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INTEGRATED HYDROGEOLOGICAL AND GEOPHYSICAL STUDY OF GROUNDWATER RESOURCES IN NORTHERN BANDAR LAMPUNG, INDONESIA

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Abstract: Threats to the sustainability of groundwater resources due to increased extraction in the last 30 years are caused by the increase in population density in the Northern part of Bandar Lampung City. Therefore, it is necessary to study groundwater resources to prevent groundwater crises. This study uses hydrogeological and geophysical data to map aquifer conditions. Fifty gravity data and 16 Vertical Electrical Soundings (VES) points were used to model subsurface conditions. Meanwhile, one drilled cutting data is used to tie the cross-section of the 2D model. The results of gravity modelling show the potential for local groundwater aquifers fills fractures and faults above the bedrock. Meanwhile, the results of the VES modelling interpret the unconfined aquifer as being in the sand layer at a depth of 10–25 m and confined aquifer at a depth of 110 m. Between the two aquifers, there is a low permeability zone of interbedding clay and sand thickness of 65 m from a depth of 25–90 m. These results indicate that the condition of groundwater resources in unconfined aquifers is prone to depletion. Furthermore, infiltration ponds could be a solution to maintain the sustainability of groundwater resource storage in Northern Bandar Lampung.

Keywords: Aquifer, geophysical, groundwater, hydrogeology, VES.

Abbreviations: Vertical Electrical Soundings (VES), Mount Kasih Complex Formation (Pzg), Tarahan Formation (Tpot), Lampung Formation (QTl), Young Volcano Formation (Qhv), Complete Bouguer Anomaly (CBA)

Introduction

Groundwater is fresh water located in the pores of soil and rocks (Elshall *et al.,* 2021), although in many cases, there is saline groundwater due to seawater intrusion, especially in coastal areas (Khalid *et al.,* 2018; Rustadi *et al.,* 2021). Nevertheless, groundwater is more naturally protected than surface water. Another advantage is that it is part of the hydrological cycle, making groundwater renewable. Undeniably, groundwater is the mainstay of meeting clean water needs in various parts of the world (Rivett *et al.,* 2019; Al Maliki *et al.,* 2020). However, economic growth that has resulted in the region's development and an increasing population has led to the extraction of large amounts of groundwater (Foster *et al.,* 2017). Significant impact due to groundwater pumping that is not adequately regulated, leading to scarcity of availability. The groundwater crisis will have a high socio-economic cost and threaten society (Lan *et al.,* 2015; Halder *et al.,* 2020; Meng *et al.,* 2021).

The context of the problem is experienced in the Kedaton District area in the northern part of Bandar Lampung City, Indonesia. Educational institutions are an attraction for regional growth and population density (Ali *et al.,* 2019; May *et al.,* 2020). The impact of population density is groundwater extraction which has been going on for 30 years and has even caused a decrease in the groundwater level (Rustadi *et al.,* 2021). This condition threatens the sustainability of groundwater resources due to the increasing water demand. An integrated groundwater management plan is needed to prevent groundwater crises. Sustainable management, as defined by Kendy & Bredehoeft (2006), is an effort to maintain water availability to meet current needs without compromising the needs of future generations.

Rainwater harvesting strategies can be considered to form groundwater in aquifer layers rapidly (Lade & Oloke, 2013; Soubeyran *et al.,* 2015; Asnaning *et al.,* 2019). The surface layer of the study area is composed of fine-grained sediments and volcanic ash from volcanic products (Mangga *et al.,* 1993). It can inhibit the natural infiltration and make more rainwater flow on the surface as runoff. Aquifer storage recovery technology development to accelerate groundwater formation and subsurface interpretation is needed regarding confined and unconfined aquifers (Camprovin *et al.,* 2017; Smith *et al.,* 2017; Alajlouni, 2019; Fan *et al.,* 2020). This research was conducted by mapping aquifers using the geoelectric method to achieve this goal. Electrical resistivity methods are widely used for subsurface investigations from a few meters to hundreds of meters beneath the surface to solve many hydrogeological issues (Costall *et al.,* 2018; Khalid *et al.,* 2018; Gao *et al.,* 2019; Zeroual *et al.,* 2020; Benaafi *et al.,* 2020). Geoelectric interpretation supported by gravity data was carried out to obtain the influence of the basement on the thickness of sedimentary formations. In addition, one production well can bind cutting lithology data to interpret the resulting geoelectric model.

The main focus of this research is to examine the condition of groundwater resources based on the integration of hydrogeological conditions and geophysical measurements. The groundwater aquifer condition is expected to provide an overview of the potential for groundwater storage and water movement in the permeable layer. The interpretation of groundwater resources will also analyze their sustainability against increasing water demand. In addition, this study will also identify potential groundwater infiltration techniques into aquifers through surface water reservoirs collected from rainwater/runoff harvesting.

Hydrogeological Conditions of the Study Area

The morphology of the Kedaton subdistrict is an undulating plain composed of a fluvial plain sedimentary environment (Mangga *et al.,* 1993). Rainwater that reaches the surface in the catchment area of Mount Betung and the hills in the west can produce runoff that reaches the Kedaton subdistrict area. High rainfall of 2000 – 2500 mm/year in the study area can support groundwater regeneration in large parts of the Bandar Lampung and Kedaton subdistrict (Kusumastuty *et al.,* 2021).

Regional geological conditions are influenced by subduction in the western part of Sumatra Island, causing the uplift of bedrock exposed in the eastern part of Bandar Lampung (Barber & Crow, 2009). The bedrock in the form of medium-order metasediments is interpreted as a schist. It forms a large part of the Bandar Lampung basement. The bedrock is the Mount Kasih Complex Formation (Pzg), Paleozoic – Pre-Tertiary age. The effect of subduction produces volcanic pathways, with a large part in the west as a catchment area (Barber, 2000).

The combination of accretion and magmatic rise results in the unconformity of the bedrock position, interpreted to form sub-basins in some parts, resulting in thicker sedimentary rock formations (Rustadi *et al.,* 2021). The sub-basin is periodically closed by the Tarahan Formation (Tpot) extensively. This formation is Tertiary in age, composed of clastic and pyroclastic sedimentary materials from volcanic eruptions of the Pre-Tertiary age (Figure 1). Tertiary – Quaternary Phase, the Tarahan Formation experienced extensive closure by the Lampung Formation (QTl). The final phase is the formation of the Young Volcano Formation (Qhv) as the product of the pyroclastic eruption of Mount Betung. Its rock formation is not aligned with the Lampung Formation (QTl) and Tarahan Formation (Tpot).

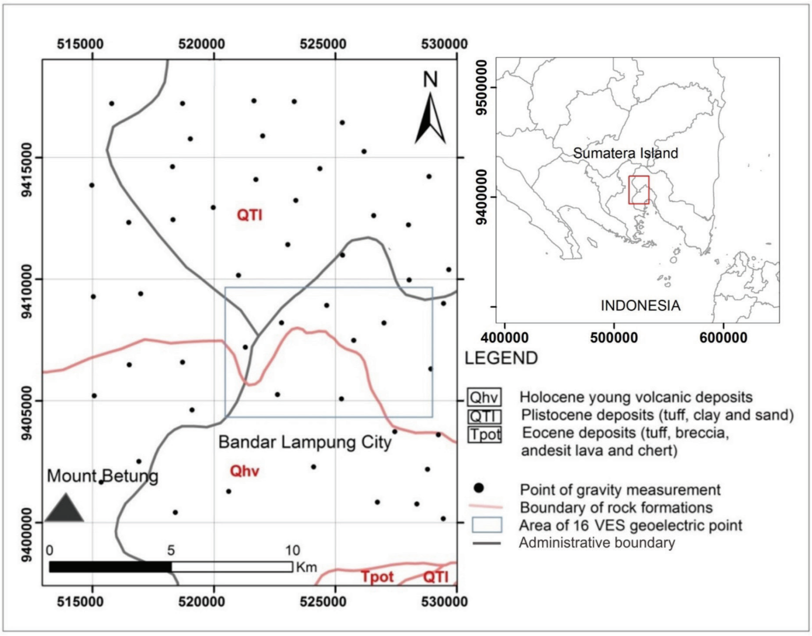

Figure 1: Geological map of the research area. The black dot represents the gravity measuring point

The research area is located in the Lampung Formation, which is interpreted to be composed of various grain sizes formed from the sedimentation process in the basin (Zaenudin *et al.,* 2018). Limitations of sedimentary facies references and drilling results in this area hinder understanding the layering pattern that acts as an aquifer and aquiclude. Infiltration from rainwater fills and flows in the primary and secondary porosity as an alternative to distinguishing permeable and non-permeable layers.

There is a correlation between water flow and electric current in rocks. Water flow depends on hydraulic conductivity, while the flow of electrolyte ions generates the electric current. Electrolytic currents indirectly form the electrical properties of rocks due to lateral and vertical water flow (Rustadi *et al.,* 2020). Primary and secondary porosity is key to hydraulic conductivity, affecting flow velocity and electrolytic electric current in sedimentary rocks. The measurement of electric current in the rocks that make up the Lampung Formation can quantitatively provide information on the hydraulic characteristics of the rocks in the study area.

Materials and Methods

Gravity Methods

Instruments called gravimeters measure gravitational acceleration at the surface to study the Earth's gravity. Gravimeters measure the difference in the force of gravity from one place to another (Raghavan, 2002; El Alfy *et al.,* 2016). Few hydrogeological studies have accompanied gravity studies to monitor geospatial variations of groundwater. It is because the estimated signals of gravity differences are minor. However, precise gravimeters can measure geospatial gravity variations due to groundwater mass changes. An infinite water table can cause about a 40 μGal gravity change with just a 1 m change in thickness (Fukuda *et al.,* 2016).

The use of gravity exploration in the study area is not focused on looking at groundwater mass changes but on identifying the influence of the structure and bedrock. The measurement of gravity in this study has various limitations from the acquisition time, which is not time series. Subsurface unconformities by differences in bedrock depth and irregular distribution of andesite are the review's objectives based on the subsurface rock density's effect. Both are included in hard rock, affecting the alignment and thickness of sedimentary rocks in the Lampung Formation.

The 50 gravity stations (Figure 1, black dots) from measurement by the geological agency in 1993 have been used for study utilizing hard rock on the Kedaton subdistrict. The gravity measurements were performed by using a Lacoste Romberg G880 Gravity Meter. Processing from Complete Bouguer Anomaly (CBA) for regional and residual anomaly extraction applied filter moving average using Surfer 8. Anomalies between regional and residual can provide information on the position of hard rock as basement and softcover (Xu *et al.,* 2015; Gómez *et al.,* 2017). The presence of groundwater in primary and secondary porous spaces cannot be mapped accurately through gravity measurements. Moreover, groundwater fills the fractures and faults with relatively small dimensions, giving more complex problems.

Geoelectrical Methods

Electrolytic conduction is formed by ions resulting from fluid flow in the lateral and vertical directions. Mapping these physical properties' magnitude can indirectly help to get a permeable area that helps the natural infiltration process. The mapping approach based on Vertical Electrical Sounding (VES) data distribution is an alternative to understanding zones with good hydraulic conductivity, which act as natural rain harvesting. For conductive material investigation, we used Archie's law (Worthington, 1993; Zhang *et al.,* 2018). Porous water-bearing rocks or sediments may be ionic:

$$\rho = a\emptyset^{-m} f^{n} \rho_w \quad \textbf{(1)}$$

where ρ and ρ_w are the rock and water resistivities, porosity, and f is the volume fraction of pores containing water. Meanwhile, a, m, and n are empirical constants with $0.5 \leq a \leq 2.5$, $1.3 \leq m \leq 2.5$, and n is approximately 2. The value of n is the saturation exponent obtained based on Archie's experiments on sandstone and carbonate reservoirs, one of which is known as Archie's core parameter estimation (CAPE). This method will determine the value directly by introducing the air saturation with the air saturation value that determines the sample (Mohamad & Hamada, 2017). However, the value of this water saturation exponent varies if the reservoir in question is not homogeneous. For example, it contains hydrocarbons (Melani *et al.,* 2015; Nazemi *et al.,* 2018). In this study, the focus of measurement is on groundwater aquifers, not on oil and gas fields.

To obtain the electrical resistivity values of the subsurface, we induced an electrical current in the ground through electrodes and measured the potentials (voltages) using other electrodes. We can infer the geological characteristics of the Earth's subsurface from these electrical properties. This investigation uses the Vertical Electrical Sounding (VES) technique to acquire geoelectrical data. An electrical resistivity meter (ARES from GF Instrument) was used to conduct the VES surveys.

The field was energized by injecting DC through current electrodes. When AC is injected through electrodes into the Earth, the current density tends to concentrate towards the surface (Koefoed, 1979). The current electrodes are moved outward to change the depth range under investigation, keeping the potential electrodes fixed. However, when the ratio between current and potential becomes too large and the potential drops between the electrodes are too small, it is difficult to measure accurately. In this situation, the potential electrodes are farther from each other. The equipment processes the constant selected current (I) and potential difference (V). The resistance R is displaced for the corresponding reading. The equation below calculates the apparent resistivity (Bellanova *et al.,* 2016; Syukri & Saad, 2017; Asfahani, 2018).

$$\rho_a = K \frac{\Delta V}{I} \quad \textbf{(2)}$$

Where ρ_a is the resistivity of homogeneous Earth. The apparent resistivity depends upon the electric current I, potential difference and geometric constant K (Kearey *et al.,* 2013). K is a Geometric constant that depends on the electrodes' arrangement and configurations. 16 VES surveys were conducted in the study area. The GPS coordinates of each site were recorded. The Schlumberger electrode configuration is utilized to conduct these surveys. The half-current electrode spacing (AB/2) ranges from 1 – 200 m, and potential electrode spacing ranges from 0.5 – 20 m is used (Figure 2).

Results and Discussions

The geology agency of the Indonesian Government processed the complete Bouguer gravity anomaly map (Figure 3). The Surfer 10 software was used for contouring the secondary data, and the contour interval was drawn with one mGal. The calculated minimum value was 34 mGal, and the maximum was 60 mGal. The low anomaly in the south – northeast direction with a value of 34 – 44 mGal is interpreted as a groundwater basin for the Bandar Lampung city area and the northwest part of the Jatiagung area of the South Lampung district. While the anomaly is 50 – 60 mGal high, the influence of igneous rocks is the constituent of the Mount Betung complex. These results strengthen the research of Zaenudin *et al.* (2020) on the groundwater basin in the northern part of Bandar Lampung. Groundwater exploration aims to supply water to residential areas on the western slopes of Mount Betung and found that thick andesite causes failure to obtain the expected quantity of water. The prospect of local groundwater filling the fractures and faults, some areas are in the breccia environment.

Highland in Mount Betung is a mainstay as a recharge to form groundwater in Bandar Lampung and Jatiagung basins. Data limitations are obstacles to getting the water flow from the rainwater catchment to the basin in the western part of the study (Figure 3). Separation of residual components that will be used to examine the thickness of sedimentary formations in the Bandar Lampung basin is carried out through filtering moving averages. The regional components resulting from the process used to obtain residual anomalies are shown in Figure 4.

The Bandar Lampung area is also known as the high basement (Bishop, 2001; Barber *et al.,* 2005). Processes from past subduction and magmatic breakthroughs formed volcanic pathways in Bandar Lampung, resulting in the

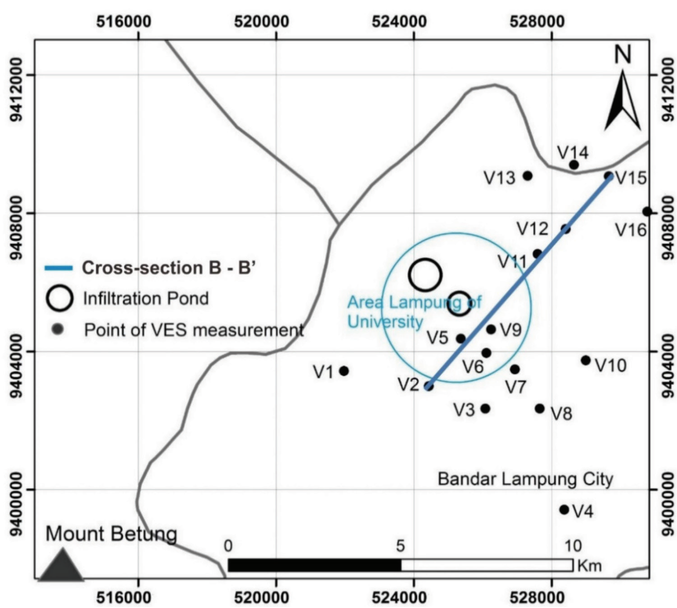

Figure 2: Distribution of VES points in the northern part of Bandar Lampung, University of Lampung and its surroundings

bending of bedrock to form groundwater basins. The interpretation of line AA’ in Figure 5 shows that the thickness of the sedimentary formations of the Tarahan Formation (Tpot) and Lampung Formation (QTl) is more than 300 m (Mangga *et al.,* 1993). There is no drilling data with a depth of more than 140 m, making this opinion a qualitative interpretation.

The existence of geological structures in the form of faults identified from the results of 2D gravity modelling is an interpretation generated from the Bouguer anomaly pattern. The anomalous decrement pattern generally indicates a changing density contrast beneath the surface. This change is caused by several factors, including the geological structure. The interpretation of this fault structure is also strengthened by the regional structural conditions in the study area, which the Sumatran Fault System influences significantly in the Lampung-Panjang Fault segment (Zaenudin, Darmawan, *et al.,* 2020; Darmawan *et al.,* 2021). The existence of a fault in the Bandar Lampung Basin is also strengthened by gravity

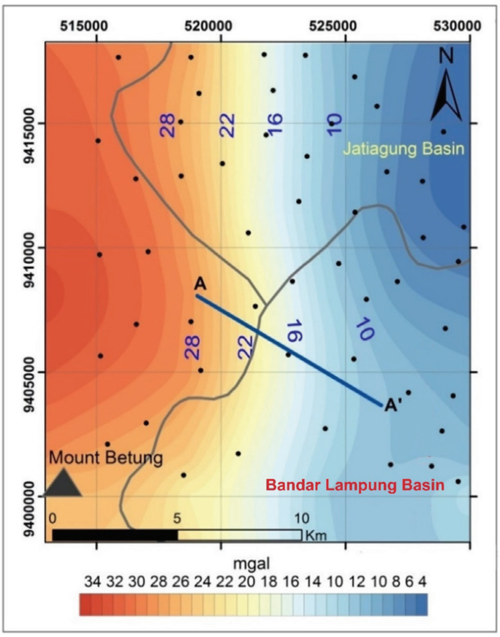

Figure 3: Anomaly Bouguer map with contour interval one mGal

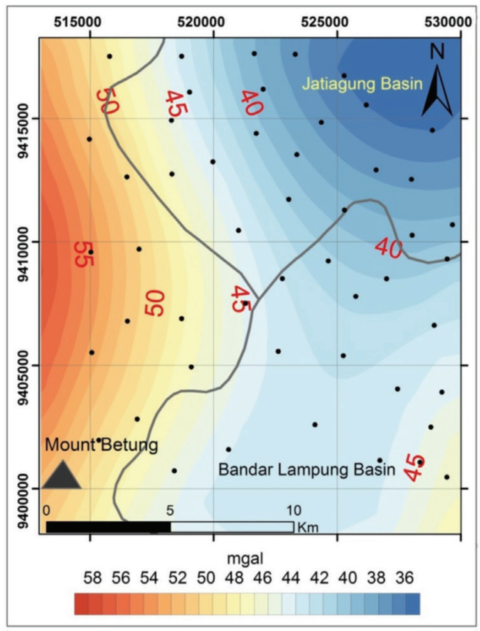

Figure 4: Anomaly residual map with contour interval one mGal

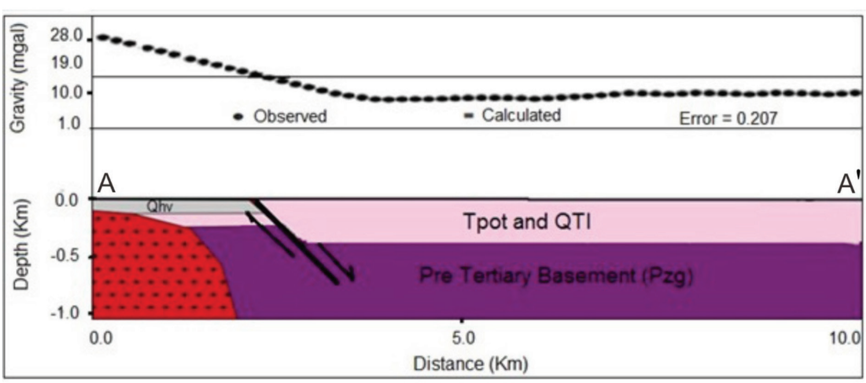

Figure 5: The subsurface model of cross-section line AA’ on residual anomaly map

research conducted by Zaenudin, Risman, *et al.,* 2020. Based on Figure 5, the Tarahan Formation served as a basement cover and extensive basin presence in the Tertiary period. The next phase is the formation of the Lampung Formation in the Quarter closing of the Tarahan Formation at the research location. Layers between aquiclude and aquifer in both formations can be formed in the sedimentation environment as a fluvial and flood plain.

The University of Lampung is located in the Kedaton subdistrict of Bandar Lampung city. A blue circle marks the location of three infiltration ponds developed to serve as rain harvesting facilities. Currently, to meet the water needs of more than 20,000 academics, they rely on groundwater from three wells with a depth of 100 – 150 m. Two wells near points V5 and V9 were constructed in 2021, and one well east of point V9 (Figure 2).

The use of 16 VES data aims to obtain a resistivity profile that complements the gravity profile in Figure 5. The subsurface resistivity profile can help obtain a groundwater prospect layer with a low resistivity value of less than 50 Ohm m (Pandey *et al.,* 2015). Sixteen VES data have similar resistivity values ranging from 15 Ohm m to 110 Ohm m. High values are in shallow layers with less than 15 m. Four examples of data processing results in V1, V2, V5, and V12 are shown in Figure 6. The drilling results at point V9 show that the subsurface layer comprises interbedding sand and clay. The drilling results did not find tuff, breccia, and lava lithology. This result is because the geoelectrical measurement location is slightly further from Mount Betung and is dominated by sand and clay rocks as part of the Lampung Formation (QTl) and Tarahan Formation (Tpot). The summary of lithological data from drilling cutting results is shown in Table 1. It is interpreted that the composition is influenced by the presence of water in the lithology, thus causing a low resistivity value. Meanwhile, the shallow layer's resistivity value exceeding 80 Ohm m is caused by the loss of groundwater. This condition is consistent with the water table measurement at a depth of 30 m during the rainy season. It shrinks at a depth of 50 m during the dry season.

A thick layer of clay material at a depth of 1 – 7 m is interpreted as a layer with low head conductivity, inhibiting water flow infiltration on the surface. The clay layer, which forms the basis for the three infiltration ponds, also inhibits infiltration so that the water in the pond can last for a long time. The cross-section resistivity from V2 to V15 has been modelled to get a clearer picture, as shown in Figure 7.

The first aquifer layer is under the clay layer after the topsoil, with an average thickness of

Table 1: Composition of constituent materials in production wells near point V9

Depth (m)	Composed material	Grain size (mm)
0 - 1	Soil	1/256
1 - 4	Clay	1/256
4 - 7	Sandy clay	1/256–1/8
7 - 28	Sand	1/4–1
28 - 36	Sandy clay	1/256–1/8
36 - 39	Sand	> 1
39 - 85	Sandy clay	1/256–1/8
85 - 103	Sand	1/4–2
104 - 126	Sandy clay	1/256–1/8
126 - 130	Sand	1/4–2

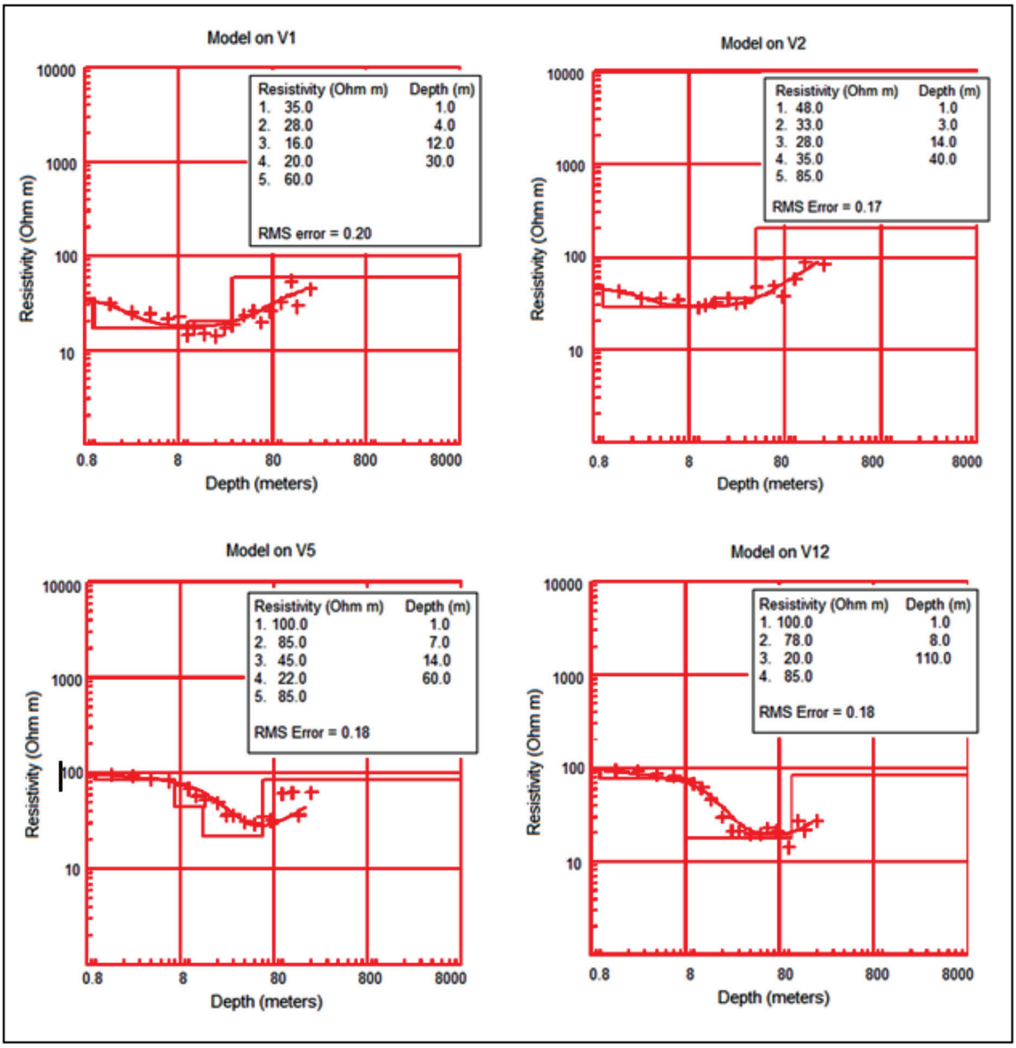

Figure 6: Modeling of 4 VES data represents the similarity of 16 other data

about 10 m. This condition causes surface water infiltration into the aquifer to be slightly slower. However, the potential for unconfined aquifers is quite good. It is located in the sand layer with a thickness of up to 15 m at a depth of 10 – 25 m. Based on the interpretation in Figure 7, the alternation between clay and sand dominates to a depth of 90 m. This result also aligns with the drill data in the Bandar Lampung groundwater basin previously studied by Rustadi *et al.* (2021). This layer can hold water but has the potential to have relatively low permeability so that groundwater storage capacity can be quickly depleted in this layer.

The confined aquifer layer is deep enough at more than 110 m. An impermeable rock limits this layer in the form of clay with a thickness of up to 20 m at a depth of 90 – 110 m. However, the subsurface profile with a confined and unconfined aquifer can be considered in adopting the aquifer storage technique. Injection of treated water in infiltration ponds can rapidly fill subsurface aquifers. It is expected to maintain the sustainability of groundwater

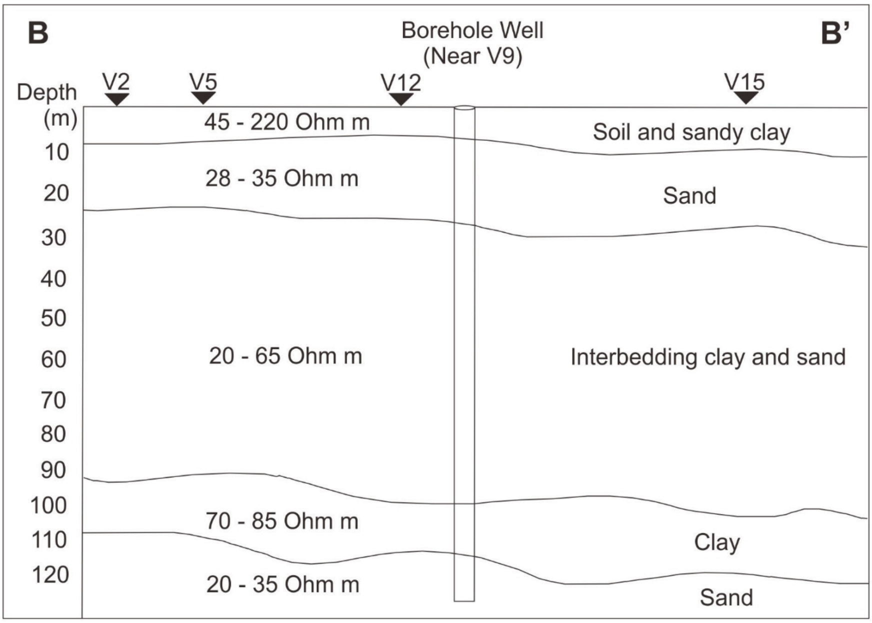

Figure 7: Cross-section correlates well with the results of the VES interpretation near the infiltration pond area

storage, especially with surface water storage at the infiltration ponds location.

Conclusion

This research has identified aquifers and groundwater resources by integrating hydrogeological conditions with geophysical methods. The gravity measurements show that groundwater is filling the fractures and faults regionally. The interpretation of the Bouguer anomaly shows that the aquifer area above the base layer is in the Tarahan Formation (Tpot) and the Lampung Formation (QTl). The results of the VES measurements align with the gravity data with high resistivity values up to 110 Ohm m in the shallow layer at a depth of less than 15 m. This layer is estimated as a pyroclastic rock from the Lampung Formation (QTl). At the same time, the aquifer is deeper in the Tarahan Formation (Tpot), which is composed of interbedding sand and clay.

The correlation of drilled well data with the VES cross-section found three aquifers in the study area. The unconfined aquifer is located in a layer of sand with a thickness of up to 15 m at a depth of 10 – 25 m. Underneath is an alternation of clay and sand, predominating to a depth of 90 m. This layer is interpreted as an aquifer with low permeability. Confined aquifers are found at depths of more than 110 m, limited by clay at a depth of 90 – 110 m. These results indicate that drought in shallow aquifer layers is likely to occur. Therefore, the injection of surface water using the rainwater harvesting technique has undergone processing in infiltration ponds. It can be a solution to maintain the sustainability of groundwater resource storage in Northern Bandar Lampung.

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