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App. Envi. Res. 44(3) (2022): 76-87 https://doi.org/10.35762/AER.2022.44.3.6
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Article History Submitted: 11 May 2022 / Revision received: 3 September 2022/ Accepted: 5 September 2022 / Published online: 29 September 2022
Abstract Increased groundwater extraction from aquifers in Holo-Quaternary rock formations in Lampung Bay has caused saltwater intrusion. This indication appears in several community wells and can spread further inland. Therefore, this study aims to identify the distribution of areas exposed to saline water and the boundaries of areas that have not, especially in the Holo-Quaternary Formation. This research uses the geoelectric method integrated with salinity data and the Soil Penetration Test (SPT) analysis at four drilling points. A total of 4 lines of Electrical Resistivity Tomography (ERT) and 8 points of Vertical Electrical Sounding (VES) have been acquired with a Schlumberger configuration with an AB/2 span of up to 200 meters. Meanwhile, the salinity data was measured directly from 60 samples from community wells. The ERT and VES analysis results show that the coastal aquifer in Lampung Bay is at a depth of 2–24 m. SPT analysis identified interbedded sand, silt, and clay which were interpreted as marine sedimentation from the Holo-Quaternary Formation layer. Groundwater is only in shallow aquifers (less than 24 m) but has experienced seawater intrusion with low resistivity values between 9–20 ohm m. The distribution of high salinity values up to 3,100 ppm has reached more than 1 km from the coastline. Furthermore, ERT results reinforce this finding, which shows low resistivity values of less than 10 ohm m in the shallow aquifer zone. VES data detects low resistivity values (18 ohm m) at a depth of 12– 13 m.
Keywords: Aquifer; Holo-quaternary; Geoelectrical; I ntrusion; Salinity

Introduction

Coastal ecosystems are the most economically productive and densely populated globally [1–2]. Groundwater from coastal aquifers is the primary source of clean water needs in various sectors, including households, tourism, industry, and commercial centers on the coast. Since the early 20th century, groundwater from coastal aquifers in Bandar Lampung has been used for drinking

water and other Applied Environmental Research Journal homepage : http://www.tci-thaijo.org/index.php/aer Identification of Saline Water Intrusion Using Integrated Geoelectrical Method in the Coastal Aquifer of HoloQuaternary Formation, Lampung Bay Rustadi1,* , Agus Setiawan2 , I Gede Boy Darmawan1 , Suharno1 , Nandi Haerudin1 App. Envi. Res. 44(3) (2022):

76-87 77 water resource purposes. The use of groundwater increases yearly and threatens groundwater's sustainability, which is the drinking water source for more than 280,000 people and the industrial sector [3]. Overexploitation of groundwater in coastal areas of Bandar Lampung has caused environmental problems, including decreased groundwater quality due to seawater intrusion [4–7] with a salinity of more than 1 ppt [8–9]. Seawater intrusion in Bandar Lampung's coastal aquifer significantly affects the health and social problems of the people on the coast of Bandar Lampung who depend on groundwater [10–13]. Other environmental impacts are subsidence of the soil surface and damage to building foundations by corrosion [14–15]. The subsidence has caused several coastal sub-districts to be flooded by rainwater from the catchment area in the western part of Bandar Lampung [16]. Groundwater contamination in coastal aquifers has become a global issue [17–18], especially in low and middle-income countries [19–20]. Groundwater management in coastal areas is an environmental issue that requires a holistic approach. The limited ability to provide clean water and the weak application of regulations are factors for uncontrolled groundwater extraction on the coast of Bandar Lampung [21]. Indications of seawater intrusion have been identified on the coast of Bandar Lampung based on gravity and geoelectric data [22]. However, groundwater aquifer salinity data integrated with geoelectric and drilling data has not confirmed this result. Therefore, an effort is needed to monitor the condition of groundwater aquifers, especially those related to the potential for seawater intrusion in groundwater aquifers. Detailed analysis of seawater intrusion into aquifers requires the availability of monitoring wells to measure geochemistry and groundwater level fluctuations [23–25]. This process requires expensive research costs and is currently a constraint in Bandar Lampung, especially regarding monitoring wells and periodic water quality measurements. Therefore, based on the limited funding sources, this study emphasized measuring groundwater salinity 1in the aquifer as the initial concentration. Groundwater Salinity testing is accompanied by 2the geoelectric method, which many researchers choose for mapping seawater intrusion [26– 28]. The study aimed to obtain areas exposed to seawater intrusion and as a reference for more detailed research in intertemporal monitoring. Geoelectric delineation is 1used to map aquifers and lithology constituents on the coast. Compared with several drilling results, the delineation area aims to analyze soil mechanics. The acquisition of salinity data from several wells around the research area was carried out to obtain the distribution of the influence of seawater intrusion. The results of groundwater salinity mapping are then integrated with 2the distribution of groundwater aquifers resulting from geoelectric measurements. These results are expected to provide an overview of groundwater aquifer areas affected by seawater intrusion, especially in the HoloQuaternary Formation. These results provide information on which areas need to be controlled for groundwater use or must be conserved and monitored continuously. Materials and methods 1) Geological setting of the study area The Bandar Lampung coast is located 8in the southern part of Sumatra Island, Indonesia (Figure 1). Geographically, Bandar Lampung city is located from 5°20' to 5°30' S and 105°28' to 105°37' E. The morphology on the coast is a plain formed from sedimentation of the Holocene – Quaternary age. The steep hills in the west and east act as a catchment area in Bandar Lampung city.

Figure 1 The geological map 1on the coast of Bandar Lampung [31]. Based on Figure 1, the red dot represents the VES resistivity measurement point. There are 6 VES points to examine aquifers on the coast, while 8 VES points are away from the coast. Besides that, there are also 4 secondary SPT measurement data located in the south and southeast of the city of Bandar Lampung. Meanwhile, 5the Electrical Resistivity Tomography (ERT) measurement is also near the SPT point. The morphology of the plains on the coast of Lampung Bay is interpreted as various formations ranging from old to young sedimentary rocks. These rocks are formed by sediment transportation from land to the coast, mixed with sedimentation in the marine environment [29, 32]. Early sedimentation resulted in the Tarahan Formation (Tpot), which covers a large area of bedrock in Bandar Lampung. The formation currently leaves outcrops in the west and east. A large part is covered by the Lampung Formation (QTl), Young Volcano Formation (Qhv), and the Coastal alluvial deposits (Qa) known as the Holo-Quaternary Formation. The Tarahan Formation (Tpot) is the bedrock cover formed from pyroclastic deposition and Tertiary -aged clastic sediments, composed of tuff, breccia, and chert. The Lampung Formation (QTl) closes the Tarahan Formation in the Quaternary with pyroclastic composition, sand, and clay. The last phase is covered by pyroclastic from Mount Betung in the west to form the Young Volcano Formation (Qhv). Coastal alluvial deposits (Qa) also make up the coastal part. The coastal alluvial f ormation combines clastic material transportation on land to the coast and a marine sedimentation system. Geological order lasts from PreTertiary to Quaternary and the presence of hard rocks in the form of metasediment and igneous rocks [29]. This order strongly influences the alignment and geometry of the aquifer on the coast of Bandar Lampung.

2) Geoelectrical method and SPT

The geoelectric method aims to determine the distribution of physical parameters in the form of resistivity of the subsurface layer through the injection of electric current on the surface

[33]. The resistivity of geological materials varies with the type of rock, the constituent minerals, and the fluids in the rock [34–35]. It is allowed to be studied through the distribution of geoelectrical data. The presence of fresh water and saline water fills the porosity, causing the aquifer to be conductive. Saline water is more conductive than fresh water, causing the resistivity value of the rock saturated by the fluid to be lower.

This study uses two geoelectric methods, namely ERT and VES. ERT is an acquisition technique that is quite detailed in measuring resistivity through lateral and vertical data distribution. The distribution of tightly organized data will be able to image the subsurface profile in more detail. Meanwhile, the VES data distribution is used to get deeper information. VES measurements provide the advantage of examining resistivity changes vertically [38–39]. Another objective is to find the linkage of coastal aquifers with parts farther inland. The measurement technique uses the Schlumberger configuration with potential electrodes (M and N) in a relatively fixed position, and the current electrodes (A and B) are placed symmetrically on the out side of the potential electrode. The M and N electrodes' positions are changed when the current electrodes are farther away. Wider positions of the current electrodes result in a decrease in potential difference, which causes a decrease in the accuracy of the measurement data [40]. All geoelectric measurements were carried out in this study using the ARES GFZ instrument. The ERT investigations were carried out in 4 coastal passes to map aquifers and the presence of seawater intrusion accurately. Measurements using the WennerSchlumberger array with an electrode distance of 6 m and a track length of 160 m. In addition, the use of ERT in four paths aims to map the presence of aquifers and the effect of saline water filling the pores. The ERT profile is obtained by inversion of the measured data and converted into actual resistivity using the Res2 DInv programs [36–37]. The VES acquisition was carried out with half current electrode spacing (AB/2) ranging from 1 m to 200 m in coastal areas caused by open space constraints. VES data modeling was carried out to obtain resistivity values and the thickness of the constituent layers using Resty software. The interpretation of resistivity and thickness of the layers that make up the ERT modeling results with VES data can produce information different from the actual subsurface geological conditions. Soil Penetration Test (SPT) analysis was carried out as secondary data at four drilling points located in coastal areas. This analysis serves as a binder of the resistivity value of the modeled layer from ERT and VES with the actual subsurface constituent. 3) Mapping of groundwater salinity Mapping groundwater exposed to seawater intrusion in the Bandar Lampung Coast was randomly carried out according to community wells availability using the Wal front EZ 9909SP water quality meter instrument. The sampling method is carried out directly on the well and placed in the measuring container. Measurements of water salinity values were also directly carried out on water samples in measuring containers at the sampling location of 60 samples. The value of the measurement results is then recorded in a notebook accompanied by information on the coordinates. All water sample measurement data was carried out at the end of the dr y season in August 2021. Results and d iscussion The results of mapping the closest aquifer to the coast in detail based on ERT in four tracks and the results of the inversion using Res2DInv are shown in Figures 2 to 5. The ERT profiles in Figures 2 to 5 align with the composition of the geological material found in Table 1. The groundwater prospects are 1at a depth of 2–24 m and are composed of interbedding sand,

silt, and clay with coral reefs. These were read as one conductive layer with a resistivity value of 10– 70 ohm m. However, the influence 2of saline water that fills the aquifer produces a resistivity value of 9– 20 ohm m. 1The existence of a resistive layer with a value of 800–3000 ohm m symbolized by red in the four ERT profiles has been an unsolved problem for a long time. However, drilling results at four SPT points provide essential information on the presence of claystone basements on the coast of Lampung Bay. The resistive layer was initially interpreted as pre-tertiary age bedrock (Pzgs) undergoing accretion in the eastern part. However, the drilling results indicated 3the presence of a claystone layer as a constituent of the QTI. The compressive test results on this clay stone layer have an SPT value of 60, which is strengthened by the drilling process's difficulty penetrating this layer. Figure 2 ERT profile on line 1. Figure 3 ERT profile on line 2. Figure 4 ERT profile on line 3. Figure 5 ERT profile on line 4. Table 1 Subsurface geological materials 1on the coast of Lampung Bay Location Depth (m) Composed Location Depth (m) Composed SPT-1 0–1 Soil SPT-3 0–14 Seawater 1–3 Sand and coral reef 14–30 Interbedding sand, silt, and clay with coral reef 3–21 Silt and clay with lenses igneous rock 30–36 Claystone from Lampung Formation SPT-2 0–2 Soil and clay SPT-4 0–3 Soil and clay 2–24 Interbedding sand, silt, and clay with coral reef 2–24 Interbedding sand, silt, and clay with coral reef 24–30 Claystone from Lampung Formation 24–30 Claystone from Lampung Formation 5The interpretation of the ERT profile (Figures 2 to 5) refers to the drilling data at SPT-1, SPT-2, SPT-3, and SPT-4 with the results presented in Table 1. Conductive layers with a thickness of up to 24 m are interpreted as a product of shallow marine sedimentation. This product was formed during the Holocene period, which resulted 1in the Coastal Alluvial Formation [32], composed of interbedding sand, silt, and clay. The existence of coral reefs is a reinforcement for sedimentation on the continental shelf with a tropical climate on the coast of Lampung Ba y. Aquifers with freshwater saturation are interpreted to produce resistivity values of 15– 60 ohm m [35]. Mixing seawater with fresh water on the coast of Bandar Lampung is interpreted to have a resistivity value of 9– 20 ohm m. As for the increase in salinity that occurred in the coastal aquifer of Bani Nador, it showed a lower value [23, 28]. The thickness of the aquifer on the coast of Lampung Bay will vary by the influence of ocean current circulation, which produces sand, silt, and clay layers. As the base of the alluvial formation, claystone is composed at a depth of 24 m on land (in SPT-1, SPT2, and SPT4) and 30 m in the sea (SPT4). The results of the ERT on the coast of Bandar Lampung are in line with the results of VES data modeling, shown in Figure 6. The presence of claystone indicates a thick basement, the base for a thin layer of Alluvial Formation. In contrast, the VES model 3away from the coast (Figure 7) shows changes in the sedimentation environment, which are interpreted as fluvial and floodplain environments. Aquifers away from the coast were found at varying depths, corroborated by the presence of wells that were less than 40 m deep and more than 100 m deep (Figure 8). The limitation of the depth of the drilling data is an obstacle to interpreting the alignment of the aquifers formed in the fluvial and flood plains in the Tpot and

QTl. A blue layer distribution as a conductive layer with a 1resistivity of fewer than 20 ohm m was found in shallow aquifers in all ERT profiles and VES models. The results obtained from the four ERT profiles are corroborated 11by the measured salinity of groundwater test results from the well with the distribution shown in Figu re 8. Assuming that salinity greater than 500 ppm is interpreted as the threshold for groundwater mixed with seawater, a radius of 1.5 km from the coastline has been contacting groundwater and seawater. Meanwhile, in some areas south and southeast 1of Bandar Lampung, seawater intrusion is located at a radius of less than 1.0 km from the coastline. Figure 6 Interpretation of VES data at points V4 (left) and V2 (right) on the coast of Lampung Bay. Figure 7 Interpretation of VES data at points V10 (left) and V12 (right) on the coast of Lampung Bay .

Figure 8 Map of saline groundwater on 2the coastal aquifer of Lampung Bay. The southern part of the Bandar Lampung is a zone with high contamination where the measured salinity value reaches 3100 ppm. Meanwhile, in the southeastern part 1of Bandar Lampung, salinity in groundwater reaching 1,500 ppm takes second place. The southern and southeastern parts of Bandar Lampung are centers of trade, various industries, and warehouses 3related to the presence of the port, causing extensive groundwater use. These results indicate that the high level of groundwater salinity 1in Lampung Bay has reached a radius of more than 1 km from the shoreline. These conditions are mainly in the southern and southeastern parts of Bandar Lampung. It indicates that the groundwater intrusion zone has polluted the shallow groundwater aquifer, following the ERT results on lines 1 and 3 (Figure 2 and Figure 4). Those explain the low resistivity values up to less than 10 ohm m in the aquifer zone. This result is also consistent with the VES data at locations V2 and V4 (Figure 6), which detects low resistivity values (18 ohm m) at a depth of 12– 13 m. This finding is significant to previous studies, which stated that there was a rate 9of land subsidence in this area [41]. Furthermore, the results of groundwater testing from wells far from the shoreline indicate the distance of influence of seawater intrusion to the mainland. The well distribution with the aquifer 1at a depth of 50–70 m (y ellow point) and more than 80–150 m (red point) in Figure 8 is assumed to align with the coastal a quifer. The results of salinity testing on groundwater samples indicate that they have not been exposed to marine intrusion with a value of less than 200 ppm. However, groundwater extraction by household needs, and the presence of hotels, can undoubtedly threaten seawater intrusion further inland. The distribution map of groundwater that has been exposed to seawater intrusion (Figure 8) can be a baseline to see changes in exposure to seawater intrusion in the future, especially in the Holo-Quaternary Formation.

The utilization of groundwater without proper management in shallow aquifers on the coast of Bandar Lampung results in a decrease in groundwater quality. Salinity values greater than 500 ppm in groundwater samples in several wells with a depth of 5– 30 m (black dot) with the distribution shown in Figure 8. Seawater intrusion has reached a 1.0– 1.5 km radius from the coastline and has contacted groundwater and seawater. The aquifer system on the coast of Bandar Lampung is connected to the catchment area in the western part of Mount Betung and the hills in the eastern part of Bandar Lampung. However, the decreasing forest area, settlement development, and population explosion significantly caused the deficit ratio between extraction and recharge [42]. Furthermore, environmental problems that can occur in Bandar Lampung refer to groundwater use without adequate management, such as in Jakarta, the capital of the province of Indonesia. Extraction that has been carried out by domestic and industry in the 1980s has caused groundwater loss and seawater intrusion [43]. Exposure to seawater intrusion can move further inland by the effect of increasing extraction in coastal aquifer systems and aquifers in the Bandar Lampung basin. Currently, groundwater in the Bandar Lampung basin is the primary source of drinking water for more than 1 million people [22]. The groundwater extraction has reached the aquifer at 40–70 m. It is connected to a shallow aquifer on the coast of Bandar Lampung. This situation is a problem that can result in an accelerated intrusion in the aquifer system in Bandar Lampung. For further research, it is necessary to study the infiltration capacity of the hills around the hard rock Formation [42] and the application of monitoring wells in industrial areas. Various alternative artificial recharge through aquifer storage and recovery (ASR) techniques can be an issue that can be developed to inhibit the rate of groundwater loss and seawater intrusion, which has limited absorption [44– 45]. Conclusions ERT, VES, and SPT effectively describe the characteristics of aquifers on the coast of Bandar Lampung as part of interbedding sand, silt, clay, and coral reefs. The interbedding at a depth of 2– 24 m is interpreted as a Holocene – Quaternary coastal alluvial formation and is above a basement composed of thick claystone. Coastal aquifers have a resistivity value of 9– 20 ohm m due to mixing freshwater and seawater. Meanwhile, the basement has a resistivity value of more than 800 ohm m and acts as an aquifer. M easurement of groundwater salinity at 40 wells on the coast is more effective in describing areas that have been exposed to seawater intrusion. Seawater intrusion has polluted the coastal aquifer with a radius of 1.5 km from the coastline. The salinity value of groundwater reaches 750 ppm. Therefore, if groundwater extraction on the coast of Bandar Lampung is not appropriately managed, it will accelerate the process of saline water intrusion, which contaminates the aquifer even further to the groundwater basin of Bandar Lampung. To overcome this problem, aquifer storage recovery techniques can be considered to restrain t he infiltration rate on the coast and its surroundings. The high rainfall on the coast of Bandar Lampung can be harvested through the roof of the building and fill the aquifer through existing wells. Furthermore, it is necessary to research the infiltration capacity of the hilly area and groundwater flows in the fluvial aquifers and flood plains to the coast to reduce seawater intrusion pressure.

Acknowledgements We thank Mr. Ari for supporting SPT data and suggestions for improving the original manuscript.

Sources

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