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Groundwater exploration using integrated geophysics method in hard rock terrains in Mount Betung Western Bandar Lampung, Indonesia

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Abstract: The presence of hard rock in Mount Betung has caused the misalignment of the groundwater aquifers, and resulted in many drilling failures for groundwater. An integrated geophysics method using gravity survey and Geoelectric Vertical Electrical Soundings (VES) were conducted to study the effect of basement and hard rock on groundwater prospects. From the gravity method, 38 mapping points were carried out randomly, with a distance of 1-2 km in-between. Meanwhile, from the geoelectric method, 51 VES points were acquired at the foot of Mount Betung. The acquisition was conducted with a Schlumberger configuration with AB/2 = 1 m to 250 m. The results show the Bouguer Anomaly in the west is 50-68 mgal due to the presence of hard rock in Mount Betung. This anomaly responds to relatively shallow hard rocks near surface. Hard rocks composed of andesite and breccia normally present at the depth of 5-180 m during well construction. Resistivity isopach mapping from VES data (at AB/2 = 50 m, 100 m, and 150 m) shows the dominant constituents of hard rock. Fractures in hard rock contribute to secondary porosity, which could be a prospect zone that transmit groundwater. This finding shows that the fractures are randomly scattered, causing several well failures that have been worked. Furthermore, the fractures in the hard rock at the foot of Mount Betung acts as conduits between recharge at Mount Betung and the aquifer in the Bandar Lampung Basin.

Keywords: Geoelectric; Gravity; Groundwater; Hard; Rocks; VES Received: 30 Sep 2021/ Accepted: 26 Dec 2021 2305-7068/

Introduction

Bandar Lampung has developed rapidly in the last twenty years. The increasing population density has driven the shift of residential areas from downtown to the western Bandar Lampung. In this area, the forests in Mount Betung provide abundant water sources that can meet the community’s needs for clean water. However, as the population increases and the catchment area decreases, water shortage becomes a problem. Due to limited seepage flow from shallow groundwater, rivers on Mount Betung stop to flow in the dry season. Residential clusters switch to groundwater utiliza- tion in confined aquifers. The presence of hard rock influences the geological setting of Mount Betung, which results in the misalignment of aquifers. However, groundwater is found in many volcanic rock fractures, also termed as secondary porosity in hard rock. Although groundwater in secondary porosity of igneous rocks is found a few meters underneath Osmansagar and Himayathsagar in India (Varalakshmi et al. 2014) and 100 m below the surface in north-central Australia (Raghavan, 2002), geographical differences, climatic and tectonic influences can have different impacts on the formation of secondary porosity and the presence of groundwater in Mount Betung. Groundwater in secondary hard rock aquifers have more complex problems than groundwater in primary aquifers mainly composed of sand and sandstone. Groundwater exploration in the research area requires the proper approach to identify the prospect zone. Integrated studies and effective management can help to understand geological characteristics and to ensure the sustainability of groundwater availability (Vélez-Nicolás et al. 2020). The use of the gravity method has assisted in interpreting the position and distribution of hard rock that affects the presence of groundwater (Lachassagne et al. 2021; Raghavan, 2002; Varalakshmi Rao et al. 2021). In the meantime, the conductive zone as a response to the presence of groundwater can be effectively mapped through geoelectrical measurements (Aizebeokhai et al. 2018; Teikeu et al. 2012). Geology, gravity, geoelectric, and analysis of exploration wells have been carried out to analyze the hydrogeological characteristics of the research

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area. 1 Geologic and hydrogeologic setting of the study area Mount Betung in the western Bandar Lampung City is included in the Kemiling and Langkapura district administrations. The hydrogeology of this area is influenced by the basement accretion of the Pre-Tertiary period. The plutonic and extrusive formations have occurred during the Pliocene –Quaternary (Barber and Crow, 2009). The Gunung Kasih Formation (Pzg) is the dominant basement [7]in Bandar Lampung. Schist metasediment rock formed in Paleozoic PreTertiary age. The basement outcrop [1]is located in the south of Mount Betung, uplifted due to subduction in the western part of Sumatra Island. Subduction plays a role in magmatism as a source for the formation of Mount Betung and Mount Ratai, breaking through the basement (Barber, 2000). The Young Volcano Formation (Qhv), which is the product of the pyroclastic eruption of Mount Betung, closes out of alignment with the Lampung Formation (QTl) and the Tarahan Formation (Tpot). Lampung Formation is the product of the Tertiary pyroclastic deposits, and Tarahan Formation is the product of Pre-Tertiary pyroclastic deposits (Fig. [1]1). In the geological map of the research area, the black dot represents the gravity measuring point, and the blue rectangle is the location area for the 51 geoelectrical VES points. The blue line is the administrative boundary of Bandar Lampung City. The Young Volcano Formation composed of tuff and bomb-sized fragments, lava andesite and basalt, and clay could be observed in shallow wells. Shallow plutonic andesite is also found in some parts of the slopes and mined by the community. High rainfall [1]occurs in the hills in the study area (Kusumastuty et al. 2021) provides source for groundwater occurrence (Mulyasari et al. 2019). The vegetation in the forest on Mount Betung helps capture rainwater feeds shallow groundwater as an aerial zone. Aquicludes and igneous rocks are shallow below the surface, preventing infiltration to deeper parts. Groundwater in the aerial zone is the source of springs on the slopes, and groundwater also discharges to the Holocene young volcanic deposits Pleistocene deposits; tuff, tuffaceous claystone and tuffaceous sandstone Eocene deposits, welded tuff, breccia with intercalations of chert Paleozoic basement; pelitic schist and minor gneiss Area of 51 VES geoelectric Point of gravity measurement LEGEND Pzg Tpot QTI Qhv 515000 0 5 10 Km

9390000 9395000 9390000 9395000 9400000 9405000 9410000 520000 525000 515000 520000 525000 N Fig. 1 Geological [1]map of the research area Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 http://gwse.iheg.org.cn 11 Way Kahuripan River. Deep groundwater can be formed through percolation processes from aerial zones flowing vertically through fractures and faults in breccia and andesite rocks. 2 Methods and theoretical consideration 2.1 Gravity method Gravity data processing have been done using LaCoste & Romberg-778 gravimeter throughout the study area. The measurement data was from 38 random acquisition points (Fig. 1). The elevation was measured using Garmin GPS combined with Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) obtained from USGS. [1]The application of geophysics for subsurface mapping, especially groundwater prospect zone mapping, can help reduce the risk of failure in drilling, especially in hard rock environments. The presence of hard rock, which is the main source of the anomaly, can be mapped accurately by recording the gravitational response on the surface. The gravitational effect is influenced by the interaction of the tensile strength, mass density and depth of the subsurface rock. Igneous rock has a density of >2.67 g/cm3, [7]which is the dominant indicator in measuring gravity anomalies, compared to pyroclastic with a density around 2.2-2.4 g/cm3. Several corrections to the gravity measurement data have been made to obtain the Bouguer anomaly value, which is then separated into the regional and residual effects (Khan et al. 2018; Panjaitan and Astawa, 2016; Salapare et al. 2015). The method used to separate the Bouguer anomaly is spectrum analysis, commonly [1]used to determine the boundary zone between regional and residual gravitational anomaly characteristics (Karunianto et al. 2017; Purnomo et al. 2016; Subagio and Patmawidjaya, 2016). The residual anomaly value from this separation is used in subsurface modelling (Ayala et al. 2016; Madu and Mosto, 2016). Mapping hard rock at the base of pyroclastic and sedimentary materials with lower density will be effective through gravity. The difference between the two rock masses and the difference in basement undulation will produce anomalous contrasts. Anomalies between regional and residual can provide information on the position of hard rock as basement and softcover (Gómez et al. 2017; Xu et al. 2015). However, the presence of groundwater in primary and secondary porous spaces cannot be mapped accurately through gravity measurements. The presence of groundwater in hard rock, such as water filling cracks and faults with relatively small dimensions, can introduce more complex problems. Nevertheless, gravity mapping can help to locate fault lines. 2.2 Vertical electrical sounding (VES) No geophysical methods can be directly applied to measure the in-situ water content in geological formations(Wyns et al. 2004). However, the geoelectric method is an alternative that is widely used for groundwater exploration (Abdulrazzaq et al., 2020; Mohamaden and Ehab, 2017; Waswa, 2019). Water saturation in primary and secondary porosity affects the conductivity of rocks. It produces a contrast to the surroundings, which can be traced through geoelectrical measurements (Chandra et al. 2008; Rao et al. 2021; Teikeu et al. 2012; Varalakshmi et al. 2021). The resistivity value rapidly decreases when the pores are filled with fluids (Montaña et al. 2012; Pandey et al. 2015). Fractures are potential pathways for groundwater flow in hard rock. The presence of conductive zones related to groundwater occurrence in fractures and faults can be mapped through a welldistributed Vertical Electrical Sounding (VES). VES is used to determine the resistivity variation with depth, especially for the response caused by the presence of groundwater in rock pores. Mapping through 51 VES points was used to characterize the presence of groundwater in the hard rock at the foot of Mount Betung (Fig. 2). The VES measurement uses a Schlumberger configuration with a minimum electrode interval of 5 meters. The instrument used is the ARES GF Instrument. The potential electrodes (M and N) are placed in a relatively fixed position between the current electrodes (A and B). [3]The distance between A and B is gradually shifted wider from M and N to obtain a deeper layer count. The ideal widest distance between A and B is five times the distance between M and N to avoid weakening the measured potential difference (Bouderbala et al. 2016). VES [1]measurements were carried out with a half current electrode distance (AB/2) ranging from 1 m to 250 m. This distance is sufficient to reach the depth of groundwater in crystalline rock composed of andesite, basalt and breccia in the study area. Data processing was carried out through the isoresistivity map on AB/2 = 50, 100 and 150 m to obtain a conductive zone caused by presence of lateral groundwater. Isoresistivity maps is produced using the Surfer 8 software. Meanwhile, Resty Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 12 http://gwse.iheg.org.cn software was used for the qualitative interpretation of VES data through a forward modelling approach, which gives the results of resistivity values and layer thickness. The 2D model was obtained by correlating several data from two wells with depths of 180 m and 76 m. 3 Results and discussion [8]The Bouguer gravity anomaly of the study area is generally over 50 mgal. The anomaly [1]is caused by the influence of igneous rocks from the bedrock of Mount Betung (Fig. 2A). The data from the observation well also shows the presence of massive andesite with a thickness of more than 150 m covered by thin pyroclastic deposits. However, the distribution of andesite with density >2.6 g/cm3, is relatively complex, which can be formed through melting and intrusive processes. Anomaly values are medium and low away from Mount Betung. In the west, the Bandar Lampung Basin is interpreted to have a higher groundwater prospect than other areas. The basin is relatively small and shallow compared to the South Sumatra Basin. However, according to the interpretation, these basins have similarities in the formation process due to basement expansion during the Pre-Tertiary period (Barber and Crow, 2009; Bishop, 2001; Pubellier and Morley, 2014). Bandar Lampung is a regionally elevated basement and affects the thickness of the sedimentary formations overlying it. Fig. 2A shows the Bouguer anomaly with the contour interval of 2 mgal and Fig. 2B shows the residual anomaly with the interval contour of 1 mgal. The red line is cross-section A-A′, and the yellow line is B-B′ for the 2D subsurface gravity model. The [1]qualitative interpretation of the residual component along A-A′ shows the depth of the hard rock and basement and the thickness of the sedimentary material that forms the cover layer (Fig. 3). The research area is 1.5 km from the peak of Mount Betung, with an altitude of 1 150 m above sea level. The presence of hard rock is interpreted as the same sequence as the volcanic rocks that make up Mount Betung. From gravity interpretation, hard rock is at a depth of 100 m with a thick cover of pyroclastic, clay, andesite, and basalt lava melts. Pyroclastics form layers of tuff and bombs, while in the basin, the low anomaly is caused by the basement graben. The basement cover layer has a thickness of 200-300 m (Mangga et al. 1993). It is interpreted as an alluvial and fluvial environment, a place for accumulating sediments resulting from pyroclastic and clastic since the Tertiary period. In Fig. 4, the yellow line is cross-section line BB′ for the 2D subsurface model of geoelectrical. The measuring area is 9 km2, in which 51 measuring points were placed on a grid with a distance of 500 m in-between aiming to obtain aquifer prospects for several housing estates who 515000 0 5 10 Km 9390000 9395000 9400000 9405000 9410000 9390000 9395000 9400000 9405000 9410000 520000 525000 Interval contour 2 mgal 515000 520000 A. Anomaly bouguer 525000 N 515000 0 5 10 Km 9390000 9395000 9400000 9405000 9410000 9390000 9395000 9400000 9405000 9410000 520000 525000 Interval contour 1 mgal Line profile gravity; Line profile geoelectric 515000 520000 B. Anomaly residual 525000 N A A' B B' Fig. 2 Bouguer gravity anomaly map for Bandar Lampung Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 http://gwse.iheg.org.cn 13 have had frequent well failures (Fig. 4). Isopach mapping of apparent resistivity to identify the distribution of the conductive zone was carried out at AB/2 = 50 m, 100 m, and 150 m. The presence of hard rock is reinforced by the mapping results from the 51 VES points with high resistivity values (Fig. 5). The conductive zone is composed of fractures in breccia and andesite rocks, observed from rock samples in several successful wells. These wells were previously sited based on geoelectrical estimation results, while several wells failed without using geoelectrical estimation results. The production well near point G7 is one of the successful ones and is capable of producing a discharge of 2 400 liters/minute. The depth of the well reaches 180 m, composed by the following lithology: Soil (0-5 m), andesite breccia (5-44 m), breccia (4459 m), andesite (59-64 m), breccia (64-77 m), andesite (77-106 m), breccia (106-141 m) breccias, and andesites (141-180 m). The presence of groundwater is mainly within breccia rocks with higher secondary porosity. Meanwhile, well G4 with a depth of 70 m has failed, composed of a thin layer of tuff and andesite with a thickness of 67 m. Fracture water in the study area comes from the infiltration in Mount Betung. Groundwater stores and travels in hard rock fractures, feeds the streams in the aerial zone, and flows from high topography to the foot of Mount Betung. Groundwater in hard rock fractures plays an important role in the groundwater occurrence in the fluvial sediments of the Bandar Lampung Basin. Two bottled water companies have taken advantage of the groundwater abundance in Bandar Lampung Basin. Great and Tripanca drinking water companies (Fig. 4) are believed to use large amounts of groundwater for daily production, similar to Danone Company which uses groundwater sourced from volcanic areas to produce bottled water. The interpretation of VES data at points G4, G7, and Great Company, is shown in Fig. 5. Resistivity data at these three points at the foot of Mount Betung shows high values and low values only appear where water presents in andesite and breccia fractures. The correlation [1]of the subsurface model between the hard rock environment at the foot of Mount Betung and Great is shown in Fig. 6. Rainwater infiltration takes place in the recharge area at Mount Betung can sustainably feed the fracture system at the foot of Mount Betung and subsequently fill the aquifer in the Bandar Lampung Basin. Groundwater in Mount Betung shows a pattern of conductive lenses on the isopach map of resistivity on the slopes and foothills of the mountain, as presented in Fig. 6. [1]The presence of conductive lenses with resistivity values of 15-60 ohms m is interpreted as groundwater saturation zone occurring in the lateral and vertical columnar joints. It acts as an aquifer in a hard rock environ- 0 Holocene young volcanic deposits Andesite, basalt and breccia Pleistocene volcanic deposits Eocene deposits Palezoic basement composed by schist Distance/Km Depth/Km Gravity/mgal Pzg Pzg Tpot Tpot QTI QTI A A' Qhv Qhv−1.0 −0.5 −6 6 0 0 10 Observed = Calculated Error 0.307 Fig. 3 Subsurface model along cross-section line A-A′ from gravity anomaly 516000 0 1 2Km [7]Bandar lampung city Mount Betung Great company B B′ 9398000 9400000 9402000 9398000 9400000 9402000 518000 520000 522000 524000 516000 518000 520000 522000 524000 N Fig. 4 [2]The distribution map of 51 geoelectric VES measuring points at the foot of Mount Betung Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 14 http://gwse.iheg.org.cn ment composed of andesite and breccia. Two wells near G4 and G7 with rock compositions are described in Table 1. Meanwhile, no secondary porosity was formed in the well with a depth of 76 m near G4. The resistivity values at AB/2 = 50 m, 100 m, and 150 m are 300-400 ohm m. These values s fall in the category of dry andesite rocks, which are nearly impermeable. Different results were obtained in the well near point G7, where conductive lenses with resistivity values of 25-60 ohms m were captured at AB/2 = 50 m, 100 m and 150 m. The well is capable of producing a discharge of 4 l/s. Based on the results from point G7, the groundwater prospect in the hard rock environment are distributed on the slopes and foothills of Mount Betung, where fractures and columnar joints act as permeable zones. Unfortunately, the existence of secondary porosity is random, which has caused the drilling failure in several wells. Groundwater stored and transmitted in secondary porosity is a characteristic in hard rock environments. The fractures and columnar joints in the research area serve as lens aquifers. The lens aquifer in Fig. 6 form flow paths originating from infiltration at Mount Betung and fill various aquifers in Eocene and Pleistocene rock formations in the Bandar Lampung Basin. A tentative model to describe the relationship of the groundwater infiltration area on the slopes and foot of Mount Betung (Fig. 6) with the aquifer in the basin, based on the results of qualitative processing of 3 VES data at points G4, G7 and Great Company (Fig. 5). The modelling results at the three VES points are correlated with the layering data and the presence of groundwater is obtained in Table 1. The model that explains the presence of aquifer lenses (Fig. 6) is the reason of groundwater occurrence in the Great Company area, as shown in Fig. 7. The conductive path in Fig. 7 is in the form of fractures in andesite and breccia rocks in the hard rock environment. In contrast, the Great Company production wells located in sedimentary formations are still being interpreted. The prospec zone in Fig. 6 can describe both the conductive zone and groundwater flow path that connects the area of the foot of Mount Betung and the aquifer in the Bandar Lampung Basin. Water stored and flowed in the breccia fractures comes from the infiltration of Mount Betung, which is in the southwest of the study area. The high rainfall reaches up to 2 500 mm/a, providing continuous groundwater recharge at the foot of Mount Betung, and augmented by the presence of several springs. Rainwater is interpreted to rapidly infiltrate into a thin layer of young volcanic deposits composed of tuff and lava cove- [1]VERTICAL ELECTRICAL SOUNDING G4 kemiling district 10 10 100 100 Depth/meters Resistivity/Ohm m Resistivity R.M.S Error=0.1 1. 230.0 2. 530.0 3. 150.0 4. 300.0 Depth 2.0 25.0 60.0 1000 1000 10000 10000 VERTICAL ELECTRICAL SOUNDING G7 kemiling district 10 10 100 100 Depth/meters Resistivity/Ohm m Resistivity R.M.S Error=0.3 1. 220.0 2. 120.0 3. 30.0 4. 140.0 Depth 7.0 9.0 25.0 70.0 5. 40.0 6. 300.0 90.0 1000 1000 10000 10000 VERTICAL ELECTRICAL SOUNDING great company 10 10 100 100 Depth/meters Resistivity/Ohm m Resistivity R.M.S Error=0.2 1. 90.0 2. 50.0 3. 110.0 4. 10.0 Depth 1.5 9.0 35.0 110.0 5. 30.0 6. 70.0 140.0 1000 1000 10000 10000 Fig. 5 VES data interpretation on G4, G7, and Great Company Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 http://gwse.iheg.org.cn 15 ring large bodies of intrusive rocks with fractures as conductive zones. Gravity plays a vital role in further infiltration of shallow groundwater at Mount Betung, filling fractures in intrusive rocks, flowing towards the lower part and entering the east basin. However, what is happening now is the rapid depletion of groundwater in the Bandar Lampung Basin, as [1]the impact of exploitation exceeding the natural groundwater replenishment.

4 Conclusions [2]The use of gravity mapping and geoelectric VES mapping can provide good results for ground water mapping in hard rock in Western Bandar Lampung. The hard volcanic rocks of Mount Betung produces an anomaly value of 50-68 mgal. Hard rock in the production well is at a depth of 5180 m, composed of andesite and breccia. Isoresis- 520000 AB/2=50 m 9401500 9402000 9402500 520500 521000 521500 5220000 520000 AB/2=100 m 9401500 9402000 9402500 520500 521000 521500 5220000 520000 AB/2=150 m 9401500 9402000 9402500 520500 521000 521500 5220000 N 40 80 120 160 200 240 [4]280 320 360 400 60 100 140 180 220 260 300 340 380 420 440 80 120 160 200 240 280 320 360 400 440 480 Ohm m Fig. 6 [2]Isopach map of resistivity from 51 VES measuring points at the foot of Mount Betung Table 1 Approximate depths, widths and the nature and geological conditions of aquifers of boreholes in the study area Well Depth/m Geological composition Groundwater presence G4 0-2 Clay and tuff 2-76 Dry andesite G7

0-4 Clay and tuff 4-30 Breccia 30-44 Dry andesite 44-59 Breccia Groundwater presence atdepth of 45-52 m 59-64 Dry andesite 64-77 Breccia Groundwater presence at depth of 69-73 m 77-106 Dry andesite 106-141 Breccia Groundwater presence at depth of 108-139 m 141-180 Dry andesite Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 16 http://gwse.iheg.org.cn tivity map can indicate a conductive [1]zone in the form of fractures. The presence of conductive lenses with resistivity values of 15-60 ohms m is interpreted as groundwater saturation zone occurring in the lateral and vertical columnar joints. It [2]acts as a lens aquifer in a hard rock environment composed of andesite and breccia. Fractures and columnar joints are secondary porosity that stores and transmit groundwater in the study area. The production well, if placed in the fracture area, can produce water of 2 400 liters/minute. Meanwhile, the random distribution of secondary porosity [6]in hard rock is the cause of many drilling failures. The integrated method of gravity and geoelectric VES was found [1]very useful in the of groundwater prospect mapping in the hard rock environment on the slopes and foothills of Mount Betung, where fractures and columnar joints act as permeable zones. The fractures in the hard rock at the foot of Mount Betung act as a transmission area between recharge at Mount Betung and the aquifer in the Bandar Lampung Basin. Acknowledgements This work was supported by grants from Indonesia's National Research and Innovation Agency, Doctoral Dissertation Research scheme. Holocene deposits 0 100 200 300 Meter Andesite and breccia Pleistocene deposits Eocene deposits Fracture Well on G4 Well on G7 Well on great company Tpot QTI Qhv B B′ Fig. 7 Interpretation of subsurface model from geoelectrical cross-section line B-B′ Journal of Groundwater Science and Engineering Vol.10 No.1 : 10—18 17

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