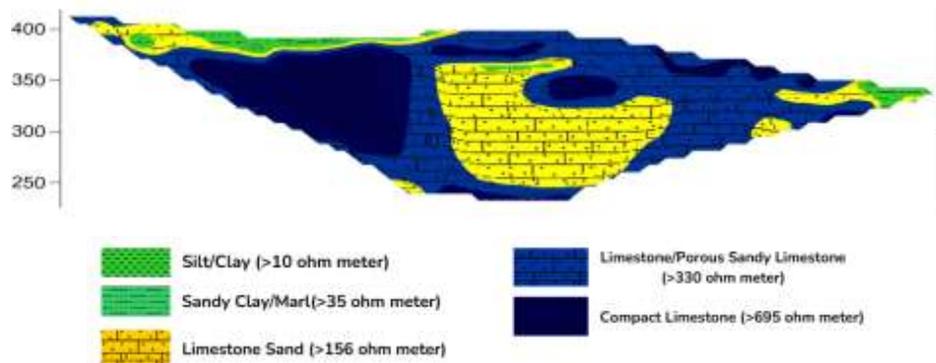**Figure 6**. Resistivity Cross-section of Line WNG-1

Figure 7. Lithological Interpretation of Line WNG-1

3.1.1 ERT Model Interpretation for Aquifer Potential (Line WNG 1)
Based on resistivity cross-section modelling and lithological interpretation of line WNG 1 (Figures 6 and 7), a potential aquifer zone was identified at depths between 30 and 130 m below ground surface. This zone is dominated by porous limestone sand and sandy clay or marl layers, with resistivity values ranging from 35 to 156 $\Omega \cdot$m. According to the literature, this range indicates medium to high porosity and moderate permeability, capable of supporting significant groundwater storage and flow. The ERT results support subsurface resistivity patterns consistent with the findings of Utama & Anindya in the Gunung Kidul karst region [24]. The ERT inversion reveals subsurface anomalies defined by clear resistivity contrasts. Water-bearing conduit cavities are represented by resistivity values ranging from 0.174 to 25 $\Omega \cdot$m, in agreement with the low-resistivity response of groundwater-filled karst voids. Limestone layers with moderate water saturation exhibit resistivity values of 25 to 100 $\Omega \cdot$m, whereas more compact and relatively dry limestone is characterized by resistivity values of >100 $\Omega \cdot$m.

The shallow layer, at depths of 0 to 20 m, exhibits resistivity values below 10 $\Omega \cdot$m, interpreted as water-saturated silt or clay. This layer functions as an aquitard hindering vertical groundwater movement while still allowing limited percolation consistent with stratigraphic and hydrogeological maps of the Wonosari Punung region and groundwater vulnerability profiles in Wonogiri. Meanwhile, a compact limestone layer deeper than 130 m shows resistivity values above 695 $\Omega \cdot$m and is interpreted as an aquiclude, serving as the impermeable base of the aquifer system, consistent with the substrates observed in Gunung Kidul–Pacitan.

3.1.2 Geological Features: Supporting and Counter Arguments (Line WNG 1)

Along line WNG 1, significant lateral resistivity variations were observed. Local resistivity anomalies are interpreted as aquifer pockets formed by carbonate dissolution processes and tectonic fractures. This interpretation is consistent with findings of Utama & Anindya in the Gunung Kidul karst region [24], who reported that lateral resistivity heterogeneity can reflect underground water channels, cavities, or permeable zones in karst environments.

Nevertheless, caution is required when interpreting these aquifer pockets, as topographic effects (terrain effects) can distort current distributions and elevate RMS errors 11.4 % in this case. Although within acceptable limits, this figure underlines the need for topographic correction. Such corrections have proven effective in improving model accuracy. Consequently, resistivity interpretations should be corroborated with additional data such as surface geology, borehole logs, or hydrogeochemical measurements to ensure reliability.

This research is supported by previous studies conducted in Europe, which confirm that RMS errors in 2D ERT inversions of highly heterogeneous karst aquifers commonly fall within the 10–15% range and are still considered reliable for subsurface structural interpretation. The ERT profile in this study has an investigation depth of approximately 60 m, and the data were truncated at −40 m to maintain a consistent and comparable scale. Although the inversion quality indicator is relatively high (*relative root mean square/RMS error = 11.77%*), this value remains within the typical error range reported in European karst studies. The measured resistivity contrast is very large, ranging from 50 to >10,000 $\Omega \cdot m$, with a high average background resistivity (~8,000 $\Omega \cdot m$), whereas groundwater-indicated zones exhibit low resistivity (<300 $\Omega \cdot m$) and sharp variations relative to the surrounding sections, suggesting the presence of discontinuities or water-filled voids within the karst system [25]. The karst topography along the line affects current flow, increasing noise and raising RMS error to 11.4%, though still acceptable. Topographic corrections have proven effective in reducing such disturbances and maintaining interpretative quality.

3.2. Interpretation of Survey Line WNG 2

The following section presents the interpretation of the 2D Electrical Resistivity Tomography (ERT) model acquired along survey line WNG 2, with an emphasis on interpreting resistivity contrasts to describe the subsurface conditions as illustrated in Figures 8 and 9.
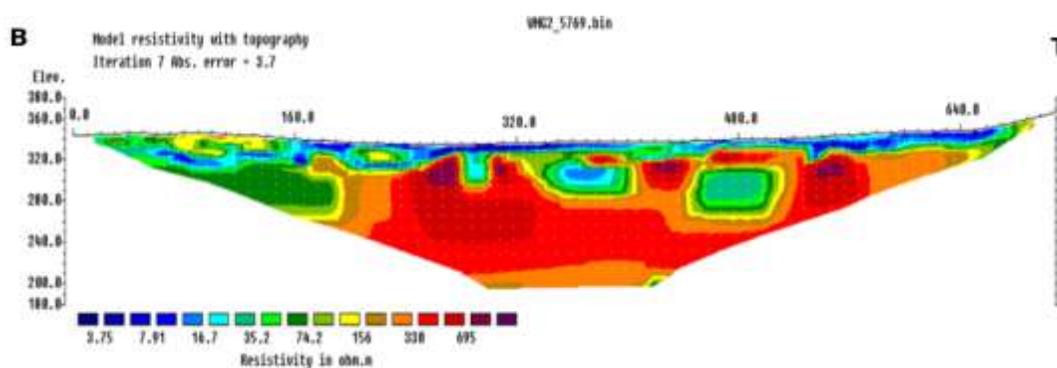

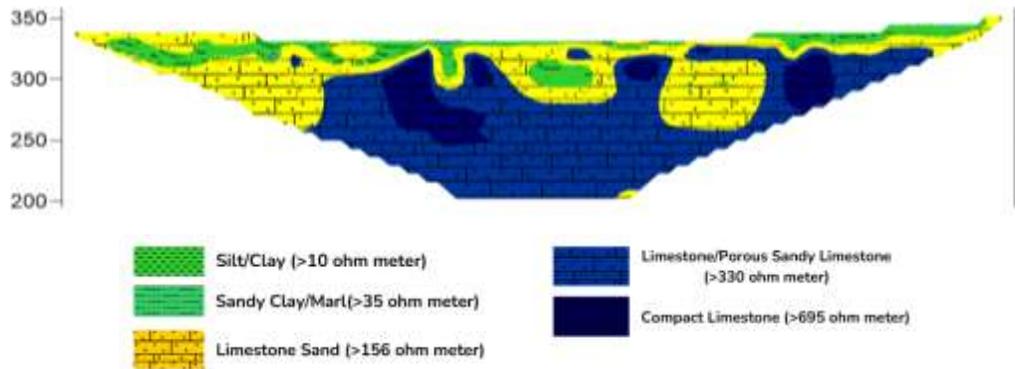**Figure 8**. Resistivity Cross-section of Line WNG-2

Figure 9. Lithological Interpretation of Line WNG-2

3.2.1   ERT Model Interpretation for Aquifer Potential (Line WNG 2)

The ERT model interpretation of line WNG-2 (Figures 8 and 9) shows a medium-resistivity zone of 35–156 Ω·m at depths of 50–150 m, interpreted as a porous limestone layer with high aquifer potential in tropical karst settings. This result is consistent with previous studies in Europe, which report that medium resistivity ranges in highly heterogeneous karst aquifers remain a reliable indicator for detecting water-bearing porous carbonates and karst void systems [25].The finding also aligns with the work of Abdul Wahid, who identified karst conduits as the dominant groundwater flow pathways in carbonate rocks in Sendang Biru, East Java [26]. Additionally, Wilopo demonstrated a strong correlation between medium resistivity anomalies and groundwater occurrence in complex karst systems in Gunung Kidul, Indonesia, supporting the interpretation of this zone as a high-potential karstic aquifer [9].

In addition, the consistency of the resistivity results with geological and hydrogeological data strengthens the validity of the interpretation, particularly when compared with similar findings from Ghana by Bienibuor, who identified aquifer layers within porous sedimentary rocks with a comparable resistivity range. These findings suggest that intermediate resistivity values in carbonate rocks and tropical sediments can serve as indicators of water-saturated zones [12]. A similar study in Ethiopia also supports this observation, where water-bearing sedimentary layers exhibited resistivity ranges between 100–500 Ω·m, indicating that resistivity values within this interval are regionally and geologically elevant across tropical settings.

Nevertheless, the dominant groundwater zone depth in profile WNG 2, located below 50 m, differs from other profiles, suggesting local lithological variations and non-uniform aquifer formation processes. This difference provides important insights into hydrogeological heterogeneity, particularly in karst systems influenced by selective dissolution and subsurface geological structures.

3.2.2   Geological Features: Supporting and Counter Arguments (Line WNG 2)

The geological phenomena identified in Line WNG 2 display the characteristics of an active karst system, marked by lateral resistivity anomalies and the presence of structural fractures and cavities. One important feature is the identification of aquifer pockets, represented by high-resistivity zones embedded within intermediate layers, which are presumed to have formed as a result of carbonate dissolution or structural fracturing. This interpretation is consistent with studies A case study from the Spain, which reported the development of localized water pockets due to limestone dissolution. In this study, the Electrical Resistivity Tomography (ERT) results reveal sub-vertical discontinuity structures extending to depths of >170 m, characterized by downward-widening geometry. In karst geophysics, this structural pattern is critical, as ERT effectively maps high–low resistivity contrasts that represent fractures, conduit channels, and water-saturated cavities in the subsurface [27].

Additional evidence supporting groundwater potential includes chemical weathering and extensive limestone fracturing, which enlarge pore space and enhance interconnectivity between underground voids. Dissolution and fracturing play a central role in the development of secondary aquifers, reinforcing the interpretation that intermediate resistivity values may represent active permeable zones within the karst system.

Nevertheless, caution is required because intermediate resistivity can also be associated with semi-impermeable, water-saturated lithologies such as marl or highly porous silt, which challenges the interpretation of a free aquifer zone. In this context, the lateral resistivity variations observed in the ERT section are more indicative of subsurface geological heterogeneity rather than a homogeneous saturated layer, emphasizing the complexity of groundwater occurrence in karst environments.

The irregular topography along Line WNG-2, particularly the presence of cliffs and significant surface elevation differences, caused disturbances in electrical current distribution (terrain effect). This condition increased noise and resulted in higher RMS error values, although still within the acceptable tolerance of 5–10%. The RMS error obtained on Line WNG-2 is 3.7%, which is supported by previous research in China by Jiang et al.,who reported reliable ERT inversion results with RMS errors around 3.9%, demonstrating that moderate inversion errors remain acceptable for interpreting karst-related subsurface features [28]. Consistent with these findings, obvious vertical preferential groundwater flow paths were identified in this study using high-resolution ERT, confirming strong hydrological connectivity between shallow and deeper karst water during rainfall events. ERT has also been proven effective for interpreting moisture development, infiltration direction, and water-filled karst voids.

The ability of ERT to detect vertical anomalies also supports the interpretation of preferential groundwater flow paths, which commonly develop through fracture–conduit networks in carbonate aquifers. With dense electrode spacing, ERT has proven effective for identifying zones with strong potential for karst aquifers or subsurface voids, making it highly relevant for karst aquifer mapping and detection targets in geophysical research.

3.3. Interpretation of Survey Line WNG 3
The following section presents the interpretation of the 2D Electrical Resistivity Tomography (ERT) model acquired along survey line WNG 3, with an emphasis on interpreting resistivity contrasts to describe the subsurface conditions as illustrated in Figures 10 and 11.
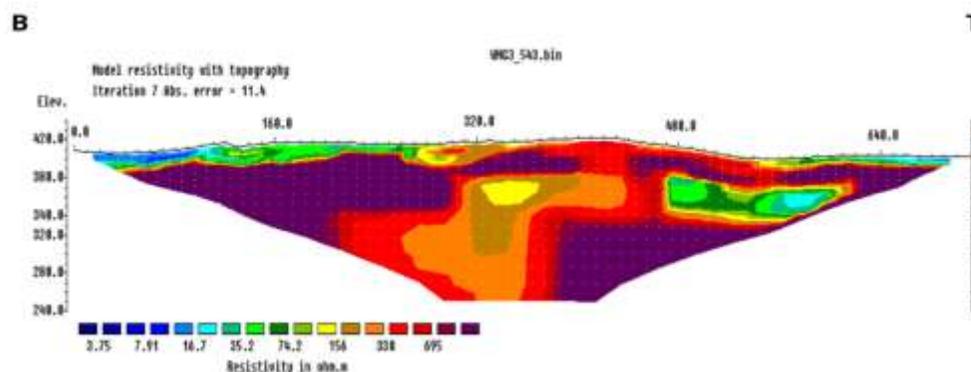

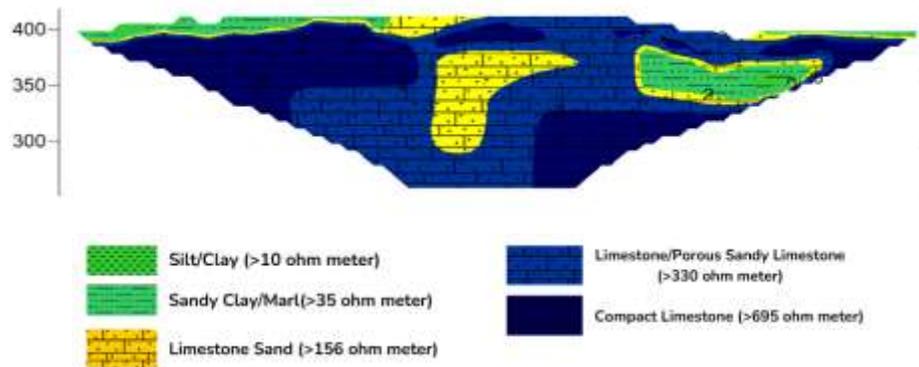**Figure 10**. Resistivity Cross-section of Line WNG-3

Figure 11. Lithological Interpretation of Line WNG-3

3.3.1 ERT Model Interpretation for Aquifer Potential (Line WNG 3)

The interpretation of Electrical Resistivity Tomography (ERT) modeling results along Line WNG 3 (Figures 10 and 11) reveals the presence of a major aquifer zone at depths between 50 and 130 m below the ground surface. This zone is characterized by intermediate resistivity values ranging from 35 to 156 $\Omega \cdot$m, which are geologically interpreted as porous sandy limestone layers These findings are consistent with Bienibuor who reported similar resistivity ranges for carbonate aquifers in tropical regions [12].

However, the resistivity distribution pattern along Line WNG 3 shows lateral heterogeneity, resembling discontinuous pocket-like features, which strongly indicate a heterogeneous karst aquifer system. This supports the notion that karst aquifers cannot be generalized horizontally, as local lithological controls, fracture networks, and dissolution processes play critical roles in groundwater distribution. Local studies by in Utama & Anindya in the Gunung Kidul karst area support this interpretation, emphasizing that cavities and fractures are dominant factors in the development of secondary aquifer zones [24].

3.3.2 Geological Features: Supporting and Counter Arguments (Line WNG 3)

The resistivity section of Line WNG 3 indicates sharp lateral anomalies, interpreted as aquifer pockets formed by carbonate dissolution or tectonic fracturing. This interpretation is consistent with Jabrane et al., who identified dissolution zones in karst systems in Tunisia and Florida [29]. At the local scale, studies by Abdul Wahid, in the Sendang Biru karst, South Malang, also reported underground water channels and cavities formed by dissolution, which are detectable through intermediate resistivity values with limited lateral distribution. As a supporting argument, the occurrence of sporadic lateral anomalies in the ERT profile is believed to represent shallow-to-intermediate aquifer pockets trapped within carbonate fracture systems [26].

On the other hand, a counter argument suggests that these intermediate resistivity zones may also correspond to semi-impermeable lithologies, such as marl or water-saturated silt, which possess high porosity but low permeability. Nevertheless, the ERT results show sharp lateral boundaries and non-uniform horizontal resistivity variations, strengthening the interpretation that these zones more likely represent aquifer pockets rather than homogeneous saturated layers. High-resistivity layers (>695 $\Omega \cdot$m) identified below 130 m are interpreted as compact limestone, functioning as an aquiclude or the basal boundary of the aquifer system. This interpretation is consistent with hydrogeological descriptions indicating that karst aquifers in the Wonogiri region and its surroundings are generally vertically bounded by dense limestone formations or by older volcanic rocks that are impermeable [30-31].

The undulating topography along the WNG-3 ERT line affected electrical current distribution during data acquisition, increasing noise levels and contributing to higher RMS error in the inversion model. Although the RMS error for this line is not below 10%, the application of surface elevation

correction and systematic data screening maintained the stability and reliability of the resistivity model. The RMS error obtained for WNG-3 is 11.4%, a value that remains acceptable and interpretable for karst subsurface characterization, as multiple ERT studies in highly heterogeneous karst terrains have reported similar RMS errors of approximately ~11% and continued to use the data for mapping fractures, water-filled conduits, and saturated karst voids. This confirms that ERT can still provide reliable resistivity contrast representing hydrogeological discontinuities and groundwater-related features in karst aquifers when topographic correction and noise filtering are properly applied during processing.

3.4. Contribution of the study to Environmental Chemistry Literature and Geoscience Education

This study makes an important contribution to the advancement of geoscience and environmental chemistry by applying the Electrical Resistivity Tomography (ERT) method for aquifer characterization in karst regions and tropical sedimentary rocks. The modeling results demonstrate that zones with intermediate resistivity values (35–156 $\Omega \cdot$m) are closely associated with porous, water-saturated rock layers such as sandy limestone and marl, indicating the presence of groundwater. Laterally varying resistivity patterns, particularly along specific profiles, reveal complex subsurface dynamics and support the concept of aquifer pockets formed through dissolution and fracturing processes. The validity of this interpretation is reinforced by comparisons with studies conducted in Ghana, Ethiopia, and several karst regions of Indonesia, all of which consistently show that Wenner–Schlumberger and dipole–dipole configurations effectively detect water-saturated zones, even in areas with steep topography.

From the perspective of environmental chemistry, resistivity measurements can serve as preliminary indicators for evaluating the physico-chemical properties of groundwater, such as conductivity, dissolved ion content, and pore medium retention capacity. These parameters can then be integrated with hydrogeochemical analyses to assess groundwater quality and contamination potential comprehensively. Furthermore, in the context of geoscience education, this study provides a practical case study that can be utilized in project-based learning, particularly in courses on hydrogeology, environmental geophysics, and subsurface surveying. The integration of geophysical, lithological, and topographic data enhances students' understanding of groundwater system dynamics, while technical issues such as terrain effects on current distribution and elevated Root Mean Square (RMS) error provide valuable lessons on data acquisition accuracy and interpretation. Therefore, this study not only enriches the scientific literature but also supports the development of multidisciplinary approaches in water resource management and the improvement of earth science education quality.

4. Conclusion

The difference This study successfully identified aquifer potential in the karst region of Giritontro, Wonogiri, Central Java, using the Electrical Resistivity Tomography (ERT) method. Based on resistivity modeling results from profiles WNG 1, WNG 2, and WNG 3, potential aquifer zones were found at depths ranging from 30 to 150 m, with intermediate resistivity values between 35 and 156 $\Omega \cdot$m. These zones are associated with sandy limestone, marl, and porous carbonate rocks, which possess sufficient porosity and permeability to support groundwater storage and flow. In contrast, shallow low-resistivity layers (<10 $\Omega \cdot$m) were interpreted as aquitards, while deeper high-resistivity layers (>695 $\Omega \cdot$m) were identified as aquicludes.

Geological interpretation indicates that the aquifer system in the study area is heterogeneous, with laterally non-uniform resistivity distributions influenced by carbonate dissolution, fracture structures, and local lithological conditions. The presence of aquifer pockets, subsurface conduits, and fracture zones consistently identified in the ERT sections further supports the argument that karst regions

exhibit complex subsurface dynamics. Nevertheless, caution is required in the interpretation since intermediate resistivity values may also represent semi-confining rocks. Therefore, the integration of geophysical data with surface geology, borehole information, and hydrogeochemical analysis is essential to improve interpretation accuracy.

The contribution of this study extends beyond the identification of aquifer zones, providing added value in the context of environmental chemistry and geoscience education. The resistivity data obtained can be used as preliminary indicators for groundwater quality assessment when integrated with hydrogeochemical datasets. Moreover, this study serves as a practical case study for project-based learning in hydrogeology and environmental geophysics. The influence of topography on ERT data, which resulted in RMS error values ranging from 3.9% to nearly 10%, also highlights the importance of terrain correction in the modeling process. Thus, this research enriches multidisciplinary approaches in water resource management and contributes to the advancement of earth science education.

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