CALCULATION OF AQUIFER DISCHARGE IN ACEH INDUSTRIAL ESTATE AREA BASED ON VERTICAL ELECTRICAL SOUNDING DATA

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Abstract. *Planning for groundwater requirements in the Aceh Industrial Area needs a study of the potential existence and types of groundwater. This study analyzes the potential and flow rate of aquifers using the Wenner configuration Vertical Electrical Sounding (VES) method. This method was applied to identify subsurface layers, determine the position and thickness of aquifers, and calculate groundwater flow rates using Darcy's law. Data acquisition was conducted at six measurement points using the ARES instrument. The number of electrodes used is 4, with 2 as current electrodes and 2 as potential electrodes. The electrode spacing applied was 2 meters. The resistivity raw data obtained was processed using EarthImager software to generate a 1D subsurface model. The interpretation results indicate the presence of a confined aquifer at depths of 80–160 meters and a thickness of 19–67 meters, characterized by resistivity values ranging from 27 to 56 Ωm. This type of aquifer indicates good groundwater quality with a TDS concentration of approximately 100–150 mg/l. The average groundwater flow rate calculated reaches 3.035 L/second, and the transmissivity value is 784.44 m²/day. 3D modeling using RockWorks 16 shows good aquifer zone continuity and a tendency for aquifer thickness to increase toward the coast, where the topography is lower. The results of this study indicate that the resistivity method is effective in supporting groundwater exploration.*

Keywords: *Aceh Industrial estate, aquifer, darcy law, VES, wenner*

INTRODUCTION

The Aceh–Ladong Industrial Area (KIA-Ladong) is an integrated industrial location that was inaugurated in 2024 and is utilized to promote leading products. A new industrial site naturally requires appropriate information, such as estimates of rock formation, rock type, and the availability of raw water. In particular, groundwater demand is expected to continue increasing and is crucial for supporting activities in the area. The demand for and availability of groundwater make groundwater exploration a critical area of study (Purwanto et al., 2022).

Currently, well location determination is often carried out based on landscape design rather than well quality. As a result, many wells with high construction costs are abandoned due to limited water discharge. However, some studies focus solely on the position and depth of water (Masrurah et al., 2024), which do not calculate the water flow rate for pumping relevance. To obtain a high-quality, well location with a long pumping lifespan, research using the resistivity geophysical method is necessary. This method utilizes the flow of electrical current beneath the surface to estimate the type and thickness of subsurface layers.

The resistivity geophysical method remains the most effective approach for delineating and characterizing subsurface aquifers due to its sensitivity to variations in water content and the physical properties of geological materials. Its main principle is based on measuring apparent resistivity, which is then inverted into a subsurface model to obtain important parameters such as layer thickness, depth, conductivity, and actual resistivity values. Low resistivity values generally indicate water-saturated layers. Conversely, high resistivity values indicate impermeable layers or dry rocks. Based on this understanding, this method is very useful in distinguishing aquifer zones, cover layers, and bedrock. In addition to being non-destructive and economical, this method is capable of describing lateral and vertical variations in hydrogeological conditions. Interpretation of resistivity results combined with geological and hydrogeological data provides a more comprehensive understanding of groundwater basin conditions (Idris et al, 2022).

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The application of resistivity methods in determining aquifer layers is beneficial in reducing exploitation failures. This method is highly effective in mapping subsurface structures and groundwater availability. Studies (Kaliraj et al., 2024; Sastrawan et al., 2020) and (Puspita et al., 2022) demonstrate the success of the resistivity geophysical method in identifying aquifers at various locations. (Marvita et al., 2021) Determined aquifer layers based on electrical logging and cutting data in Bireun Regency. The results of the study using the resistivity method show that aquifer layers can be studied using the geophysical method (Fadhli et al., 2019) and can be calculated using Darcy's law (Fadhli et al., 2024; Fadhli et al., 2025).

This study employs the Wenner configuration geoelectric method to determine subsurface conditions and identify the presence of aquifers. The Wenner configuration has the simplest electrode arrangement, resulting in a more symmetrical and uniform distribution of electrical current in the ground. This configuration is capable of producing high-quality, high-resolution data for subsurface vertical interpretation. The study was conducted to obtain a map of groundwater depth, aquifer layers, aquifer-forming rocks, and the flow capacity of water discharge at the study site. Aquifer layers will determine the presence of groundwater and its carrier rocks. The cross-sectional area of the aquifer and the porosity percentage of the aquifer-bearing layer will determine the amount of water discharge. Information on water discharge volume is crucial in groundwater exploration, as it is closely related to the amount of water that can be pumped and the economic viability of a well. Therefore, the application of geophysical methods is essential for determining the quality and quantity of clean water at a location.

GEOLOGICAL SETTING

This study was conducted in Durung Village, Mesjid Raya Subdistrict, Aceh Besar Regency, Aceh. Geographically, the study site is located on a hill at an elevation of 178 meters above sea level.

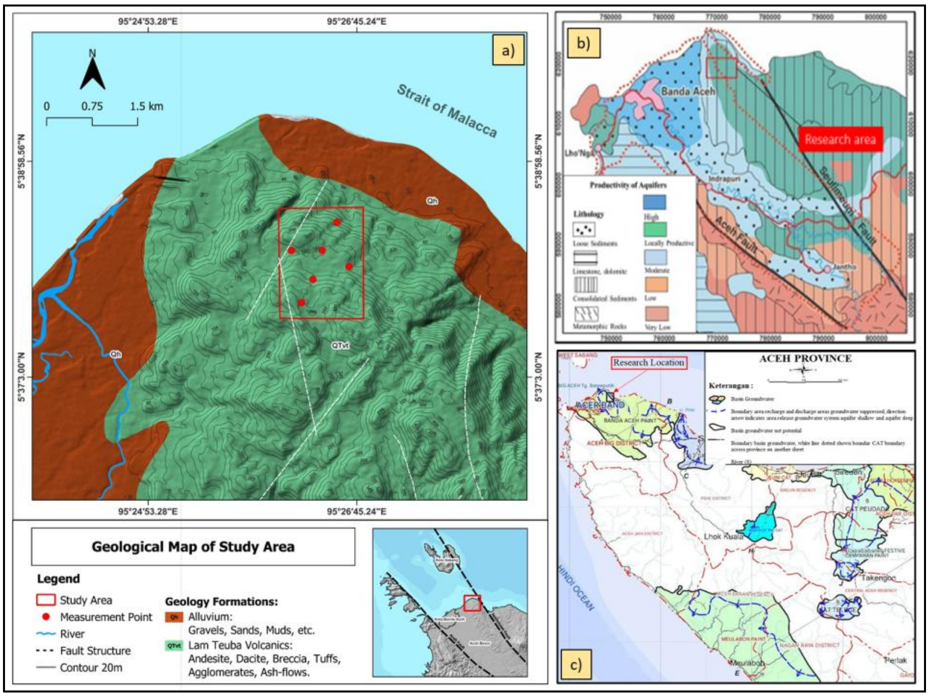

Figure 1. a) Map of Geological of Study area, b). Map of Hydrological Condition at Study area, c). Map of groundwater basin at study area

The site is situated west of the Seulimum fault segment. The northern part of the site borders the Indian Ocean, with a distance of 2 km to the coastline. Based on the geological map Figure. 1.a, the geological formations of the study area are divided into three formations.

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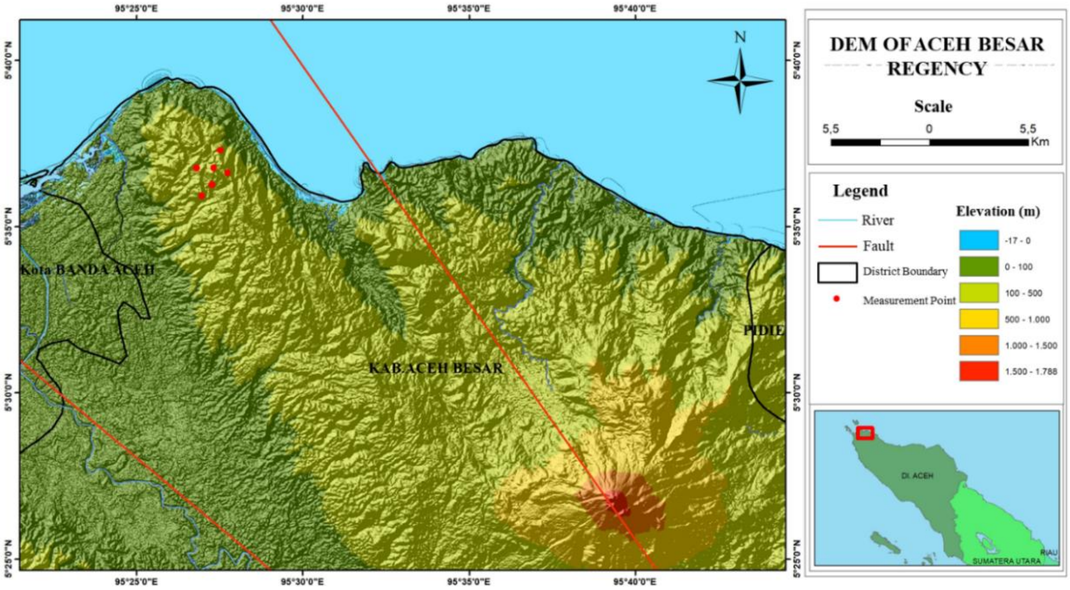

Figure 2. Digital Elevation Model and acquisition data location

The first is the Lam Teuba Volcanic Rock Formation (QTvt), which consists of Pliocene-Pleistocene rocks derived from the volcanic activity of Mount Seulawah, including volcanic breccia, tuff, conglomerate, and andesite. The second formation consists of lahar member rocks (Qvtl), which originate from lahar flows within the Lam Teuba volcanic rock. The third formation is the young alluvial formation in the western part of the study area, composed of sand, clay, silt, swamp sediments (Syukri et al, 2022),, and gravel sediments (Moechtar et al., 2009).

In the study area, several geological structures are products of subduction, forming the Seulimum fault (Muksin et al, 2018). Figure. 1.b illustrates that the study site is located within a productive aquifer area. This productivity is influenced by the hydrogeological system formed by the Lamteuba volcano, which has sedimentary lithology.

Another factor indicating the presence of an aquifer is the existence of a Groundwater Basin (CAT). A Groundwater Basin (CAT) is an area encompassing all hydrogeological processes, including the storage, flow, and release of groundwater. Within a CAT, hydrological processes occur continuously due to ongoing changes in volume and other factors. These processes include the increase in groundwater volume through percolation from surface water and the decrease due to evapotranspiration, the emergence of springs, and the seepage of water into river flows (Kodoatie, 2012). As shown in Figure. 1, Banda Aceh and Aceh Besar are located within a Groundwater Basin (CAT) characterized by a large intergranular aquifer. This highly productive basin spans the entire regions of Banda Aceh and Aceh Besar; because the city is located between two highlands in Aceh Besar, surface water flow (runoff), in this case, the Krueng Aceh River (Aceh River), flows toward the deep sea through the relatively low-lying Banda Aceh plain.

THEORY AND METHOD

This study was conducted in an industrial estate in Aceh Figure. 2. Data measurements were taken using ARES instruments powered by batteries. Data processing and modelling of measurement results were performed using EarthImager software. This software is used to process, model, and interpret data and display it in 1-dimensional form. Resistivity is the ability of a material to conduct electrical current. Rocks have electrical properties characterized by their ability to conduct electrical current (Ismail et al., 2014). Rocks with high porosity percentages, filled with liquid, can conduct electrical current well and tend to have low resistivity values (Anda et al., 2024). Rocks with low porosity tend to have high resistivity values and are not good conductors of electrical current. The resistivity value of rocks depends on the type of material,

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density, porosity, size and shape of rock pores, water content, quality, and temperature (Anda et al., 2021). Aquifers composed of loose materials such as sand and gravel have low resistivity values because they are easier to absorb groundwater (Muzambiq et al., 2025).

The resistivity geophysical method can determine the type of rock or material beneath the surface by measuring the electrical properties of the rock. The principle of operation involves injecting current into the ground and measuring the potential difference using electrodes (Febriarta et al., 2020). A visual representation of the principle of operation for the geophysical resistivity method is shown in Figure. 2. In the field of hydrology, this method is used to locate water-bearing layers (aquifers), permeable layers, and impermeable layers. Resistivity methods are divided into sounding and mapping. Mapping produces two-dimensional results. In sounding techniques, the results are vertical below the surface, where the subsurface layers obtained are only the positions at the center of the measurement point.

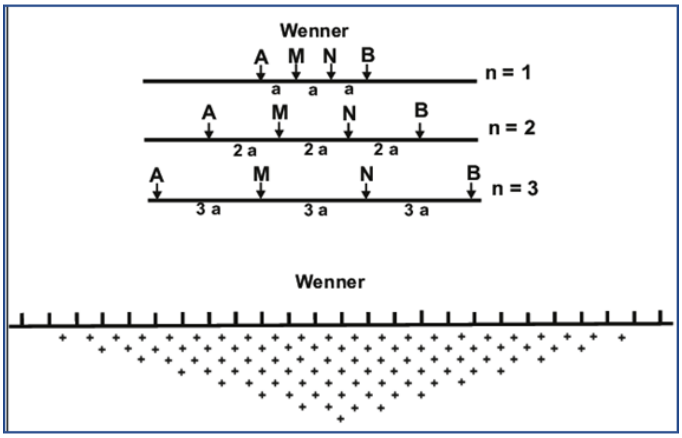

Figure 3. Two-electrode current and two-electrode potential difference scheme and datum point (Telford et al., 1990).

The physical properties and resistivity of rocks will be identified if measurements reach a certain depth determined by the distance between electrodes. The greater the distance between electrodes, the deeper the penetration obtained (Kearey et al., 2002). In geoelectricity, the resistivity measured is apparent resistivity (ρa). The value of apparent resistivity (ρa) is:

$$\mathbf{\rho a = K} \frac{\Delta V}{I} \quad (1)$$

Where ρa is the apparent resistivity, ΔV is the potential difference, I is the current value, and The value (k) in the Wenner configuration is (2πa) and will vary depending on the distance between electrodes (a) used.

In the geoelectrical method, several electrode array techniques are employed, including the Wenner, Schlumberger, and Wenner-Schlumberger methods. However, this study uses the Wenner configuration. The Wenner configuration is used in the Vertical Electrical Sounding (VES) method because it can produce data with good vertical resolution. This is achieved through relatively close electrode spacing. In this configuration, the distance between electrodes is arranged symmetrically. Each increase in measurement distance (n-level) provides continuous resistivity information with depth. The Wenner configuration is used in this study to obtain denser datum points. As a result, changes in resistivity values in each subsurface layer can be detected in greater detail without losing data continuity between depth levels. The potential electrode also undergoes movement when the current electrode is moved (Syukri et al., 2024).

Discharge is the total volume of water flowing, including solid sediments (sand), dissolved minerals, and other biological materials flowing through a specific cross-sectional area. Meanwhile, water discharge can be defined as the volume of water that passes through or is contained in a particular area per unit of time. Factors influencing water flow rate include rainfall, topography, vegetation cover, and the location of the

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drainage basin. Flow rate has numerous benefits, one of which is determining the quantity of water in an area as a water reserve to meet basic needs (Murtadlo et al., 2021).

The law of water infiltration into the ground and the principle governing the potential of aquifer reserves below the surface is known as Darcy's law (Guillermo et al., 2009). Darcy's equation can describe the ability of aquifers below the surface to flow through rock (permeability). Conceptually, Darcy's law states that the flow rate of fluid in a porous medium is directly proportional to the pressure gradient or energy driving the flow, and directly proportional to the permeability of the medium. This means that the greater the hydraulic gradient or the more permeable the rock/soil, the faster water can flow. The interpretation of resistivity values depicts the materials of the subsurface layers. The subsurface layers consist of aquifer materials and non-aquifer materials. The aquifer-containing layers are then calculated based on the concept of specific resistance values (Fadhli et al., 2025) using Darcy's equation. Groundwater potential can be calculated using the equation:

$$Q = K.A.\frac{\partial h}{\partial l} \qquad (2)$$

Where Q is the water flow rate (m³/day), K is the conductivity of the aquifer-forming rock (m/day), A is the aquifer cross-sectional area (m²), ∂h is the difference in groundwater level depth (m), and ∂l is the length, thickness, or width of the groundwater flow path (m) (Fetter and Kreamer., 2022).

Groundwater discharge is calculated using the relationship between hydraulic conductivity, hydraulic gradient, and aquifer cross-sectional area. The hydraulic gradient is obtained from the ratio between the difference in groundwater depth and the length of the flow path. Groundwater depth itself results from a combination of pressure head and elevation head. These factors reflect the potential energy of groundwater. The transmissivity value, or the ability of the aquifer layer to pass water, is determined by multiplying the hydraulic conductivity and the saturated thickness of water (pressure head). Discharge and transmissivity values are greatly influenced by the grain size and density of the aquifer's materials. Coarse, loose-grained materials have high permeability, resulting in high water discharge. Fine-grained, compact materials show low permeability, which reduces aquifer productivity.

RESULT AND DISCUSSION

Data acquisition was conducted at six measurement points, covering an area of 2,497.36 m². The distance between measurement points ranged from 100 to 250 m. This selected area is considered to represent the extent of the groundwater basin, and the distance between points is considered to represent the extent for interpolation between measurement points. Field measurements were obtained in the form of apparent resistivity values. The EarthImager software was used for 1D inversion, which provides information on lithology, depth, and resistivity values for each rock layer. The actual resistivity values are displayed as changes in resistivity parameters with depth. The data in this study has an RMS value of 3.14% to 5%, with iterative calculations performed 1–2 times. The average cable length for this measurement was 600 m with gradually varying spacing. The highest topography was at point P1, with an elevation of 263 m, and the lowest was at point P4, with an elevation of 154 m. The results of resistivity data processing, as shown in Figure. 4, were obtained using EarthImager software. The image shown is one of six results obtained.

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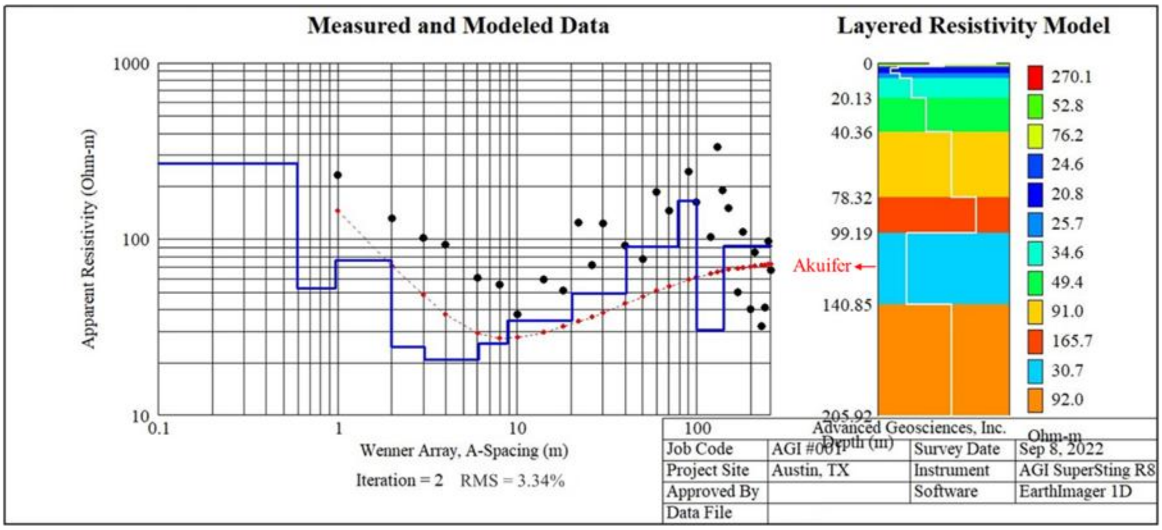

Figure 4. Results of resistivity data processing using Earthimager software for measurement points P1.

The interpretation and modelling results for the six measurement points indicate the presence of aquifer layers at each measurement point. The layers suspected to be aquifer layers have resistivity values ranging from 27 to 56 Ωm, with varying depths of ≥80 m and thicknesses of 19 to 67 m, as indicated at several sounding points. Detailed lithological interpretations and rock descriptions for each measurement point are presented in Table 1. At point P1, the aquifer is located at a depth of 99.2–141 m with a thickness of 41.8 m and a resistivity value of 30.7 Ωm. At point P2, the aquifer is located at a depth of 80–104 m with a thickness of 59 m and a resistivity value of 28.7 Ωm. At point P3, the aquifer with a thickness of 39.5 m is located at a depth of 105–144.5 m and has a resistivity value of 27 Ωm. The fourth aquifer point is located at a depth of 85.5–104.5 m with a thickness of 19 m and a resistivity value of 34.6 Ωm. The fifth aquifer point is located at a depth of 83.5–112 m with a thickness of 28.5 m and a resistivity value of 37.4 Ωm. The sixth aquifer point is located at a depth of 93–160 m with a thickness of 67 m and a resistivity value of 33.5 Ωm. The aquifers at each sounding point are indicated as confined aquifers. A confined aquifer is a type of aquifer characterized by impermeable upper and lower boundaries. This type of aquifer is highly desirable due to its abundant water supply. Additionally, with the range of resistivity values, the groundwater produced is of good quality with a TDS of approximately 100–150 mg/l (Vann et al, 2020). The lithological interpretation for each measurement point is presented in Table 1.

Table 1. Lithological interpretation of Point P1

No	depth (m)	Thickness (m)	Resistivity Value (Ωm)	Description
1	0 - 21	21	20.8 - 270.1	Topsoil
2	21 - 40.5	19.5	49.4	Sand
3	40.5 - 78.5	38	91	Clay
4	78.5 - 99.2	20.9	165.7	Breccia
5	99.2 - 141	41.8	30.7	Sand (Aquifer)
6	141 - 206	65	92	Clay

Table 2. Lithological interpretation of Point P2

No	Depth (m)	Thickness (m)	Resistivity Value (Ωm)	Description
1.	0 - 15	15	18.2 - 247.1	Topsoil
2.	15 - 45	30	197.9	Breccia
3.	45 - 80	35	56.5	Clay
4.	80 - 104	24	28.7	Sand (Aquifer)
5.	104 - 135	31	13.5	Clay

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Table 3. Lithological interpretation of Point P3

No	Depth (m)	Thickness (m)	Resistivity Value (Ωm)	Description
1.	0 - 20	20	23 - 344.8	Topsoil
2.	20 - 68.2	48.2	297	Andesite
3.	68.2 - 105	36.8	157.7	Breccia
4.	105 - 144.5	39.5	27	Sand (Aquifer)
5.	144.5 - 158.5	14	2.1	Clay

Table 4. Lithological interpretation of Point P4

No	Depth (m)	Thickness (m)	Resistivity Value (Ωm)	Description
1.	0 - 19	19	21.3 - 391.9	Topsoil
2.	19 - 41.5	22.5	191.5	Breccia
3.	41.5 - 85.5	44	252.7	Andesite
4.	85.5 - 104.5	19	34.6	Sand (Aquifer)
5.	104.5 - 111	6.5	19.7	Clay

Table 5. Lithological interpretation of Point P5

No	Depth (m)	Thickness (m)	Resistivity Value (Ωm)	Description
1.	0 - 15	15	19.9 - 381.1	Topsoil
2.	15 - 83.5	68.5	244.4 - 348.7	Andesite
3.	83.5 - 112	28.5	37.4	Sand (Aquifer)
4.	112 - 119	7	67.4	Clay

Table 6. Lithological interpretation of Point P1

No	Depth (m)	Thickness (m)	Resistivity Value (Ωm)	Description
1.	0-14	14	13.3-73.7	Topsoil
2.	14-30.5	16.5	34.3-84.2	Sand
3.	30.5-57	26.5	99.4-118.8	Breccia
4.	57-93	36	72.9	Clay
5.	93-160	67	33.5	Sand (Aquifer)
6.	160-191	31	125.6	Breccia

However, for more focused results in understanding the lithological composition and resistivity values at the research site, which have a certain range for one type of lithology, conclusions can be drawn from Table 7.

Table 7. Range of lithological classification.

No	Classification	Range resistivity (Ohm-m)	Lithologycal
1	Very Low	13-391	Clay/Top Sil
2	Low	27-34.6	Sand - Aquiver
3	Moderate	99-197	Breccia
4	High	252-348	Andesite

The groundwater discharge value can be determined using equation (2). The parameters used to satisfy this equation are the hydraulic conductivity value, hydraulic gradient, and cross-sectional area (Pangestu and Waspodo., 2019). The hydraulic gradient is calculated by dividing the difference in groundwater depth (Δh) by the length of the groundwater path (Δl). Groundwater depth is obtained by adding the pressure head and elevation head. The pressure head is the total depth minus the groundwater surface, while the elevation head is the elevation in the field minus the total depth (Syahruddin., 2014). Groundwater discharge can then be calculated by multiplying the hydraulic conductivity by the hydraulic gradient and the cross-sectional area of the aquifer. Additionally, to obtain the transmissivity or water permeability value, the conductivity value is multiplied by the pressure head value. The smaller the particle size and the more compact the material, the smaller the water permeability value. If the water permeability value is high, the resulting groundwater discharge is sufficiently large. The flow rate calculations, performed using Darcy's Law, are presented in Tables 2, 3, and 4. The calculation is divided into two sections Figure. 5 to accommodate the entire area.

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Figure 5. Split section for water discharge calculation.

Table 8. Calculation of discharge section A-A’

No	K	φ	z	h	δh	δι	i	A	$Q\ (m^3/day)$	Q (l/sec)	T(m/day)
P3	11.87	53.5	31.5	85	20	486	0.04115226	1028.48	502.3892016	5.81	635.045
P5		35.5	85	120.5							421.385
P6		98	7	105							1163.26

Table 10. Calculation of discharge section B-B'

No	K	φ	z	h	δh	δι	i	A	$Q\ (m^3/day)$	Q (l/sec)	T(m/day)
P1	11.87	106.6	57	163.6	1.2	915	0.00131148	1468.88	22.866368	0.26	1265.342
P2		90	58	148							1068.3
P3		53.5	31.5	85							635.045
P4		25.5	43	68.5							302.685

Table 11. Calculation of water flow discharge

Average Variable	Parameter Value	Units
Flow Velocity (Q)	262,63	m3/day
Discharge (Q)	3,035	L/s
Transmissivity (T)	784,44	m2/day

Based on the calculation of the water flow rate using Darcy's Law, the average water flow rate was found to be 3.035 litters/second and was classified as having economic value. The average transmissivity or water permeability was found to be 784.44 m²/day, which was classified as high transmissivity. The modelled 2D cross-section provides a more detailed description of the subsurface layers. The illustration shows that there are layers, including topsoil, breccia, andesite, sand, and clay. The dominant water-bearing layer at the study site is the sand layer, which has a sufficiently large and thick scale for aquifer availability. The presence and thickness of the aquifer in each of these layers indicate that the groundwater potential in the study area is quite good, as evidenced by 3D aquifer modelling using RockWork16 software. Figure 5 shows the modelling results, illustrating the relationship between the aquifer and topographic elevation (Mochtar, 2019).. The graph indicates that groundwater depth decreases from the surface as topographic elevation decreases toward the coast, i.e., moving northward. The graph also shows that the aquifer layer becomes thicker as the topography decreases and approaches the coast.

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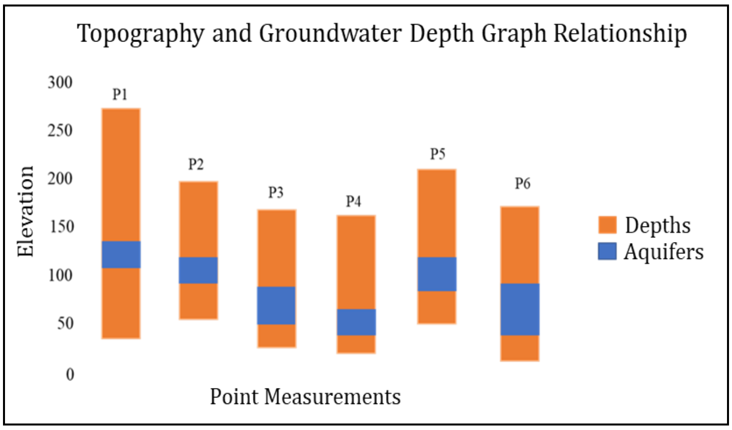

Figure 6. Graph of relationship between topography and aquifer depth.

The 3D modelling carried out can maximize the objectives of this study, namely, to determine the availability of groundwater reserves and to identify the shape of the aquifer below the surface Figure. 6. The parameters used in performing 3D aquifer modelling are information on processing values from the 1D model, such as the actual aquifer resistivity value, the distance between aquifer zones, the thickness of the aquifer, and the elevation of each aquifer layer.

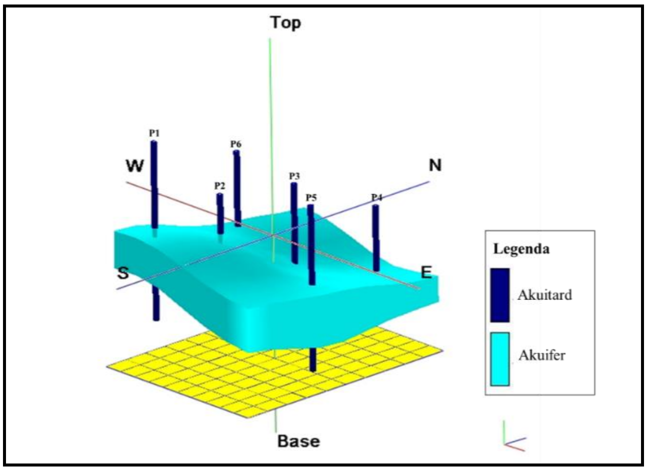

Figure 6. 3D model of Aquifer zone

CONCLUSION

The results of inversion and interpretation of 1D resistivity geophysical data at the Aceh Industrial Estate site reveal a subsurface structure composed of three rock layers consisting of andesite and volcanic breccia from Mount Lam Teuba, with resistivity values ranging from 118.8 to 297 Ωm in the first layer. The second layer consists of sand with resistivity values ranging from 27 to 56.5 Ωm, indicating an aquifer layer containing groundwater of good quality with an aquifer thickness of 19-41.8 meters. The third layer consists of clay rock with resistivity values ranging from 13.5 to 92 Ωm. The characteristics of these three layers indicate that the study site is classified as a confined aquifer. Water flow calculations using Darcy's Law, based on the aquifer potential derived from the 1-D geoelectric resistivity results, are highly economical, with a total volume of 3,053 liters/second and a permeability of 784.44 m^2/day.

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