

Aquifer Characterization through Vertical Electrical Sounding (VES), Well Logging, Petrographic Analysis, and Pumping Tests in the Monitoring Well Area, Lampung

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Abstract

This study aims to develop a calibrated interpretation framework for aquifer characterization and optimal monitoring well design at the Institut Teknologi Sumatera campus in South Lampung, Indonesia. This study employs the Vertical Electrical Sounding (VES) method using a Schlumberger configuration, with inversion processing performed to obtain a subsurface resistivity model. Dar-Zarrouk parameters were calculated to estimate aquifer hydraulic properties and were supported by well logging data and petrographic analysis for lithological identification, as well as Cooper–Jacob pumping tests for determining hydraulic parameters. The inversion results identify four subsurface layers, with the main aquifer occurring at depths greater than 75 m and characterized by resistivity values ranging from 40.49 to 71.28 Ωm . Based on well logging and petrographic analysis, two productive aquifer zones are identified at depths of 85–90 m and 110–125 m, consisting predominantly of coarse sand with minor gravel content. The Dar-Zarrouk parameter analysis indicates that the hydraulic conductivity, longitudinal conductance, transverse resistance, and transmissivity values reflect aquifer characteristics with moderate to high groundwater potential. Pumping test analysis yields a transmissivity value of 0.0051 m^2/s and a hydraulic conductivity value of $9.30 \times 10^{-5} \text{ m/s}$. The resulting hydrogeological model indicates that the aquifer system in the study area is classified as a confined aquifer. The integrated approach effectively reduces interpretive ambiguity, and well screen installation at depths of 90–120 m is recommended as the optimal interval for groundwater monitoring within volcanic aquifer systems.

Keywords: Aquifer; Electrical Resistivity; Dar-Zarrouk Parameters; Hydrogeological Model.

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Introduction

Groundwater level monitoring is an essential component of sustainable groundwater resource management because it provides information on aquifer dynamics and their responses to climate change and anthropogenic activities (Yang et al., 2025). Lampung faces challenges in groundwater management due to rapid regional development. Groundwater levels in this region reportedly vary from approximately 5 to more than 100 meters, reflecting heterogeneous hydrogeological conditions and creating uncertainty in

determining monitoring well locations and interpreting groundwater level data (Kumalasari et al., 2025). One area with potential for developing a groundwater monitoring well network is the campus area of Institut Teknologi Sumatera in South Lampung. However, no monitoring wells specifically designed for groundwater level monitoring have yet been established at this site, resulting in limited information regarding aquifer system characteristics, productive aquifer zone depths, and groundwater hydrodynamic behavior in the area. In addition, lithological complexity in sedimentary hydrogeological systems often

creates challenges in accurately identifying aquifers and increases ambiguity in subsurface interpretation (Claprod et al., 2022). Therefore, studies capable of comprehensively characterizing aquifer systems are required to support the development of reliable and sustainable groundwater monitoring systems in Lampung.

Monitoring wells constitute important infrastructure for systematically observing groundwater level fluctuations, drawdown, recovery rates, and aquifer conditions. Accurate groundwater monitoring is crucial for detecting excessive groundwater decline, evaluating pumping impacts, and supporting data-driven groundwater management decisions (Rau et al., 2020). In hydrogeological studies, several investigation methods have been widely applied to characterize subsurface conditions, including geoelectrical Vertical Electrical Sounding (VES), well logging, petrographic analysis, and pumping tests. The VES method is used to map resistivity distributions associated with lithological variations and groundwater occurrence, whereas well logging provides vertical information regarding lithology and aquifer zones. Petrographic analysis helps identify the mineralogical and textural characteristics of rocks that influence aquifer porosity and permeability, while pumping tests provide hydraulic parameters describing aquifer responses to pumping (Rau et al., 2020).

Previous hydrogeological studies conducted in the Institut Teknologi Sumatera campus area and its surroundings have provided an initial understanding of groundwater conditions in this region. Siringoringo et al. (2019) assessed groundwater hydro-geochemistry for drinking purposes in the Institut Teknologi Sumatera (ITERA) campus area and identified dominant hydrogeochemical facies through the integration of Piper diagrams, bivariate ion plots, and Gibbs

diagram analysis. Subsequently, Siringoringo & Maulana (2020) investigated unconfined groundwater flow patterns and hydrogeochemical facies changes in Way Huwi Village adjacent to the campus. Their findings indicated that shallow groundwater flows from southwest to northeast following topographic gradients, with six hydrogeochemical facies variation patterns reflecting the influence of local sedimentary lithology. In addition, Rizka & Satiawan (2019) utilized the Vertical Electrical Sounding (VES) method correlated with electrical well logging data to identify aquifer geometry and groundwater potential in the ITERA area. Their results revealed the presence of two main aquifer systems: an unconfined aquifer developed within shallow clay layers at depths of less than 5 meters and a confined aquifer associated with sand layers at depths greater than 75 meters. Collectively, these findings provide an initial framework for understanding aquifer systems developed within the sedimentary geological environment of the ITERA area.

Despite these contributions, several limitations remain that constrain the accuracy and applicability of the existing knowledge for groundwater monitoring purposes. First, the hydrogeochemical studies conducted by Siringoringo et al. (2019) and Siringoringo & Maulana (2020) focused on water quality and shallow groundwater flow patterns but did not address aquifer hydraulic behavior or provide quantitative hydrogeological parameters essential for monitoring well design. Second, the geophysical study conducted by Rizka & Satiawan (2019) was limited to correlations between geoelectrical resistivity data and well logging responses without integrating rock physical properties through petrographic analysis. This ambiguity has not yet been resolved in previous local studies. Third, none of the previous studies incorporated pumping test data to characterize aquifer hydraulic responses, leaving the

productivity and hydrodynamic behavior of the identified aquifer zones poorly constrained. Consequently, the relationships among geoelectrical resistivity values, lithological properties, and aquifer productivity remain poorly defined under the sedimentary geological conditions of this region. Therefore, a research gap persists due to the absence of a calibrated interpretation model integrating geoelectrical, petrographic, well logging, and hydraulic parameter data to improve the accuracy of aquifer identification and monitoring well design in sedimentary hydrogeological systems.

Based on these issues, this study integrates Vertical Electrical Sounding (VES) data, petrographic analysis, well logging, and pumping test data obtained from monitoring wells in the ITERA area to develop a calibrated correlation model among electrical resistivity, petrographic parameters, well logging responses, and hydraulic parameters. The urgency of this research arises from the absence of clear criteria for determining the optimal depth of monitoring wells in Lampung, while subsurface geological complexity often results in high variability in lithology and hydraulic properties, leading to uncertainty in aquifer interpretation. The presence of monitoring wells is essential for obtaining groundwater level data and understanding aquifer dynamics to support sustainable groundwater management (Rau et al., 2020). Therefore, this study aims to establish calibrated interpretation criteria for determining productive aquifer zones and appropriate screen depths for monitoring wells capable of accurately representing groundwater level conditions. This research also contributes by providing a reliable integrated methodology for aquifer characterization through the integration of geophysical and hydrogeological approaches. Specifically, this study integrates geophysical,

petrographic, and hydrogeological data to support aquifer identification and monitoring well design.

Materials and Methods

Study Area

This study was conducted at the ITERA in Lampung by integrating the VES geophysical method, well logging, rock petrographic analysis, and pumping tests as the basis for monitoring well planning. VES measurements were conducted at five VES points within the ITERA monitoring well area (Figure 1). VES-1 was designated as the central measurement point and the planned location of the monitoring well, serving as the primary reference for subsurface condition analysis. The other four VES points were systematically positioned around the central point at relatively equal distances of approximately 46 m toward the north, south, west, and east. This arrangement formed a symmetrical configuration that enabled the analysis of lateral subsurface layer variations and the interrelationship among measurement points regarding conditions surrounding the monitoring well.

Each VES point had a maximum current electrode spacing ($AB/2$) of 200 m, except for VES-03, where the maximum $AB/2$ distance was 160 m. Meanwhile, the potential electrode spacings ($MN/2$) used in the measurements were 0.5, 2.5, 8, and 16 m. In the Schlumberger configuration, the effective investigation depth generally ranges from one-quarter to one-third of the total current electrode span (AB) (Roy & Apparao, 1971). With a maximum span of $AB/2 = 200$ m, the investigation depth was estimated to reach approximately 100–133 m. The deepest layer was modeled as a half-space, representing a homogeneous layer assumed to extend continuously to infinite depth.

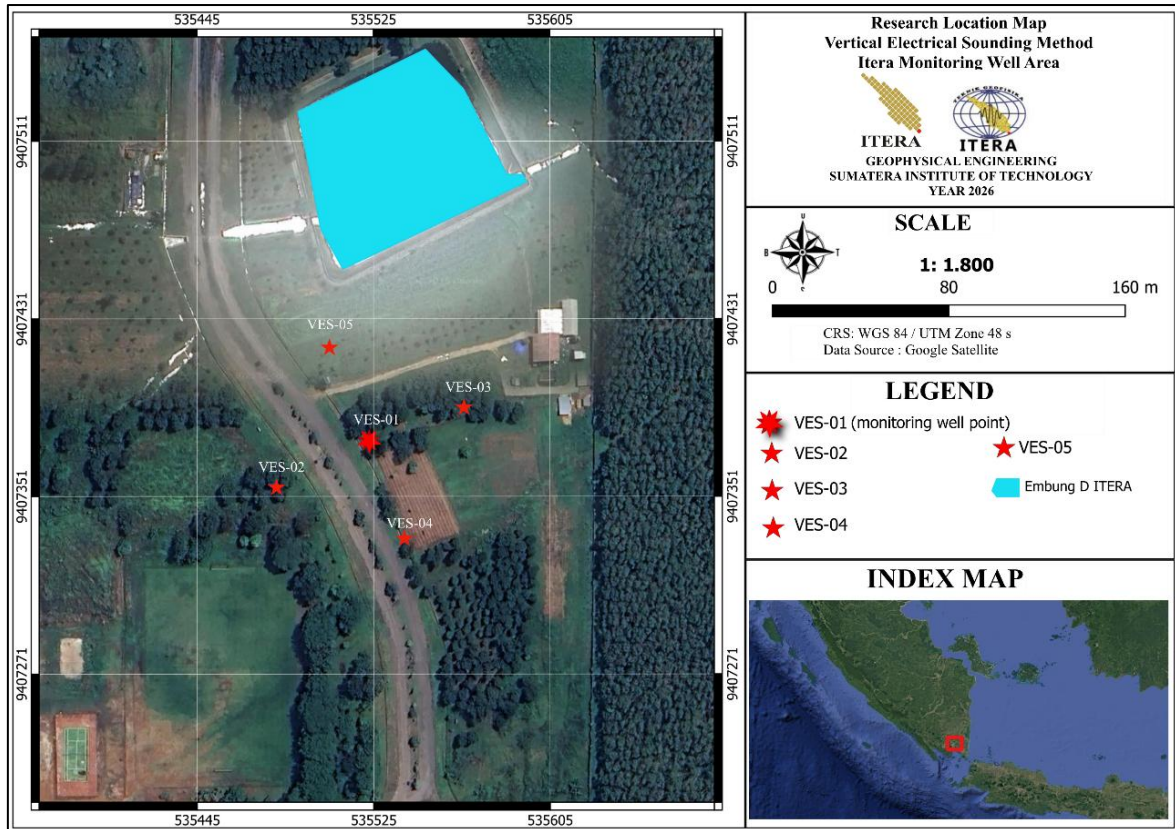


Figure 1. Research area.

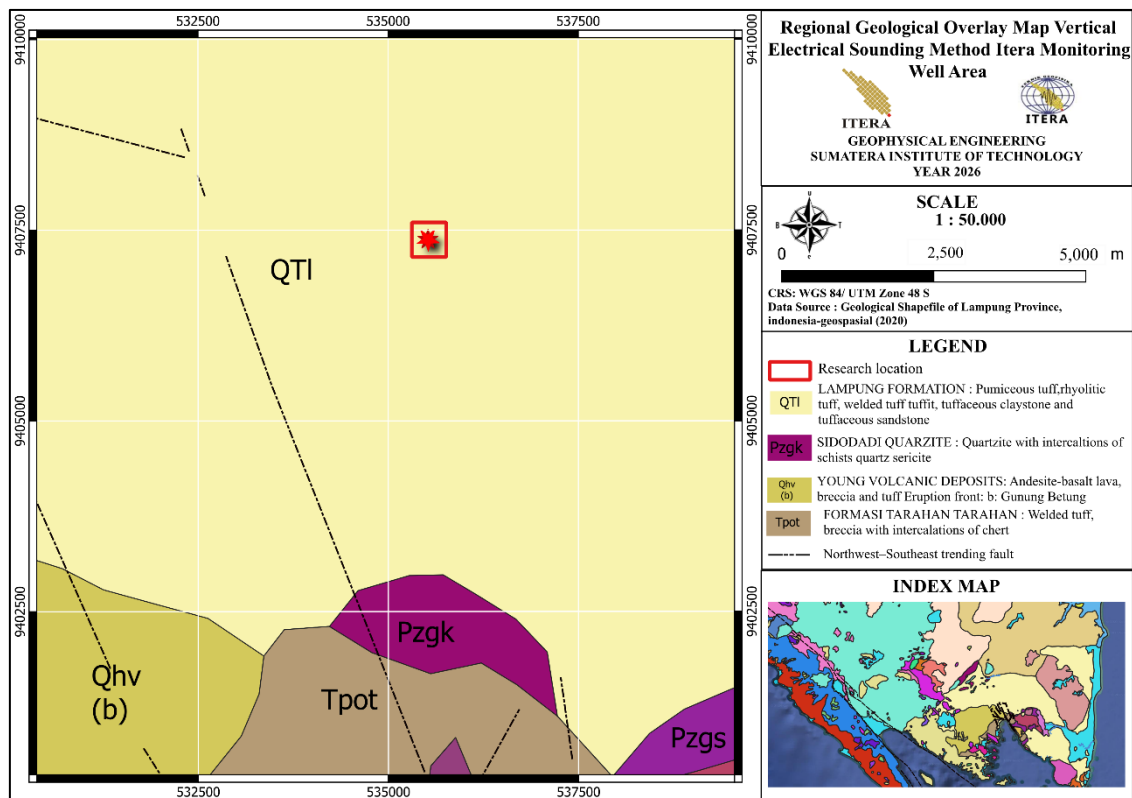


Figure 2. Regional geological map overlay (Mangga et al., 1993).

Geology of the Research Area

This research was conducted at the ITERA campus in Way Huwi, South Lampung.

Based on the regional geological map (Figure 2), the study area is located within the Lampung Formation. This formation

consists of Pumiceous tuff, rhyolitic tuff, welded tuff, tuffaceous claystone and tuffaceous sandstone, which are estimated to be of Late Quaternary age (Mangga et al., 1993). The surface rock distribution in the ITERA area is dominated by volcanic rocks formed through volcanic, tectonic, and sedimentary processes. Under certain hydrogeological conditions, tuff can function as an aquifer. Its groundwater flow characteristics are influenced by porosity, permeability, fractures, and hydraulic conductivity. Tuff with well-connected pore spaces and favorable hydraulic conductivity can support effective groundwater flow (Muauz et al., 2025).

Data Acquisition and Processing

The VES measurements were conducted using a Schlumberger array configuration centered around the borehole subjected to the pumping test. The VES data were subsequently interpreted using the curve-fitting method (Nyembwe et al., 2024). An inversion process was then performed to obtain a subsurface resistivity model (Figure 3). Based on the inversion results, the number of layers, resistivity values, and thicknesses of each layer were determined. Furthermore, the resistivity values and thicknesses of each geophysical layer were used to calculate the Dar-Zarrouk parameters (Figure 3), which are commonly applied in aquifer characteristic analysis (Yusuf et al., 2021).

The Dar-Zarrouk parameters were first introduced by Maillet (1947). and consist of longitudinal conductivity (S) and transverse resistance (Tr). Longitudinal conductivity was calculated using the following Equation 1:

$$S = \sum_i^n \frac{h_i}{\rho_i} \quad (1)$$

where h_i represents the thickness of the i -th layer and ρ_i denotes the resistivity of the i -th layer. Longitudinal conductivity indicates the ability of a layer to conduct electrical current parallel to the layer

direction. Higher longitudinal conductivity values generally indicate better aquifer protective capacity.

Meanwhile, transverse resistance was calculated using Equation 2:

$$T = \sum_i^n h_i \rho_i \quad (2)$$

Transverse resistance is obtained by multiplying the thickness of each layer by its resistivity value. This parameter is closely related to aquifer transmissivity and is therefore commonly used as an indicator of groundwater productivity potential (Oli et al., 2022).

The aquifer layer resistivity values obtained from the VES data inversion were used to estimate hydraulic conductivity (K) using the empirical Equation (3) proposed by Heigold et al. (1979):

$$K = (386.40 R_{rw})^{-0.93283} \quad (3)$$

where R_{rw} is a resistivity parameter associated with groundwater resistivity obtained from resistivity interpretation. To determine the formation water resistivity (R_w), Archie's equation is used, which states that the relationship between the resistivity of water-saturated rock, porosity, and fluid resistivity is influenced by the tortuosity factor and the cementation exponent (Archie, 1942), as shown in Equation (4):

$$R_0 = a \phi^{-m} R_w \quad (4)$$

where R_0 in Equation (4) represents the resistivity of water-saturated rock derived from geoelectrical inversion results, a is the tortuosity factor assumed to be 1, m is the cementation exponent (typically ranging from 1.3 to 2 for sand), and ϕ is porosity (Archie, 1942). Based on this relationship, the equation for determining formation water resistivity, Equation (5) becomes:

$$R_w = R_0 \phi^m \quad (5)$$

Subsequently, transmissivity (T) was calculated using the Equation (6) proposed by Todd (1980):

$$T = K h \Leftrightarrow K = \frac{T}{h} \quad (6)$$

where T denotes transmissivity (m^2/s), K represents hydraulic conductivity (m/s), and h is the saturated thickness of the aquifer (m). This approach provides a quantitative estimate of the aquifer's capacity to transmit water based on the geophysical parameters obtained.

Geophysical models are inherently prone to interpretive ambiguities that may lead to inconsistencies in aquifer data analysis. Therefore, to address this non-uniqueness problem, correlations with monitoring well data were applied (Li et al., 2021). Well drilling was conducted to identify lithological characteristics and aquifer zones vertically using resistivity logs that are sensitive to variations in pore fluids and rock physical properties (Chakraborty et al., 2021).

In this study, short-normal and long-normal resistivity logging were used to obtain resistivity information at different investigation depths, where a resistivity modeling approach has been developed to represent log responses under various geological conditions (Wilkosz, 2022). The short normal method is more sensitive to zones near the borehole and shallow formations, whereas the long normal method better represents the actual formation resistivity, particularly under drilling mud invasion conditions (Wu & Fan, 2021). These differences in investigation depth allow for the evaluation of the effects of drilling mud invasion and subsurface layer heterogeneity that influence the measured resistivity response (Zhou et al., 2023). The combination of these two logs improves the accuracy of lithological interpretation and aquifer identification, as the short normal provides high resolution in zones near the wellbore, while the long normal is more stable against borehole effects and invaded zones (Wilkosz, 2022; Wu & Fan, 2021). The interpretation of well logging data served as

the basis for understanding the distribution of petrophysical properties and variations in formation quality at each depth (Amir et al., 2025). In addition, drilling activities enabled the collection of rock samples in the form of cuttings, which were directly analyzed in the laboratory to obtain petrophysical parameters such as porosity, permeability, and mineralogical characteristics (Sanei et al., 2020). The integrated well logging approach has been shown to effectively reduce interpretation uncertainty and provide a more comprehensive representation of subsurface conditions (Wu & Grana, 2017).

Petrographic analysis was conducted to characterize rock types, textures, structures, and mineral compositions. The analyzed rock samples consisted of drill cuttings obtained from boreholes at specific depth intervals based on their correlation with well logging interpretations. The samples were prepared as thin sections and analyzed using a polarizing microscope (Figure 8). The resulting petrographic parameters were subsequently used to evaluate the relationships among rock characteristics, electrical properties, and aquifer potential, as commonly applied in petrographic and hydrogeological studies involving geophysical-geological integration (Nouradine et al., 2024; Putri et al., 2018; Prinaldi et al., 2023; Warsi et al., 2020).

A pumping test is a method used to evaluate well performance and the hydraulic characteristics of the surrounding aquifer (Agussalim et al., 2022). In this study, the pumping test was conducted using a single-well pumping test method without an observation well. Drawdown measurements were taken directly at the pumping well during pumping at a constant discharge rate to determine the hydrogeological parameters of the aquifer. The test was designed to evaluate the aquifer response to hydraulic stress by examining the relationship among pumping rate (Q), time (t), and groundwater level

drawdown (S_w), which is also influenced by drawdown changes (Δs). The analyzed hydrogeological parameters included transmissivity (T) and hydraulic conductivity (K), which serve as primary indicators of the aquifer's capacity to transmit groundwater.

Transmissivity values were calculated using the Cooper-Jacob method (Cooper & Jacob, 1946), as expressed in Equation (7):

$$T = \frac{2.3Q}{4\pi\Delta s} \quad (7)$$

where T represents transmissivity, Q is the pumping rate, and Δs denotes the drawdown change. Higher transmissivity values indicate greater aquifer capacity to transmit groundwater.

Interpretation of VES data

Vertical Electrical Sounding (VES) data interpretation is performed through an inversion process using a curve-fitting method, in which the apparent resistivity

curves obtained from field measurements are fitted to theoretical model curves to obtain a representative subsurface model (Bahri et al., 2022). The inversion process is performed iteratively by adjusting the resistivity and layer thickness parameters until the best fit between the observed data and the calculated model is achieved. The agreement between the field curve and the theoretical curve is evaluated based on the misfit value or Root Mean Square (RMS) error generated during the inversion iteration process (Grandis, 2009). A low RMS error value indicates that the inverted resistivity model has a good level of representation of the actual subsurface conditions (Pinehas & Warsa, 2019). The results of the curve fitting are used to determine the true resistivity distribution and the thickness of each subsurface layer (Oyeyemi et al., 2023). The inverted resistivity and layer thickness parameters are then interpreted to identify lithological characteristics and groundwater-bearing zones in the study area.

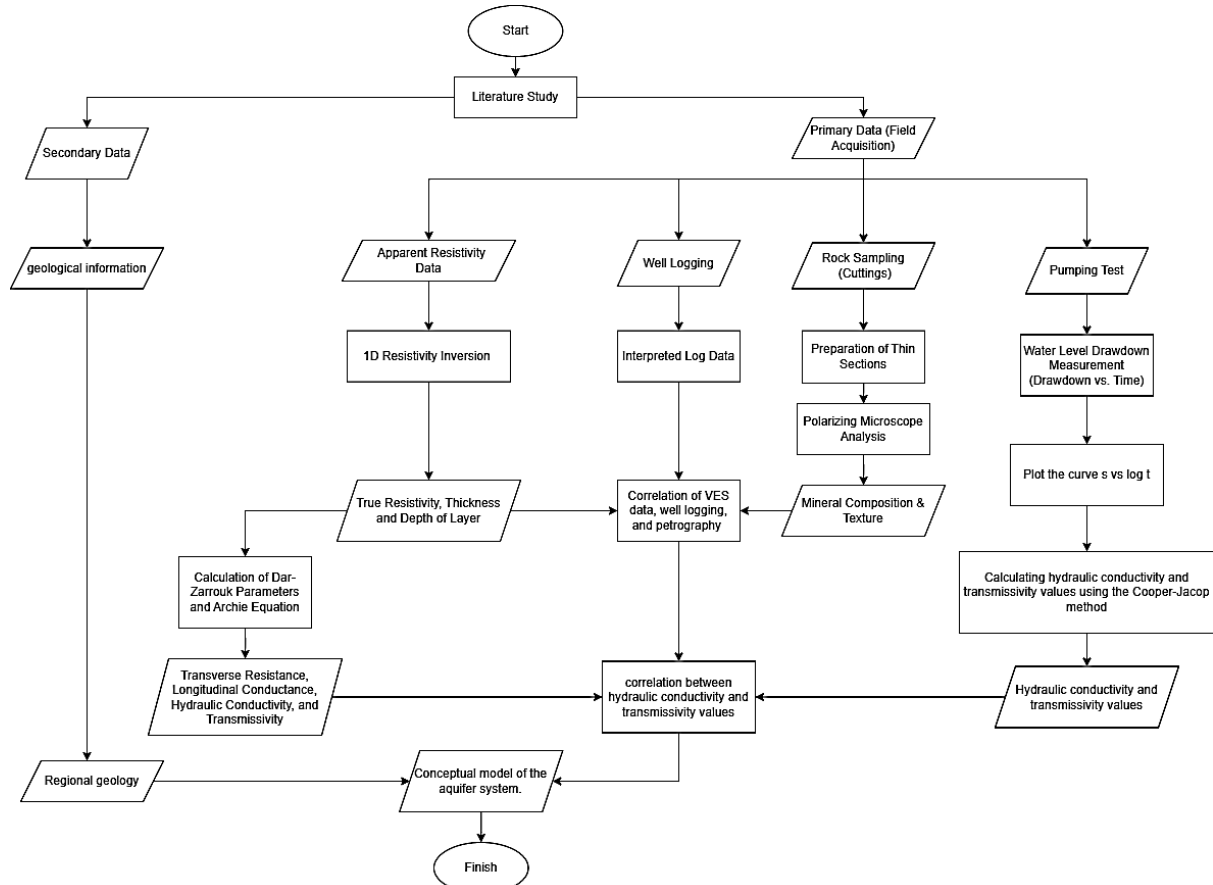


Figure 3. Research methodology workflow.

Results and Discussion

Vertical Electrical Sounding (VES) Analysis

The analysis of VES data based on apparent resistivity (ρ_a) values provides characterization of subsurface layers (Hasani et al., 2023; Syaputri et al., 2024). This characterization is performed through the interpretation of resistivity (ρ) and thickness (h) values for each subsurface layer, thereby enabling the identification of potential aquifer zones at each VES point. The measurement curves (Figure 4) were fitted to the field data to obtain subsurface resistivity cross-section models representing the distribution of subsurface layers according to their resistivity values and thicknesses. The curve patterns obtained at VES point 1 – 5 (Figure 4a – 4e) indicate variations in subsurface resistivity values, with low-resistivity layers situated between layers that have relatively higher resistivity. These patterns indicate differences in lithology and groundwater saturation conditions within the sedimentary formations (Masria et al., 2024) in the study area.

Based on the inversion results of the VES data (Table 1), a four-layer subsurface model with RMS errors ranging from 4% to 11% was obtained. The first layer exhibits resistivity values ranging from 125.14 to 209.41 Ωm with thickness between 2.41 and 4.99 m. This uppermost layer is characterized by relatively high resistivity values. A significant decrease in resistivity is observed in the second layer, where resistivity values range from 2.43 to 9.15 Ωm , with thickness of 7.15–25.32 m. The third layer is characterized by resistivity values between 10.68 and 17.78 Ωm and

thicknesses ranging from 51.69 to 70.50 m. The increase in resistivity relative to the overlying layer indicates a lithological transition, particularly toward sandy clay material.

In the deeper part of the model, resistivity values increase further, ranging from 40.49 to 71.28 Ωm . The final layer in the inversion model is interpreted as a half-space layer, meaning that its lower boundary could not be identified because it extends beyond the investigation depth of the measurements. This layer potentially represents an aquifer located at depths greater than 75 m below the surface (Rizka & Satiawan, 2019). In addition, VES point 1 function as the central reference point among the four surrounding VES points.

Dar Zarrouk Parameter

VES data were used to estimate the Dar-Zarrouk parameters, including hydraulic conductivity, longitudinal conductance, transverse resistance, and transmissivity. These parameters are commonly applied to identify aquifer characteristics and groundwater conditions (Muhammad et al., 2023). Based on the Dar-Zarrouk parameter analysis, the values of hydraulic conductivity, longitudinal conductance, transverse resistance, and transmissivity were obtained as presented in Table 2. . In this study, the Dar-Zarrouk parameters were specifically calculated for the fourth resistivity layer ($\rho = 40.49\text{--}71.28 \text{ } \Omega\text{m}$), which was identified as the main aquifer unit based on its depth (>75 m), resistivity range consistent with coarse-grained saturated sediments, and correlation with productive zones identified from the well log.

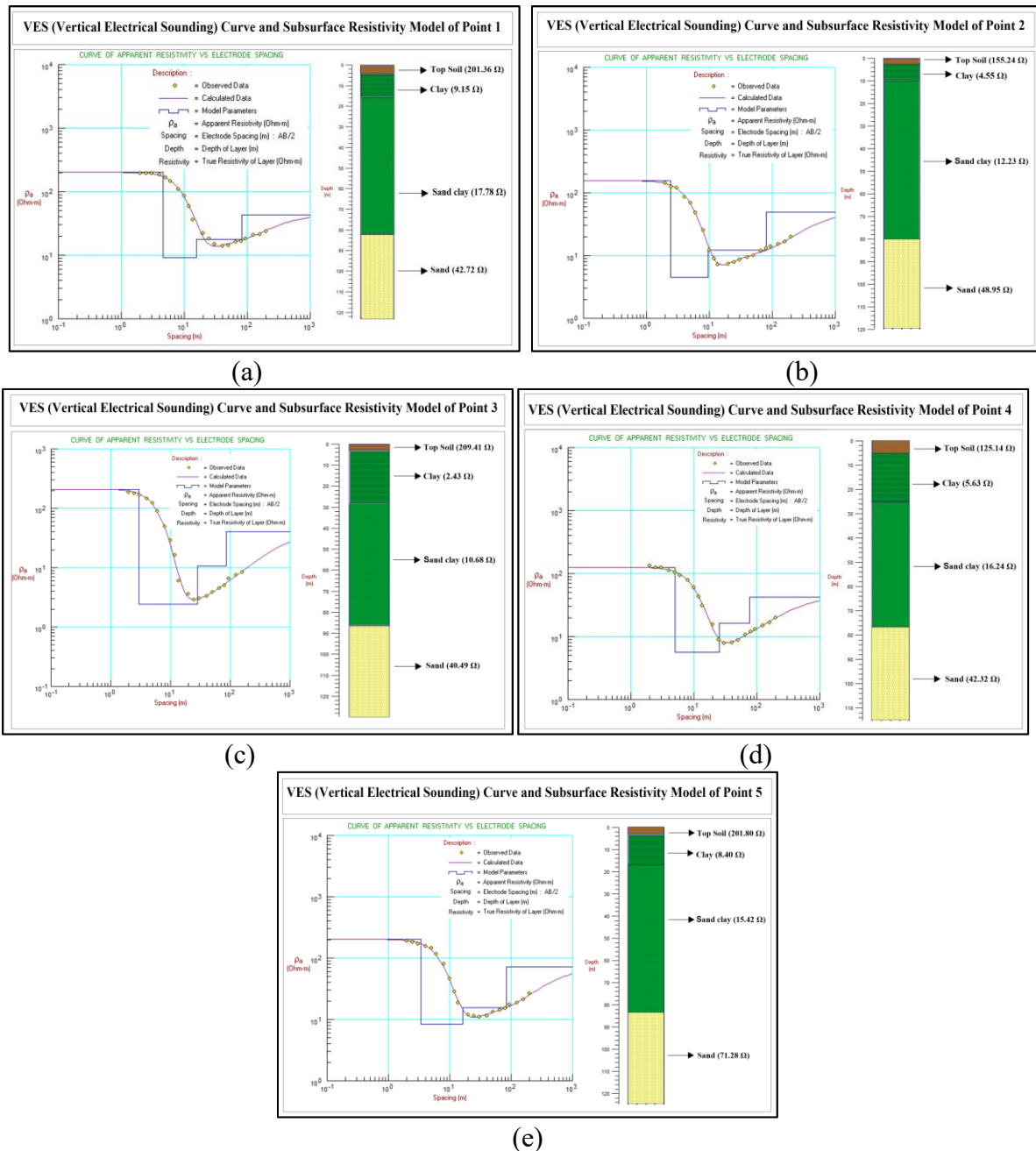


Figure 4. Resistivity curve plots, layer thickness, and lithological interpretation: (a) VES point 1 (b) VES point 2 (c) VES point 3 (d) VES point 4 (e) VES point 5.

Table 1. VES data inversion results in the study area.

VES Point	Latitude (°W)	Longitude (°S)	Electrical Resistivity (Ωm)				Thickness (m)				RMS (%)
			ρ1	ρ2	ρ3	ρ4	h1	h2	h3	h4	
VES 1	105.32062	-5.361414	201.3	9.1	17.7	42.7	4.6	10.8	63	∞	8.367
VES 2	105.32101	-5.361278	155.2	4.5	12.2	48.9	2.4	7.15	70.5	∞	4.032
VES 3	105.32046	-5.361034	209.4	2.4	10.6	40.4	2.9	25.3	58.2	∞	11.18
VES 4	105.32077	-5.361812	125.1	5.6	16.2	42.3	4.9	20.1	51.6	∞	4.366
VES 5	105.32024	-5.361604	201.8	8.4	15.4	71.2	3.4	12.9	66.9	∞	5.604

Table 2. Dar-Zarrouk parameter analysis and estimation of hydrogeological parameters based on VES method and pumping test.

VES Point	Latitude (°W)	Longitude (°S)	Longitudinal conductance (Si)	Transverse Resistance (ohm.m ²)	Hydraulic Conductivity (m/s)	Transmissivity VES (m ² /s)	Transmissivity Pumping (m ² /s)
VES 1	105.32062	-5.361414	1.004	1832.688	0.00155	0.066	0.0051
VES 2	105.32101	-5.361278	0.918	2199.813	0.00136	0.061	
VES 3	105.32046	-5.361034	0.951	1558.460	0.00162	0.063	
VES 4	105.32077	-5.361812	1.138	2037.285	0.00156	0.075	
VES 5	105.32024	-5.361604	0.585	2972.376	0.00096	0.040	

The longitudinal conductance values at the study site range from 0.918 to 1.138 Si, as shown in Figure 5. This parameter was calculated using the thickness and resistivity values of the layers interpreted as aquifers based on the VES inversion results. Longitudinal conductance is commonly used to evaluate groundwater flow characteristics, aquifer transmissivity, and groundwater potential within the Dar-Zarrouk framework (Raju et al., 2023). At VES 1, the longitudinal conductance (S) value of 1.004 indicates adequate aquifer thickness and saturation conditions, suggesting moderate groundwater potential. The values obtained at VES 2 (0.918 Si) and VES 3 (0.951 Si) are relatively similar, indicating fairly uniform aquifer conditions across these locations. Meanwhile, VES 4 exhibits the highest value (1.138 Si), indicating the most favorable aquifer potential among the investigated sites. In contrast, VES 5 shows the lowest value (0.585 Si), suggesting a thinner or less saturated aquifer layer and consequently lower groundwater potential.

In contrast to the longitudinal conductance values, VES 5 exhibits the highest transverse resistance value, reaching 2972.376. This high transverse resistance is influenced by the relatively high resistivity value of 71.28 Ωm recorded at this location. However, elevated resistivity values indicate a reduction in the conductive phase within the rock matrix (Amir et al., 2025). In a hydraulic context, this condition is associated with low effective pore tortuosity and limited hydraulic connectivity among grains, resulting in low hydraulic conductivity (K) and

transmissivity (T) values. Accordingly, VES 5, despite having the highest transverse resistance value, indicates a zone with the potential to store a large volume of static groundwater but with limited groundwater flow and transmissivity, as reflected by its low transmissivity ($T = 0.040 \text{ m}^2/\text{s}$) and hydraulic conductivity ($K = 0.00096 \text{ m/s}$) values. These characteristics indicate an aquifer dominated more by storage capacity than by groundwater flow capacity. Overall, transmissivity values within the study area range from 0.040 to 0.075 m^2/s (Table 2).

Theoretically, transverse resistivity (Tr) and transmissivity (T) exhibit a moderate correlation. The coefficient of determination obtained from the correlation between transverse resistance and transmissivity is 0.6039 (Figure 6), indicating that 60.39% of the transmissivity variation at the study site can be explained by changes in transverse resistance, whereas the remaining 39.61% is influenced by factors outside the model. Zones with high resistivity generally produce large transverse resistance values. Nevertheless, reduced pore connectivity within the rock matrix directly contributes to lower hydraulic conductivity and transmissivity values. This relationship is most evident at VES 5, which recorded the highest transverse resistance value (2972.376 Ωm^2) but the lowest transmissivity value (0.040 m^2/s), indicating an aquifer characterized more by storage than by groundwater flow. In contrast, VES 4, despite having a moderate transverse resistance value, exhibits the most favorable hydraulic performance ($T =$

0.075 m²/s). This finding confirms that aquifer prospectivity cannot be interpreted using a single parameter alone but instead

requires an integrated evaluation of multiple hydrogeological parameters (Muhammad et al., 2023).

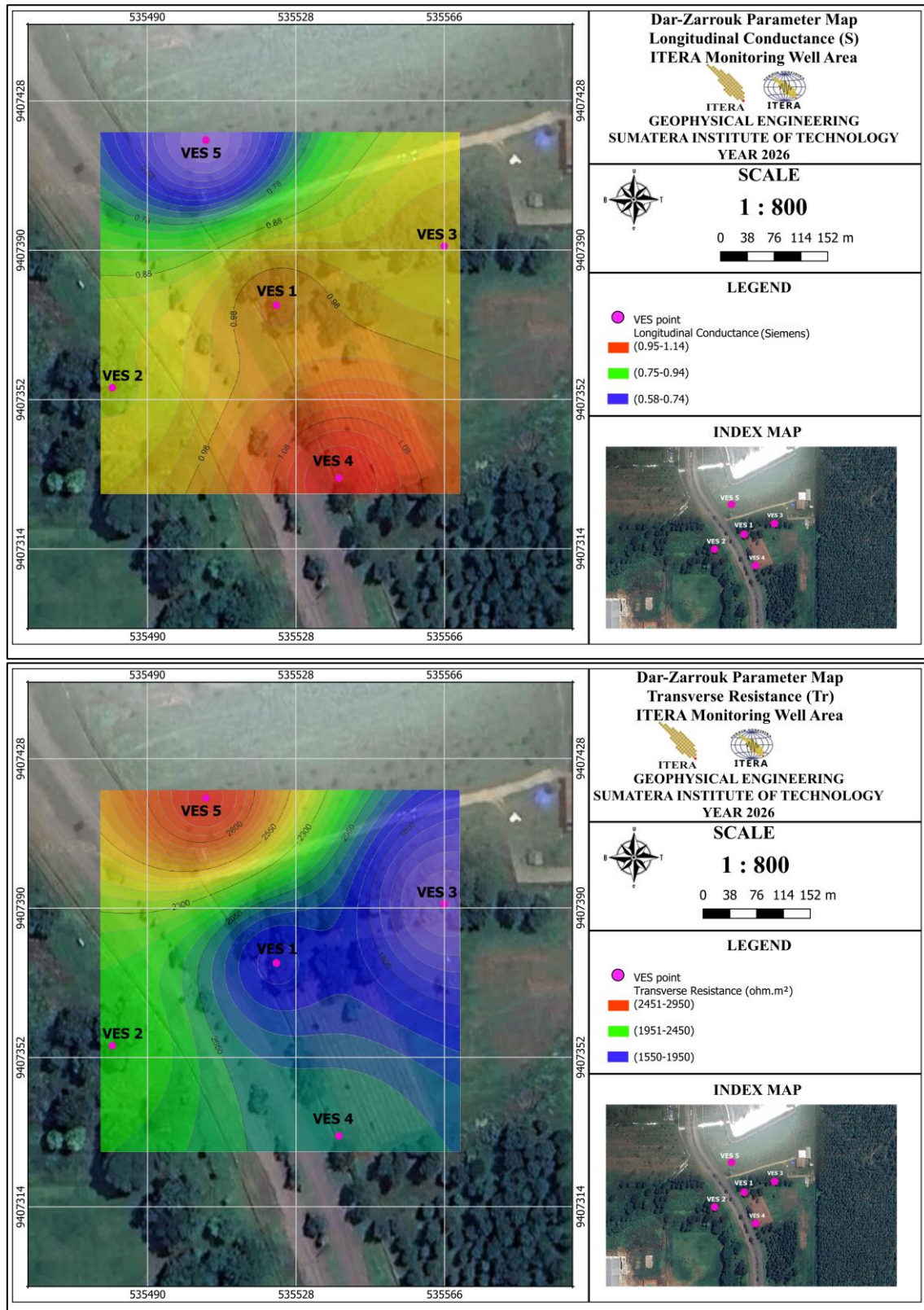


Figure 5. Distribution of longitudinal conductance (S) and transverse resistance (Tr) values based on Dar-Zarrouk parameters.

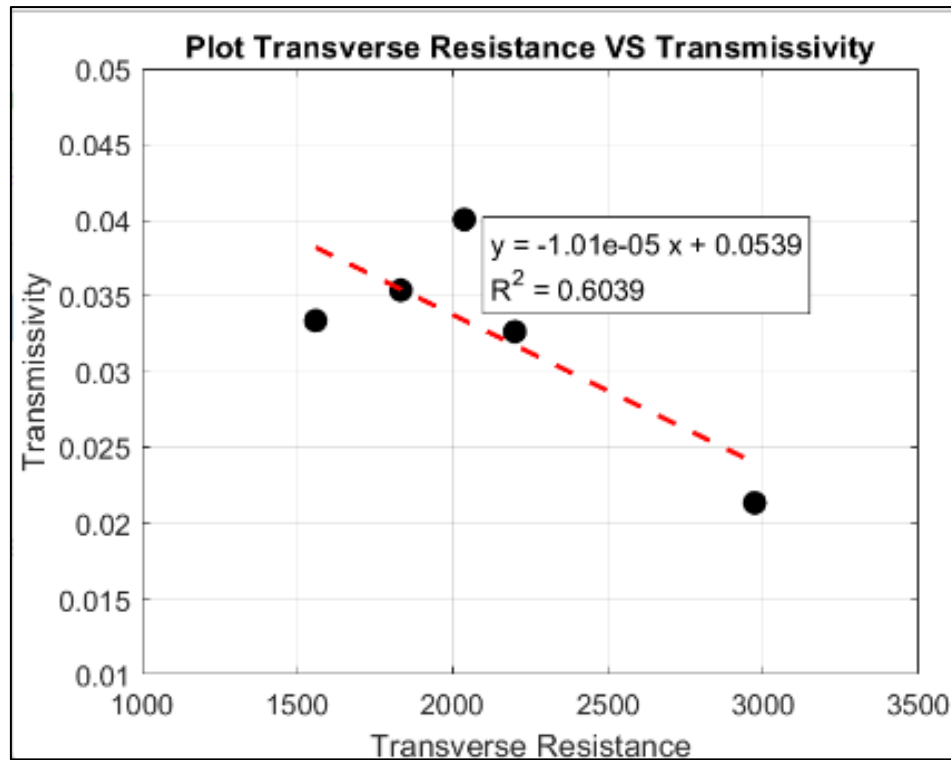


Figure 6. Correlation between transverse resistance (TR) and transmittance (T) based on VES data.

Well logging and Lithology

Resistivity logs provide important information regarding fluid content within rock formations and become more effective when integrated with other geophysical datasets (Al-Mudhafar et al., 2024). Measurements obtained using short- and long-electrode configurations represent invaded zones and true formation zones, respectively (Figure 7a). In general, low resistivity values correspond to sand, sandy clay, clayey sand, and gravelly sand of volcanic origin (Sehah et al., 2024).

At depths shallower than 65 m, the relative resistivity values recorded in the logs are relatively low, causing the log responses to appear less distinct within the display scale presented in Figure 7. The shallow subsurface layers are dominated by clay and volcanic ash, reflecting a typical volcanic depositional environment characterized by low to moderate resistivity values influenced by moisture content, texture, and parent material composition (Juwono et al., 2024). The correlation between resistivity data and lithological

information reveals the presence of two main aquifer zones at depths of 85–90 m and 110–125 m. Based on the interpretation of resistivity logs integrated with drilling cutting data, these zones are interpreted to consist predominantly of coarse sand with minor gravel components and are therefore identified as productive aquifer layers (Mohammed et al., 2025).

Geophysical well logging provides a continuous and efficient approach for aquifer characterization and offers significant advantages over conventional methods (Mohammed et al., 2025). Based on the log interpretation, the well construction design incorporates screen installation within productive aquifer intervals and gravel pack placement at depths of 70–125 m to enhance hydraulic flow efficiency. Resistivity-based analysis further supports accurate drilling placement and optimal well design (Sehah et al., 2024). In addition, cement grouting applied at depths of 0–25 m functions to prevent surface contamination because the shallow clay layers act as a natural aquitard

protecting the underlying confined aquifer
(Nugraha et al., 2022).

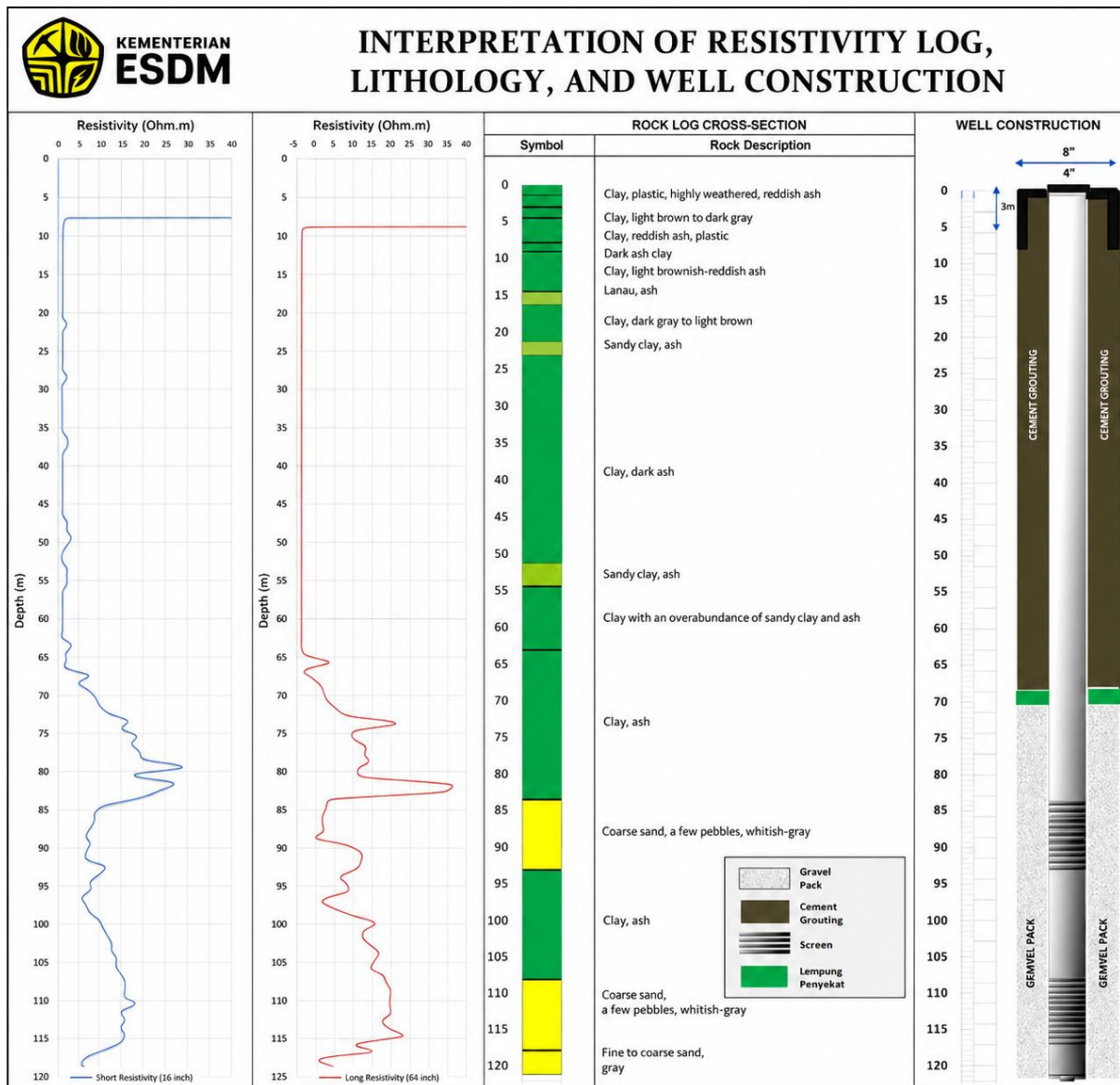


Figure 7. Well logging results and lithological descriptions showing (a) resistivity interpretation and (b) lithological descriptions.

Lithological log interpretation indicates that the subsurface from the ground surface to approximately 85 m depth is dominated by low-permeability clay, silt, and sandy clay layers that collectively function as an aquitard. A transitional zone consisting of coarse sand with minor gravel occurs at depths of 85–95 m, indicating improved porosity and permeability characteristics. The main aquifer is identified at depths of 110–125 m and consists predominantly of coarse-to medium-grained sand with favorable hydraulic properties.

Accordingly, the well screen is installed at depths of 90–120 m to optimize groundwater extraction from the productive aquifer interval.

The interbedding of clay, sandy clay, and coarse sand layers observed between depths of 70 and 125 m, as identified from the well log, indicates substantial lithological heterogeneity that is not fully represented in the VES inversion results. This heterogeneity is interpreted as the primary factor contributing to the overestimation of

transmissivity values derived from the Dar-Zarrouk parameters relative to the pumping test results because the geophysical approach assumes lateral continuity and homogeneity within each resistivity layer (Ammar & Kamal., 2019).

Petrographic Analysis

Petrographic analysis was performed on representative thin sections using a polarizing microscope under three observation modes. Plane-polarized light (PPL) was used to identify primary mineral properties, including color, pleochroism, relief, and cleavage (MacKenzie & Guilford, 1980). Cross-polarized light (XPL) was subsequently applied to determine birefringence, interference colors, extinction angles, and crystal twinning, thereby enabling systematic mineral identification (Nesse, 2014). Additionally, a 530 nm gypsum plate (λ -plate) was employed as a retardation compensator to enhance the visibility of low-birefringence minerals and clay alteration products commonly associated with volcanic sequences. This integrated approach facilitated comprehensive characterization of the mineralogical composition and textural properties of the subsurface geological formations.

As shown in Figure 8, petrographic analysis of Samples 22 (22 m), 23 (23 m), 29 (29 m), and 108 (108 m) obtained from drilling cuttings reveals variations in lithology and rock texture characteristics. The thin sections were impregnated with blue-colored resin to enhance the visibility of porosity distribution during microscopic observation. Petrographic interpretation was conducted based on thin-section observations and subsequently correlated with resistivity log data to support the calibration of subsurface lithological identification.

Samples 22, 23, and 29 are dominated by clay matrix material characterized by very fine grain sizes, poor sorting, and matrix-supported fabrics, indicating low porosity and permeability consistent with clay-rich sediments. Sample 22 consists predominantly of clay-sized particles with minor quartz and lithic components, whereas Sample 23 contains limited fine sand fractions but remains matrix-dominated. Sample 29 exhibits similar characteristics with strong matrix dominance and minimal pore space development. In contrast, Sample 108 exhibits a higher proportion of framework grains, including quartz, plagioclase, and lithic fragments, with grain sizes ranging from coarse silt to very fine gravel. The relatively more open grain arrangement and partially grain-supported fabric indicate improved pore space development and suggest a tendency toward sand or conglomeratic lithology.

Overall, the petrographic observations indicate that Samples 22, 23, and 29 predominantly consist of clay-rich sediments characterized by very fine grain sizes, high matrix content, poor sorting, and low porosity. These characteristics indicate low permeability and limited potential as productive aquifer units. In contrast, Sample 108 exhibits relatively coarser grain sizes, higher quartz content, and improved textural maturity, suggesting more favorable reservoir properties than the clay-dominated samples.

From a regional geological perspective, the study area is dominated by tuff, but petrographic analysis indicates a sedimentary/ volcanoclastic character. This is likely due to the reprocessing of pyroclastic material and its subsequent re-deposition by water, which has resulted in a sedimentary texture in the rocks. Additionally, alteration and weathering may cause the original volcanic texture to be less visible in thin sections.

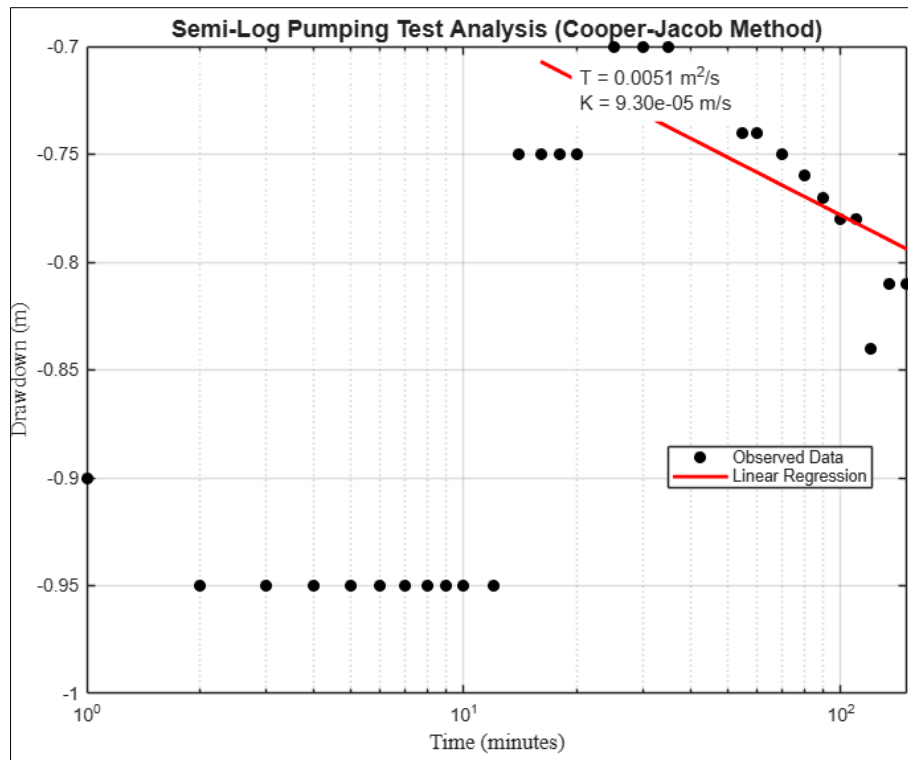


Figure 9. Pumping tests analysis using the Cooper–Jacob method.

It should be noted that the transmissivity and hydraulic conductivity values obtained in this study were derived from a single pumping well, thereby limiting their spatial representativeness at the aquifer scale. Consequently, the reported hydraulic parameters are more appropriately interpreted as point estimates applicable to the immediate vicinity of the monitoring well. Caution is therefore required when extrapolating these values across the broader study area. More comprehensive characterization of aquifer-scale hydraulic properties would require multi-well pumping tests involving additional observation wells.

The agreement between transmissivity estimated from the Dar-Zarrouk parameters (TDZ) and transmissivity obtained from the pumping test (T_{pump}) was evaluated using the ratio (R) presented in Equation (8). This comparison follows the hydrogeophysical validation approach commonly applied to assess the consistency between geoelectrical estimations and field-based hydraulic measurements (Heigold et al., 1979):

$$R = \frac{TDZ}{T_{pump}} \quad (9)$$

Based on the transmissivity values obtained from the Dar-Zarrouk parameters and the pumping test (Table 2), a ratio of 12.94 was obtained, indicating that the geophysical method produces higher transmissivity estimates than the pumping test. This discrepancy is influenced by differences in measurement scale and by the homogeneity assumptions inherent in the geophysical approach. The VES method represents subsurface conditions over a broader spatial extent, whereas the pumping test primarily reflects localized conditions surrounding the well (Singh & Mondal, 2025). In addition, lithological heterogeneity characterized by alternating clay and sand layers at depths of 70–110 m further influences the effective field permeability values. Therefore, integrating geophysical data with pumping test results is necessary to obtain more representative permeability estimates for sedimentary hydrogeological systems.

Integration of Hydrogeological Models

The conceptual hydrogeological model presented as cross-sections in the west–east and south–north directions demonstrates both lateral continuity and thickness variations among the investigated layers across the study area (Figure 10). The first layer represents the surface soil layer with relatively limited thickness. The second layer exhibits very low resistivity values and is interpreted as clay, a material characterized by low permeability. The third layer consists of sandy clay with moderate resistivity values and functions as a transitional layer. Meanwhile, the fourth layer is located at greater depth and functions as the principal aquifer, consisting predominantly of sand with relatively higher resistivity values (Table 1).

In the west–east section, the aquifer layer exhibits its greatest thickness in the western part of the study area and gradually becomes thinner toward the east, particularly at VES 3. In contrast, the south–north section (VES 1–4–5) shows less significant thickness variation. The southern section at VES 4 exhibits a slightly greater aquifer thickness than the northern section at VES 5. The hydrogeological cross-section (Figure 10) illustrates the vertical and lateral relationships among subsurface strata that control groundwater occurrence and movement within the study area. The subsurface sequence extends to a depth of approximately 125 m and consists of layers with contrasting physical characteristics that influence their hydraulic responses.

The observation well is located at VES 1, which serves as the primary reference point for correlation among measurement locations. Based on the integrated interpretation of VES data, resistivity logging, and lithological information, the groundwater-bearing zone is interpreted to occur at depths of approximately 76–84 m below ground surface. Lateral variations within the groundwater-bearing zone

indicate heterogeneity in hydraulic gradients among locations, which may influence groundwater flow directions and flow patterns within the aquifer system. Groundwater flow within the sand layer develops predominantly in the horizontal direction following the hydraulic pressure gradient. The presence of an overlying low-permeability layer causes the groundwater to remain under pressure, thereby supporting its interpretation as a confined aquifer system (Lodh, 2021). The hydrogeological conceptual model presented in Figure 10 illustrates the lateral and vertical relationships among hydrostratigraphic layers, infiltration zones, and groundwater flow directions within the study area. The subsurface sequence extends to a depth of approximately 125 m and consists of layers with contrasting physical characteristics that influence their hydraulic responses. The observation well is located at VES 01, which serves as the primary reference point for correlation among the sounding locations.

Vertically, the study area consists of four main layers. The uppermost layer is topsoil, which functions as an infiltration zone (Dahan, 2020). In this layer, groundwater movement predominantly occurs vertically; however, the downward movement becomes restricted upon reaching the underlying clay layer. This clay layer is relatively impermeable and therefore acts as a barrier to vertical groundwater flow. Beneath the clay layer lies a sandy clay layer with moderate permeability that functions as a transitional zone. The deepest layer consists predominantly of sand and is interpreted as the principal aquifer. The groundwater table is interpreted to occur at depths ranging from 76 to 84 m below the ground surface. Lateral variations in groundwater level indicate differences in hydraulic head that may influence groundwater flow direction within the aquifer system. Groundwater flow within the sand layer develops

predominantly in the horizontal direction following the hydraulic gradient. Because the aquifer layer is confined beneath an

impermeable layer and controlled by hydraulic pressure differences, the system is classified as a confined aquifer.

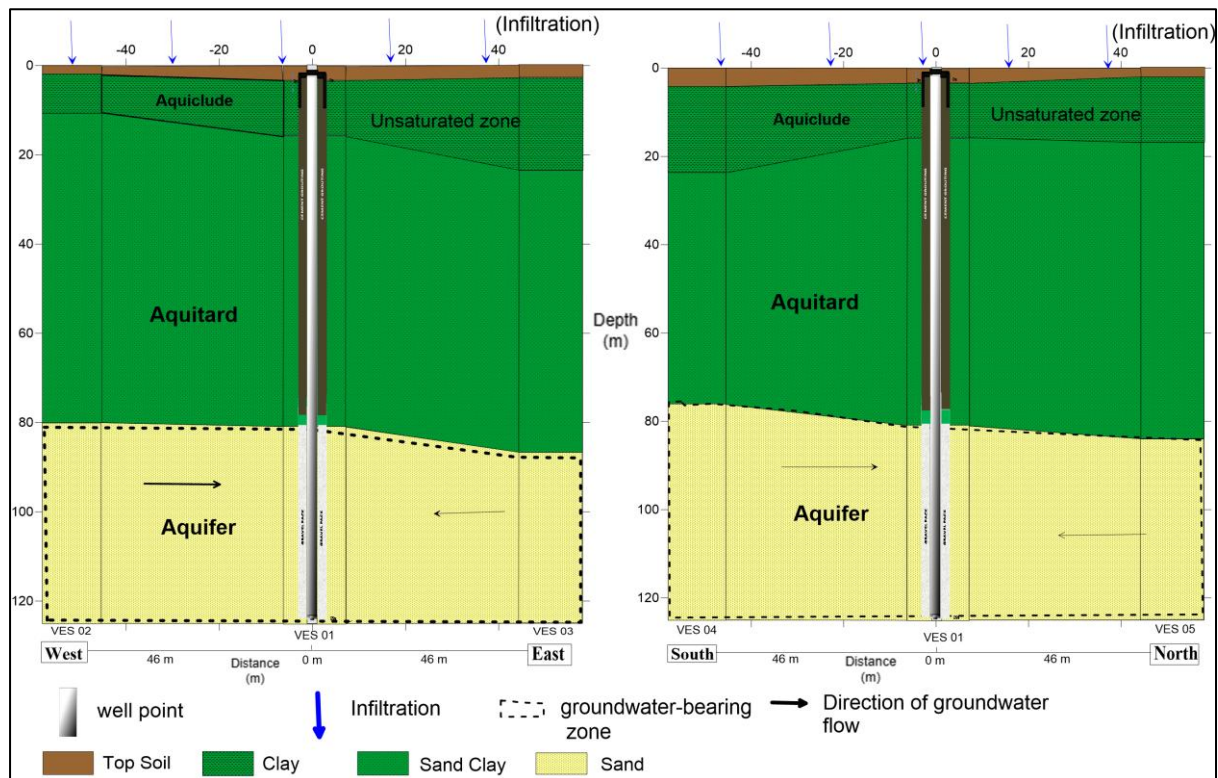


Figure 10. Conceptual hydrogeological model.

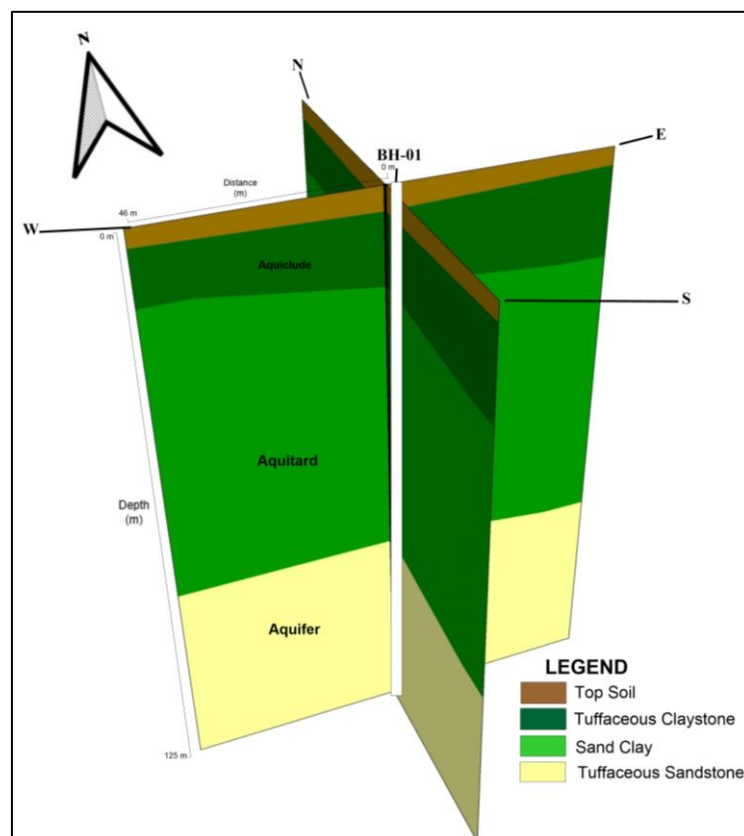


Figure 11. Hydrogeological fence diagram.

The hydrogeological diagram illustrates the subsurface stratification within the study area based on the interpretation of integrated geophysical and borehole data (Figure 11). The identified subsurface units consist of topsoil, clay, sandy clay, and sand layers (Table 3). The topsoil layer functions as an infiltration zone, whereas the clay layer is interpreted as an aquiclude (Vincent et al., 2024). The sandy clay layer functions as an aquitard, while the lowermost sand layer is interpreted as the principal aquifer (Mohamed et al., 2023).

Table 3. Range of resistivity values, lithology, and hydrogeological classification in the ITERA monitoring well area, Lampung.

Resistivity Range	Lithology	Hydrogeological Classification
< 10 Ω m	Clay	Aquiclude
10 – 20 Ω m	Sandy clay	Aquitard
20 – 80 Ω m	Sand	Aquifer

Conclusion

This study successfully achieves its primary objective of developing a calibrated interpretation approach for aquifer identification and determining optimal well construction depths within complex volcanic geological environments. Through the integration of Vertical Electrical Sounding (VES), well logging, petrographic analysis, and pumping test data, a more reliable understanding of the relationships among resistivity values, lithological characteristics, and hydraulic parameters is achieved. The results indicate that the main aquifer occurs at depths greater than 75 m, with two productive zones identified at depths of 85–90 m and 110–125 m. These zones predominantly consist of coarse-grained sand materials with favorable permeability characteristics. The integrated approach effectively reduces the ambiguity commonly associated with resistivity interpretation in volcanic materials, thereby improving the accuracy of aquifer delineation.

The main strength of this study lies in the application of a multidisciplinary approach that integrates geophysical, petrographic, and hydraulic data to produce a more comprehensive and calibrated interpretation. This approach not only enhances the reliability of aquifer identification but also provides a stronger basis for determining the optimal screen depth for monitoring wells. Based on the integrated interpretation results, the recommended screen interval is 90–120 m, representing the most productive aquifer zone within the study area.

Nevertheless, this study has several limitations that introduce uncertainty into the hydrogeological model outputs. The limited vertical resolution of the VES method in detecting thin layers may result in incomplete characterization of transitional zones within the aquifer system. In addition, the pumping test data derived from a single well constrain the spatial representativeness of the hydraulic parameters and introduce uncertainty into aquifer-scale estimates. Furthermore, the assumption of subsurface homogeneity in geophysical interpretation, reflected by the overestimation of Dar-Zarrouk transmissivity by a factor of approximately 12.94 relative to the pumping test results, highlights the inherent limitations of standalone geophysical approaches in heterogeneous sedimentary systems. Collectively, these uncertainties influence the reliability of the proposed hydrogeological model and should therefore be considered when applying the framework to broader areas. From a practical perspective, the findings of this study have significant potential applications in the planning and development of groundwater monitoring systems, particularly for determining the location and design of monitoring wells in volcanic geological environments. In addition, the calibrated interpretation framework developed in this study can be applied to similar hydrogeological

investigations to improve aquifer identification accuracy and support sustainable groundwater resource management.

Future research should focus on validating and expanding the proposed interpretation framework through multi-well pumping tests involving observation wells to better constrain aquifer hydraulic properties at broader spatial scales. Additional long-duration pumping tests would also be beneficial for evaluating boundary effects and confirming steady-state conditions. Furthermore, complementary geophysical surveys, such as Electrical Resistivity Tomography (ERT) and Time-Domain Electromagnetic (TDEM) methods, could improve lateral resolution and reduce interpretation ambiguity, particularly within transitional zones between aquifer and aquitard units.

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Author Contribution

Cherly Rizka Susanti: Conceptualization (lead); lithological, petrographic, and pumping test analysis (lead); writing and editing (equal). Astrik Rahmi Yati: Methodology (lead); geoelectrical and Dar-Zarrouk analysis (lead); conceptual model development and interpretation (lead); writing—original draft (lead). Rizka: Supervision (lead); validation (lead); writing—review and editing (equal). All

authors have read and approved the final version of the manuscript.

Conflict of Interest

The authors report no conflict of interest concerning the publication of this article.

References

- Agussalim, A., Djafar, M., & Rizal, A. S. (2022). Analisis potensi debit air tanah melalui pumping test metode step draw down pada sumur bor irigasi di Desa Bonto Rannu, Kecamatan Kajang, Kabupaten Bulukumba, Sulawesi Selatan. *Jurnal Fisika dan Terapannya*, 9(2), 127–137. <https://doi.org/10.24252/jft.v9i2.32277>
- Al-Mudhafar, W. J., Abbas, M. A., & Wood, D. A. (2024). Integration of electromagnetic, resistivity-based and production logging data for validating lithofacies and permeability predictive models with tree ensemble algorithms in heterogeneous carbonate reservoirs. *Petroleum Geoscience*, 30(1), petgeo2023-067. <https://doi.org/10.1144/petgeo2023-067>
- Amir, H. S., Fathy, M., Reda, M., & Mostafa, T. (2025). Integrated core-log petrophysical evaluation of the Sarir Formation reservoir units, southeastern Sirte Basin, Libya. *Journal of Umm Al-Qura University for Applied Sciences*. <https://doi.org/10.1007/s43994-025-00295-6>
- Ammar, A. I., & Kamal, K. A. (2019). Effect of structure and lithological heterogeneity on the correlation coefficient between the electric–hydraulic parameters of the aquifer, Eastern Desert, Egypt. *Applied Water Science*, 9(4), 83. <https://doi.org/10.1007/s13201-019-0963-3>

- Archie, G. E. (1942). The electrical resistivity log as an aid in determining some reservoir characteristics. *Transactions of the AIME*, 146(1), 54–62. <https://doi.org/10.2118/942054-G>
- Bahri, S., Appono, S. V., & Zulfiah. (2022). Global optimization very fast simulated annealing inversion for the interpretation of groundwater potential. *Jurnal Geofisika Eksplorasi*, 8(3), 225–236. <https://doi.org/10.23960/jge.v8i3.233>
- Chakraborty, S., Yadav, A., & Chatterjee, R. (2021). Comprehensive rock physics, petrophysics workflow to correct sonic logs for improved seismic QI: Study using wells of Krishna Godavari Basin. *Journal of Applied Geophysics*, 192, 104394. <https://doi.org/10.1016/j.jappgeo.2021.104394>
- Claprood, M., Gloaguen, E., Béraud, T., Blouin, M., Dupuis, C., Ferron, P., Ouellet, M., Chaussé, M., Martel, R., Paradis, D., & Ballard, J.-M. (2022). A case study using seismic reflection and well logs to reduce and quantify uncertainty during a hydrogeological assessment. *Frontiers in Water*, 3, 779149. <https://doi.org/10.3389/frwa.2021.779149>
- Cooper, H. H., Jr., & Jacob, C. E. (1946). A generalized graphical method for evaluating formation constants and summarizing well-field history. *Eos, Transactions American Geophysical Union*, 27(4), 526–534. <https://doi.org/10.1029/TR027i004p00526>
- Dahan, O. (2020). Vadose zone monitoring as a key to groundwater protection. *Frontiers in Water*, 2, 599569. <https://doi.org/10.3389/frwa.2020.599569>
- Grandis, H. (2009). *Pengantar Pemodelan Inversi Geofisika*. Himpunan Ahli Geofisika Indonesia (HAGI)
- Hasani, M. F., Hendrayana, H., & Taufiq, A. (2023). Determination of aquifer system using resistivity method in Pekalongan City and surrounding areas, Central Java, Indonesia. *Proceedings of the 4th International Seminar on Science and Technology (ISST 2022)*, 7, 100–108. https://doi.org/10.2991/978-94-6463-228-6_12
- Heigold, P. C., Gilkeson, R. H., Cartwright, K., & Reed, P. C. (1979). Aquifer transmissivity from surficial electrical methods. *Groundwater*, 17(4), 338–345. <https://doi.org/10.1111/j.1745-6584.1979.tb03326.x>
- Juwono, A. M., Susilo, A., Hasan, M. F. R., Yunika, N. A., Annabil, A. A., Mujtaba, M. W. H., & Haniyyah, S. (2024). Investigation of groundwater sources in Banyol Hamlet Malang Regency using the geoelectrical resistivity method to overcome drought strategy. *Indonesian Physical Review*, 7(2), 240–248. <https://doi.org/10.29303/ipr.v7i2.320>
- Kumalasari, I. N., Mulyasari, R., Dewanto, O., Mulyatno, B. S., Wibowo, R. C., Maulida, N. H., Hidayatika, A., Hesti, H., Dani, I., & Erfani, S. (2025). Identifikasi akuifer air tanah menggunakan metode geolistrik di Perumahan Gang Jati Baru, Hajimena, Natar, Lampung Selatan. *Jurnal Riset Fisika Indonesia*, 5(2), 71–78. <https://doi.org/10.33019/jrfi.v5i2.6504>
- Li, J., Wang, W., Cheng, D., Li, Y., Wu, P., & Huang, X. (2021). Hydrogeological structure modelling based on an integrated approach using multi-source data. *Journal of Hydrology*, 600, 126435. <https://doi.org/10.1016/j.jhydrol.2021.126435>
- Lodh, A. (2021). Simulating the impact of extended desertification on Indian hydroclimate using ICTP-RegCM4.4.5.10 model. *Journal of Hydrology*, 598, 126405. <https://doi.org/10.1016/j.jhydrol.2021.126405>

- MacKenzie, W. S., & Guilford, C. (1980). *Atlas of Rock-Forming Minerals in Thin Section*. Routledge. <https://doi.org/10.4324/9781315837413>
- Maillet, R. (1947). The fundamental equations of electrical prospecting. *Geophysics*, 12(4), 529–556. <https://doi.org/10.1190/1.1437342>
- Mangga, S. A., Amiruddin, A., Suwanti, T., Gafoer, S., & Sidarto, S. (1993). *Peta geologi lembar Tanjungkarang, Sumatera (Skala 1:250.000)*. Pusat Penelitian dan Pengembangan Geologi.
- Masria, A., Alshammari, T. O., Ghareeb, M., Seif, A. K., Abd-Elmaboud, M. E., & Ammar, A. I. (2024). 2D and 3D modeling of resistivity and chargeability to identify the type of saturated groundwater for complex sedimentary facies. *Hydrology*, 11(8), 120. <https://doi.org/10.3390/hydrology11080120>
- Mohamed, A., Alarifi, S. S., & Abdelrady, A. (2023). Sedimentary cover and structural trends affecting groundwater flow in the Nubian Sandstone Aquifer System: Inferences from geophysical, field and geochemical data. *Frontiers in Earth Science*, 11, 1173569. <https://doi.org/10.3389/feart.2023.1173569>
- Mohammed, M. A. A., Szabó, N. P., Eltijani, A., & Szűcs, P. (2025). An integrated workflow combining machine learning and wavelet transform for automated characterization of heterogeneous groundwater systems. *Scientific Reports*, 15, 4973. <https://doi.org/10.1038/s41598-025-89410-5>
- Muauz, A., Berehanu, B., & Bedru, H. (2025). An alternative approach using electrical well logging for estimating porosity and hydraulic conductivity in volcanic aquifers of the Upper Awash River Sub-Basin, Ethiopia. *Journal of Hydrology: Regional Studies*, 60, 102547. <https://doi.org/10.1016/j.ejrh.2025.102547>
- Muhammad, S., Khalid, P., Ehsan, M. I., Qureshi, J., & Farooq, S. (2023). Evaluation of aquifer parameters through integrated approach of geophysical investigations, pumping test analysis and Dar-Zarrouk parameters in the central part of Bari Doab, Punjab, Pakistan. *Environmental Monitoring and Assessment*, 195, 1435. <https://doi.org/10.1007/s10661-023-12049-0>
- Nesse, W. D. (2014). *Introduction to Optical Mineralogy* (4th ed.). Oxford University Press. <https://global.oup.com/academic/product/introduction-to-optical-mineralogy-9780199846283?cc=my&lang=en>
- Nouradine, H., Schamper, C., Valdes, D., Moussa, I., Ramel, D., & Plagnes, V. (2024). Integrating geological, hydrogeological and geophysical data to identify groundwater resources in granitic basement areas (Guéra Massif, Chad). *Hydrogeology Journal*, 32(3), 759–784. <https://doi.org/10.1007/s10040-024-02766-2>
- Nugraha, G. U., Bakti, H., Lubis, R. F., Sudrajat, Y., & Arisbaya, I. (2022). Aquifer vulnerability in the coastal northern part of Lombok Island Indonesia. *Environment, Development and Sustainability*, 24, 1390–1410. <https://doi.org/10.1007/s10668-021-01459-0>
- Nyembwe, I., Nwanosike, A. A., Ndatimana, G., Okot, N., & Muamba, R. T. (2024). Evaluation of aquifer hydraulic properties from resistivity and pumping test data in parts of Gwagwalada, Northcentral Nigeria. *Journal of Groundwater Science and Engineering*, 12(3), 309–320.

- <https://doi.org/10.26599/JGSE.2024.9280023>
- Oli, I. C., Opara, A. I., Okeke, O. C., Akaolisa, C. Z., Akakuru, O. C., Osi-Okeke, I., & Udeh, H. M. (2022). Evaluation of aquifer hydraulic conductivity and transmissivity of Ezza/Ikwo area, Southeastern Nigeria, using pumping test and surficial resistivity techniques. *Environmental Monitoring and Assessment*, 194(10), 719. <https://doi.org/10.1007/s10661-022-10341-z>
- Oyeyemi, K. D., Aizebeokhai, A. P., Ukabam, C. S., Kayode, O. T., Olajo, A. A., & Metwaly, M. (2023). Nonlinear inversion of electrical resistivity sounding data for multi-layered 1-D earth model using global particle swarm optimization (GPSO). *Heliyon*, 9(6), e16528. <https://doi.org/10.1016/j.heliyon.2023.e16528>
- Pinehas, D., & Warsa, W. (2020). Determination of Groundwater Surface using Damped Least-Squares Inversion in the Bekasap Field, Riau. *Jurnal Geofisika*, 17(2), 5–8. <https://doi.org/10.36435/jgf.v17i2.414>
- Prinaldi, D. R., Pratiwi, S. D., & Rosana, M. F. (2023). Karakteristik petrologi dan petrografi satuan batugamping terumbu dan batupasir karbonatan pada Formasi Cibodas daerah Pasiripis dan sekitarnya, Kabupaten Sukabumi, Provinsi Jawa Barat. *Padjadjaran Geoscience Journal*, 7(6), 1749 – 1756. <https://jurnal.unpad.ac.id/geoscience/article/view/53360/22344>
- Putri, S. A., Putra, A., & Abdurrachman, M. (2018). Studi petrografi batuan beku dan sinter silika di Kecamatan Alam Pauh Duo, Kabupaten Solok Selatan. *Jurnal Fisika Unand*, 7(4), 320–327. <https://jfu.fmipa.unand.ac.id/index.php/jfu/article/view/371>
- Raju, B. A., Rao, P. V., & Subrahmanyam, M. (2023). Estimating aquifer transmissivity using Dar-Zarrouk parameters to delineate groundwater potential zones in Alluri Seetharama Raju District, Andhra Pradesh, India. *Journal of Groundwater Science and Engineering*, 11(2), 116–132. <https://doi.org/10.26599/JGSE.2023.9280011>
- Rau, G. C., Cuthbert, M. O., Post, V. E. A., Schweizer, D., Acworth, R. I., Andersen, M. S., Blum, P., Carrara, E., Rasmussen, T. C., & Ge, S. (2020). Future-proofing hydrogeology by revising groundwater monitoring practice. *Hydrogeology Journal*, 28(8), 2963–2969. <https://doi.org/10.1007/s10040-020-02242-7>
- Rizka, R., & Satiawan, S. (2019). Investigasi Lapisan Akuifer Berdasarkan Data Vertical Electrical Sounding (VES) dan Data Electrical Logging; Studi Kasus Kampus ITERA. *Bulletin of Scientific Contribution: Geology*, 17(2), 91–100. <https://jurnal.unpad.ac.id/bsc/article/view/22393>
- Roy, A., & Apparao, A. (1971). Depth of investigation in direct current methods. *Geophysics*, 36(5), 943–959. <https://doi.org/10.1190/1.1440226>
- Sanei, H., Ardakani, O. H., Akai, T., Akihisa, K., Jiang, C., & Wood, J. M. (2020). Core versus cuttings samples for geochemical and petrophysical analysis of unconventional reservoir rocks. *Scientific Reports*, 10(1), 7920. <https://doi.org/10.1038/s41598-020-64936-y>
- Sehah, S., Aziz, A. N., Raharjo, S. A., Buliyanti, S. C., Mubarak, F., Wicaksono, G. F., & Asahi, W. (2024). Study of the Potential of the Purwokerto-Purbalingga Groundwater Basin as a Source of Irrigation using Gravimetric Satellite Data. *Water Conservation and Management*, 8(2), 140–149.

- <https://doi.org/10.26480/wcm.02.2024.140.149>
- Singh, S., & Mondal, N. C. (2025). Aquifer hydraulic characteristics using D-Z parameters: A case study of Lohaghat Block, Champawat District, Uttarakhand, India. *Discover Applied Sciences*, 7(11), 1293. <https://doi.org/10.1007/s42452-025-06778-9>
- Siringoringo, L. P., Rizki, R., & Nababan, J. (2019). Hydrogeochemical and groundwater assessment for drinking purpose at ITERA Campus Area and its surroundings. *Journal of Geoscience, Engineering, Environment, and Technology*, 4(1), 40–47. <https://doi.org/10.25299/jgeet.2019.4.1.2478>
- Siringoringo, L. P., & Maulana, S. (2020). Unconfined groundwater flow pattern and facies changes at Way Huwi Village, South Lampung. *RISSET Geologi dan Pertambangan*, 30(1), 109–118. <https://doi.org/10.14203/risetgeotam2020.v30.1076>
- Syaputri, T. D., Suhendra, S., Halauddin, H., Lidiawati, L., & Nurhidayah, R. (2024). Groundwater study using vertical electrical sounding (VES) data based on resistivity and porosity of rocks in Kampung Melayu, Bengkulu City. *Jurnal Ilmiah Sains*, 24(1), 38–47. <https://doi.org/10.35799/jis.v24i1.54133>
- Todd, D. K. (1980). *Groundwater hydrology* (2nd ed.). John Wiley & Sons.
- Vincent, A., Daigre, C., Fischer, O., Aðalgeirsdóttir, G., Violette, S., Hart, J., Guðmundsson, S., & Pálsson, F. (2024). A hydrogeological conceptual model of aquifers in catchments headed by temperate glaciers. *Hydrology and Earth System Sciences*, 28(14), 3475–3494. <https://doi.org/10.5194/hess-28-3475-2024>
- Warsi, T., Kumar, V. S., Kumar, D., Nandan, M. J., Biswas, G., Sahadevan, D. K., Manikyamba, C., Rao, T. V., Rangarajan, R., Ahmed, S., & Chandrasekhar, V. (2020). Integration of geophysics and petrography for identifying the aquifer and the rock type: A case study from Giddalur, Andhra Pradesh, India. *Journal of Earth System Science*, 129(1), 44. <https://doi.org/10.1007/s12040-019-1321-4>
- Wilkosz, M. (2022). ReMo3D – an open-source Python package for 2D and 3D simulation of normal and lateral resistivity logs. *Geology, Geophysics & Environment*, 48(2), 195–211. <https://doi.org/10.7494/geol.2022.48.2.195>
- Wu, W., & Grana, D. (2017). Integrated petrophysics and rock physics modeling for well log interpretation of elastic, electrical, and petrophysical properties. *Journal of Applied Geophysics*, 146, 54–66. <https://doi.org/10.1016/j.jappgeo.2017.09.007>
- Wu, Y., & Fan, Y. (2021). Fast hierarchical inversion for borehole resistivity measurements in high-angle and horizontal wells using ADNN-AMLM. *Journal of Petroleum Science and Engineering*, 203, 108662. <https://doi.org/10.1016/j.petrol.2021.108662>
- Yang, L., Gao, M., Chen, J., Shi, W., Hou, C., Liu, Z., Luo, C., Yu, J., Yang, X., & Dong, J. (2025). Effects of climate variables and human activities on groundwater level fluctuations in unconsolidated sedimentary aquifers: A data-driven approach. *Hydrology*, 12(8), 215. <https://doi.org/10.3390/hydrology12080215>
- Yihdego, Y. (2017). Hydraulic in situ testing for mining and engineering design: Packer test procedure,

preparation, analysis and interpretation. *Geotechnical and Geological Engineering*, 35(1), 29–44. <https://doi.org/10.1007/s10706-016-0112-9>

- Yusuf, S. N., Ishaku, J. M., & Wakili, W. M. (2021). Estimation of Dar-Zarrouk parameters and delineation of groundwater potential zones in Karlahi, part of Adamawa Massif, Northeastern Nigeria. *Warta Geologi*, 47(2), 103–112. <https://doi.org/10.7186/wg472202101>
- Zhou, F., Giannakis, I., Giannopoulos, A., Holliger, K., & Slob, E. (2023). Extracting mud invasion information using borehole radar—A numerical study. *Geophysics*, 88(2), D69–D83. <https://doi.org/10.1190/geo2022-0121>