HISTORY OF MANUSCRIPT PUBLICATION

(Applied Environmental Research)

Identification of Saline Water Intrusion Using Integrated Geoelectrical Method in the Coastal Aquifer of Holo-Quaternary Formation, Lampung Bay

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DAFTAR ISI

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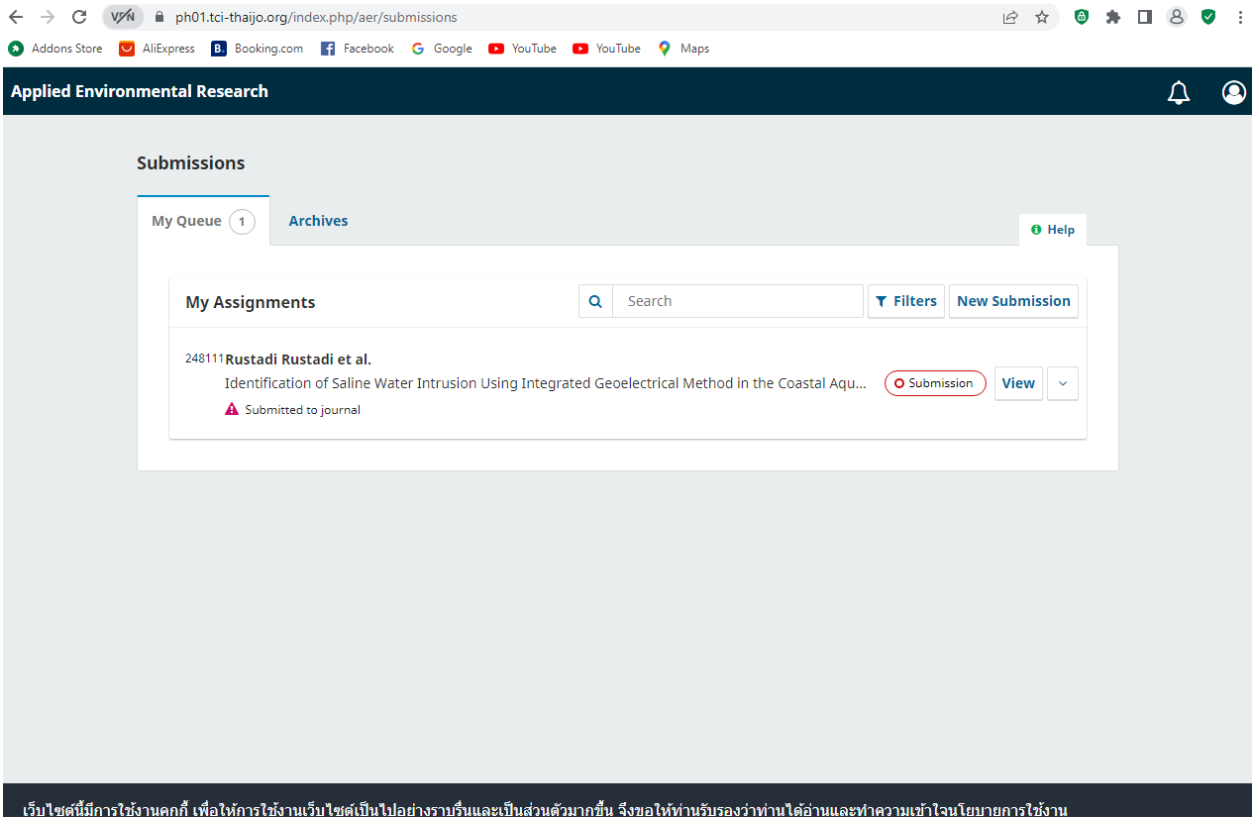

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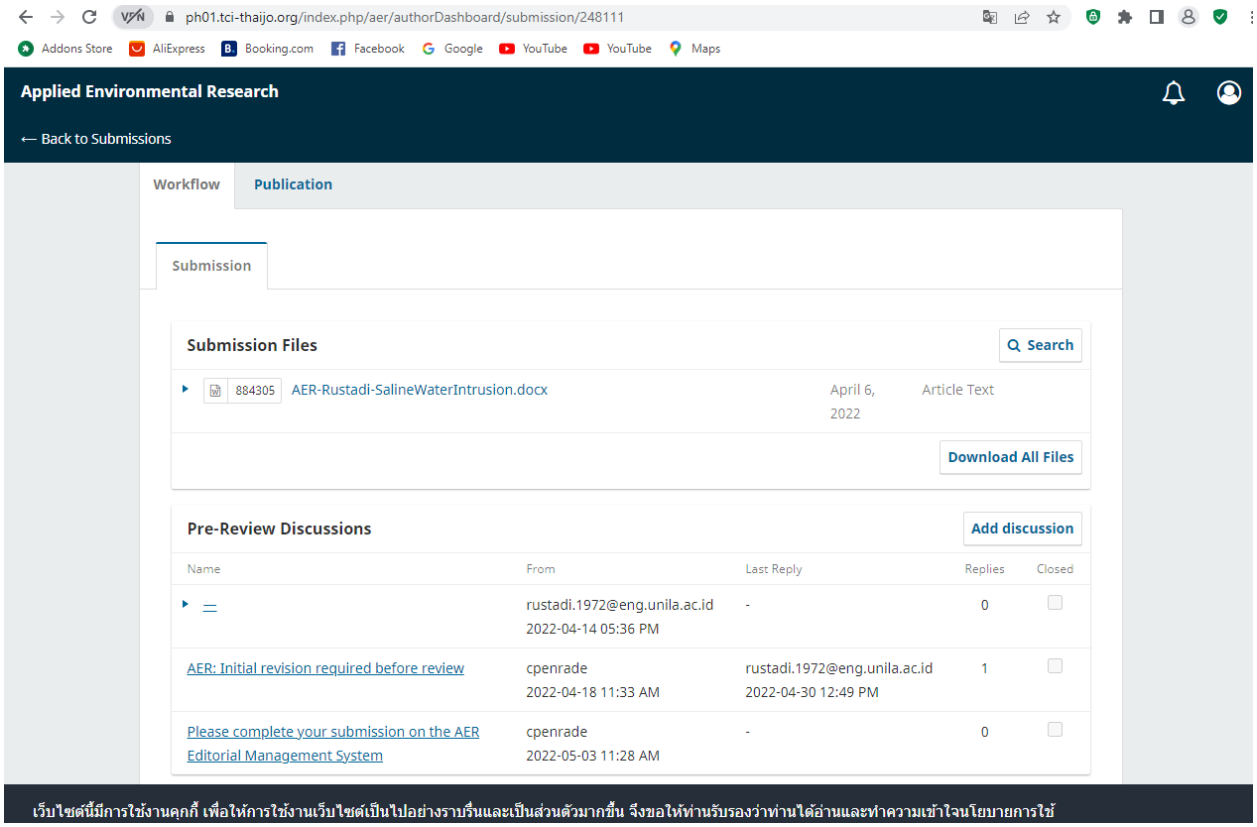

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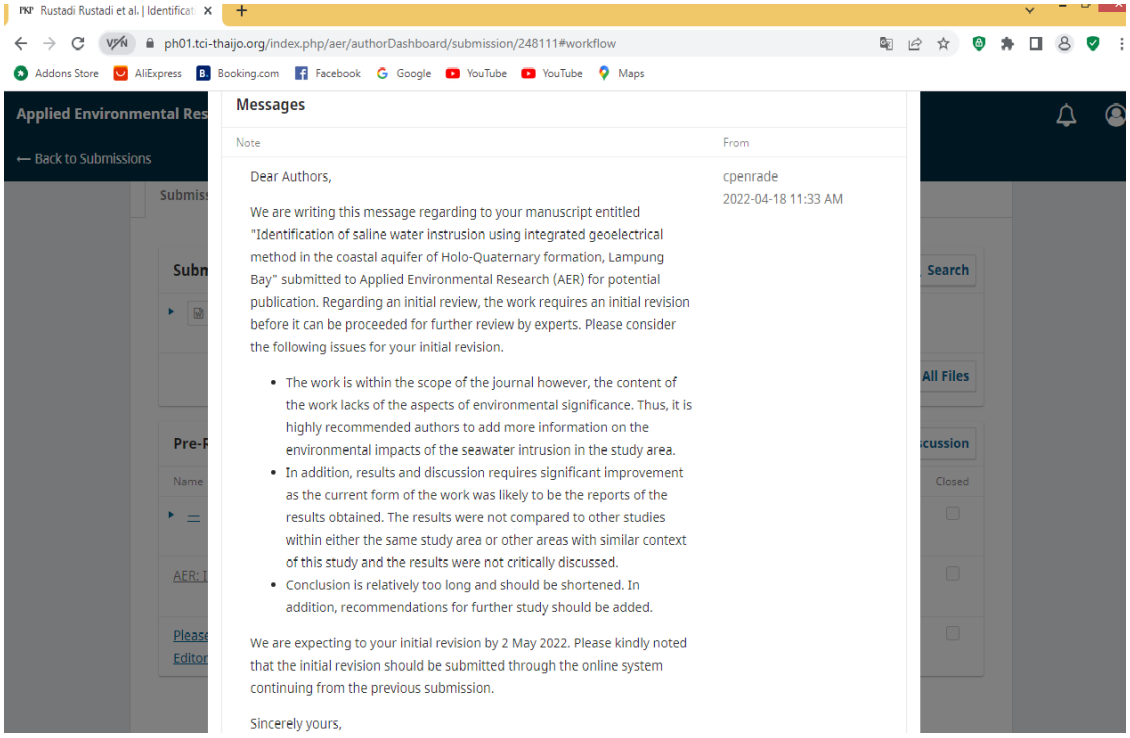

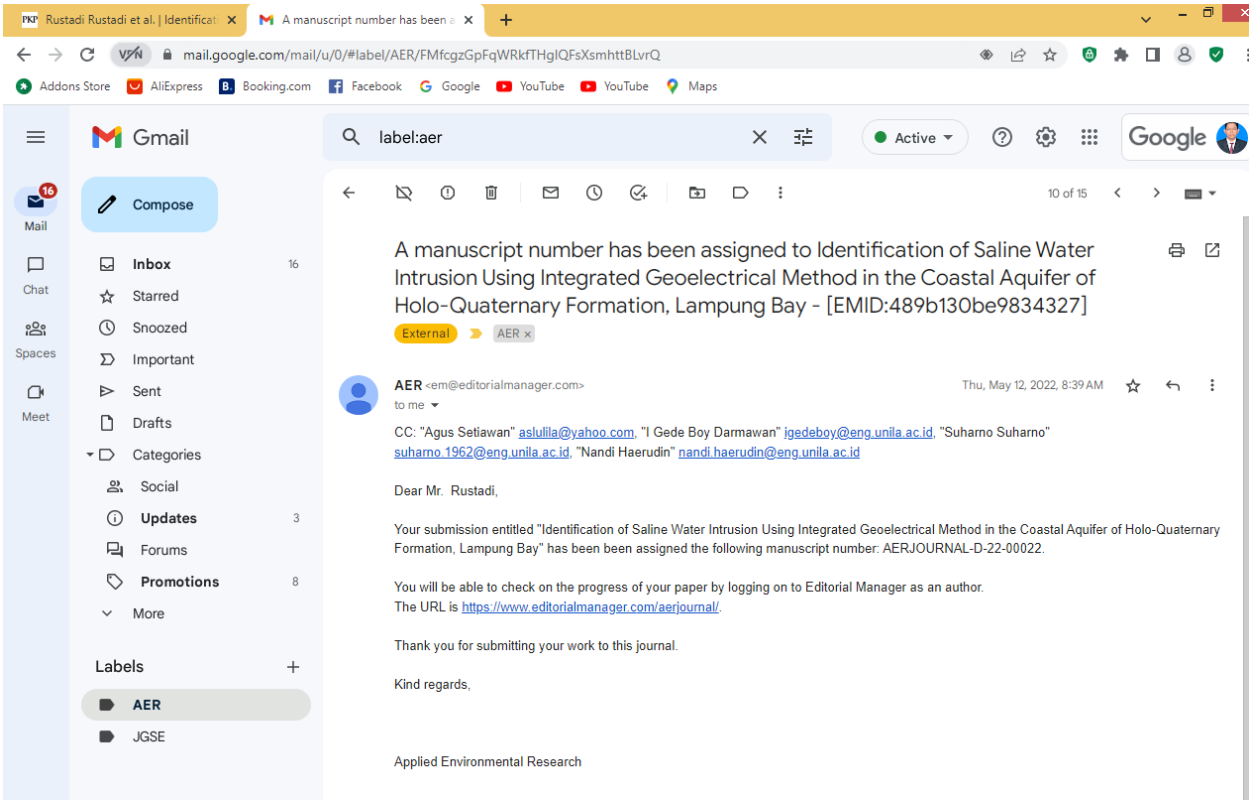

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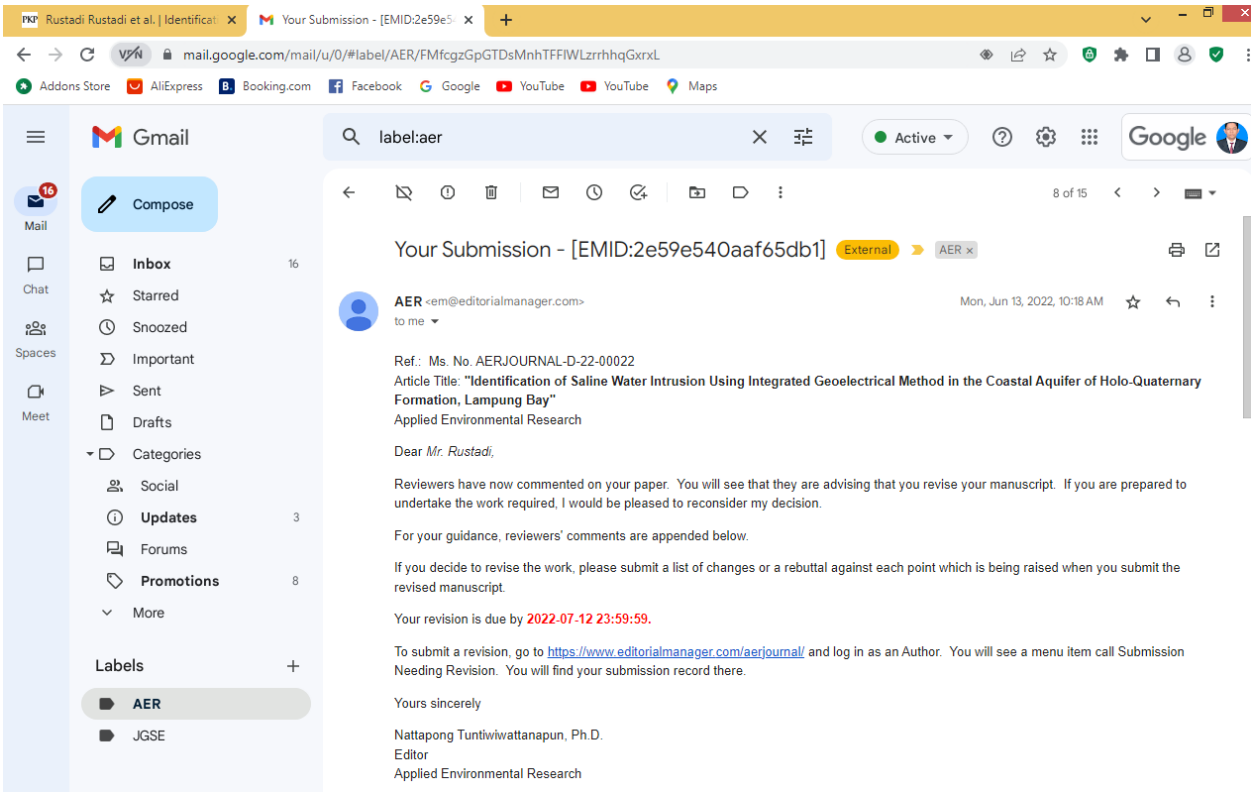

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Dear *Mr. Rustadi,*

Reviewers have now commented on your paper. You will see that they are advising that you revise your manuscript. If you are prepared to undertake the work required, I would be pleased to reconsider my decision.

For your guidance, reviewers' comments are appended below.

If you decide to revise the work, please submit a list of changes or a rebuttal against each point which is being raised when you submit the revised manuscript.

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Yours sincerely

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Comments from the Editor and Reviewers :
Reviewer #1: The article is possible to be published, but some revisions are needed. Here are some suggestions to modify the article:
1. The article should clearly state its novelty and significance as well as it distinction to other studies. Firm statements about these issues have not appeared on the manuscript.
2. Some claims in the introduction need clarification or references. For example, "Seawater intrusion in the coastal of Bandar Lampung.....(Line 39-41)" or "The limited ability to provide.....on the coast of Bandar Lampung.(Line 49-51). Are there any studies to support these statements or they are merely author's opinions?.
3. Statement in line 59-61 sounds like a personal reason that is not really necessary to be mentioned. However, if the author can convince the readers about better results obtained in spite of low budget, it can be a strong point of this research.
4. To introduce the case study area, I suggest the author to add the orientation map of the case study area relatively to the Indonesian map or paragraphs to describe where the case study area is. Therefore, general audiences can easily recognize the case study area.
5. Figures and their explanations in this manuscript need to be rearranged to guide the readers follow the flow of the research. For example, figure 1 (line 109) has no explanation while the statements to refer figure 1 (line 148 and line 219) are too far. Moreover, the readers will be confused since the author suddenly jump to figure 8 (line 167) before mentioning figure 2,3,4, and so forth.
6. Figure 2,3,4,5 are essential for this study but they are not widely explained. I suggest the author to explore these figures more widely (e.g. what do they mean, how they are interpreted, compare their similarities or differences, etc.)
7. In line 237 - 238 the author mention Bumiwaras sub-district and Way Lunik village that suddenly appear but never be discussed before and I guess sub-district and village are not equal to be compared (in term of geographical scale). Indeed, it confuses the readers. I suggest the author to give more clearly geographical orientation on this issue.
8. (Line 288 - 290) "The problem of....., which will focus on further research." is something that hasn't been conducted in this research. Thus, it is not necessary to be mentioned. In addition, a similar case also appears in line 290 - 293. The author mentioned about environmental problems..... and make a comparison with Jakarta (That is actually never analyzed in this manuscript). Moreover, is Bandar Lampung and Jakarta fair comparison (in terms of geographical scale,

population, sosio-economic activities, etc)?
9. The conclusion should wrap up the whole story and revisit the research purposes with findings. This aspect has not been found in this manuscript. Besides, the conclusion should avoid new things that were not analyzed in the discussion. (Line 313-314) The author mentions about land fertility, land subsidence, and flooding caused by groundwater exploitation. How can the author conclude without any analysis or literature review?
10. The manuscript uses understandable English, but proofreading is highly recommended. Some typos, wordiness, run on sentences (e.g. Line 121-123, Line 252-254), strange vocabularies or phrases (e.g. weak application (Line 49), strengthened by the difficulty of.... (Line 193), the use without holistic management (Line 268), rain catch engineering (Line 316)), and other grammatical errors are found in this manuscript.

Reviewer #2: This manuscript discussed the approach for phytoremediation of wastewater. It seems novel and interesting to the reader of this Journal (AER) and in the scope of this Journal. It does add something new in the field of environmental management/construction and so on. Therefore, the reviewer suggests to accept this manuscript with major revision.
1. The authors should provide more information about the "aquifer/holo-quaternary" is there any contained for industrial wastewater treatment.
2. Please add one topic of "Implications" for Indonesia's case with and try to link out.
3. Based on the outcome of the present study, the author(s) should recommend the extension of the present study as future scope of study. Especially in industrial section.
4. The motivation for the work is propose an integrated geoelectrical method which is profitable as well as environmentally sound, but the paper could be more convincing this is the case.
5. Some figures need to improve high solution.
6. Improve English

Reviewer's Responses to Questions

Is the subject of the article within the scope of the journal? (Yes/No)

Reviewer #1: Yes

Reviewer #2: Yes

Is this a new and original contribution? (Yes/No)

Reviewer #1: Yes

Reviewer #2: Yes

Does the title of this paper clearly and sufficiently reflect its contents? (Yes/No)

Reviewer #1: Yes

Reviewer #2: No

Are the keywords and abstracts/summary informative? (Yes/No)

Reviewer #1: No

Reviewer #2: Yes

Are the interpretation, organization and length satisfactory? (Yes/No)

Reviewer #1: No

Reviewer #2: No

Are the interpretations and conclusions sound and justified by the data? (Yes/No)

Reviewer #1: No

Reviewer #2: No

Are the references relevant and up-to-date? (Yes/No)

Reviewer #1: Yes

Reviewer #2: Yes

Is the quality of the English language satisfactory?

Reviewer #1: No

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Comments from the Editor and Reviewers :
Reviewer #1: The author has made a significant improvement to respond the review on the first round. However, some issues need more attention to make the manuscript ready to be published:
1. The author have replaced the Bumiwaras and Way Lunik with the terms showing the geographical orientation, which guide readers clearer about the case study area. However, the terms "Bumiwaras" and "Way Lunik" still appear on the highlight section. I suggest to synchronize them.
2. On the method section (line 125 - 165), the author widely explained about the definition of sampling techniques. Nevertheless, what are applied in the case study area has not been thoroughly explored. It's better to explain this issue extensively and arrange the paragraph a sequential style explaining what have been conducted. If it is possible, the paragraph can be equipped with the flowchart to help readers follow the flow of the study.
3. Result and Discussion section have been significantly improved.
4. On the conclusion section, some findings are presented to revisit the research objectives. However, it is better to add some consequences that can be occurred based on the current status. Therefore, some recommendations (either to prevent worse events or to formulate future research) can be given.

Reviewer #2: The revised version can now be considered for acceptance.

Reviewer's Responses to Questions

Is the subject of the article within the scope of the journal? (Yes/No)

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Reviewer #1: Yes

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Reviewer #2: Yes

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Reviewer #1: Yes

Reviewer #2: Yes

Are the interpretations and conclusions sound and justified by the data? (Yes/No)

Reviewer #1: Yes

Reviewer #2: Yes

Are the references relevant and up-to-date? (Yes/No)

Reviewer #1: Yes

Reviewer #2: Yes

Is the quality of the English language satisfactory?

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Reviewer #2: Yes

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Identification of Saline Water Intrusion Using Integrated Geoelectrical Method in the Coastal Aquifer of Holo-Quaternary Formation, Lampung Bay

Rustadi[1,2*], Agus Setiawan[2], I Gede Boy Darmawan[1], Suharno[1], and Nandi Haerudin[1]

[1]Department of Geophysical Engineering, University of Lampung, Bandar Lampung 35145, Indonesia

[2]Department of Environment Science, University of Lampung, Bandar Lampung 35145, Indonesia

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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 that have been 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 (< 24 m) but has experienced seawater intrusion with low resistivity values between 9 – 20 ohms m. The distribution of high salinity values up to 3100 ppm has reached >1 km from the coastline. Furthermore, ERT results reinforce this finding, which shows low resistivity values up to <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, intrusion, salinity

1. 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. Overexploitation of groundwater in coastal areas has caused environmental problems, including decreased groundwater quality due to seawater intrusion [3–6]. Groundwater contamination in coastal aquifers has become a global issue [7, 8], especially in low and middle-income countries [9, 10].

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. Indications of seawater intrusion have been identified on the coast of Bandar Lampung based on gravity and geoelectric data [11]. However, this result has not been confirmed by groundwater aquifer salinity data integrated with geoelectric data and drilling data. 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 [12–14]. This process requires expensive research costs and is currently a constraint. Therefore, based on the consideration of limited funding sources, this study emphasized measuring the salinity of groundwater in the aquifer as the initial concentration. Groundwater salinity testing is accompanied by the geoelectric method, which many researchers choose for mapping seawater intrusion [15–17].

The purpose of the study was to obtain areas that have been exposed to seawater intrusion and as a reference for more detailed research in intertemporal monitoring efforts. Geoelectric delineation is used 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 the distribution of groundwater aquifers resulting from geoelectric measurements. These results are expected to provide an overview of groundwater aquifer areas that have been affected by seawater intrusion and which have not been affected, especially in the Holo-Quaternary Formation. These results provide information on which areas need to be controlled for groundwater use or must be conserved and monitored continuously.

2. Materials and methods

2.1. Geological setting of the study area

Geohydrology on the coast of Bandar Lampung is influenced by the bedrock height of the Gunung Kasih Complex Formation (Pzgs) of the Pre-Tertiary Paleozoic age (Figure 1). Subduction processes in the past caused the accretion of bedrock in the east [18, 19], with medium-order metasediment constituents in the form of schist and gneiss. Another result is the formation of Mount Betung in the west with hilly morphology by the side with bedrock in the east. The volcanic pathway in the eastern part is interpreted to be the Tertiary age composed of andesite, rhyolite, and granodiorite rocks exposed. Meanwhile, Mount Betung is interpreted to be of Quaternary age with a basal-andesite composition. Various sedimentary rock formations began to form from the Tertiary to the Quaternary as bedrock cover [20].

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 [18, 21]. 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 (QTI) and the Young Volcano Formation (Qhv). 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 (QTI) 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 formation combines clastic material transportation on land to the coast and a marine sedimentation system. Geological order that lasts from Pre-Tertiary to Quaternary and the presence of hard rocks in the form of metasediment and igneous rocks [18]. This order strongly influences the alignment and geometry of the aquifer on the coast of Bandar Lampung.

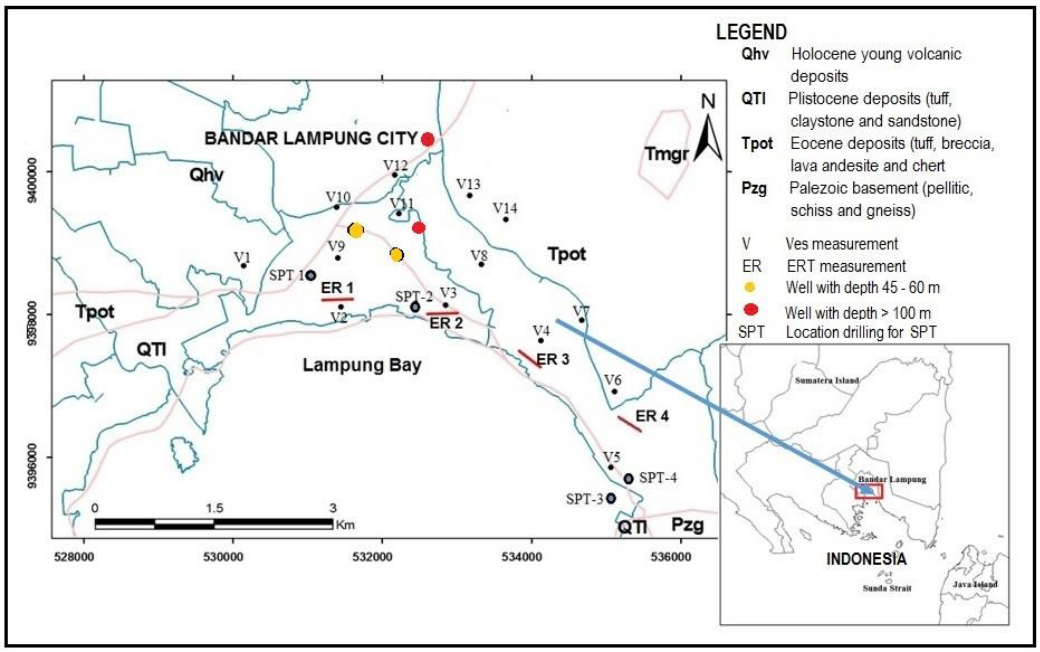

Figure 1 The geological map on the coast of Bandar Lampung [20]. The black dot represents the VES resistivity measurement data. In contrast, the red line represents the electrical resistivity tomography (ERT) measurement line.

2.2. Geoelectrical method and SPT

The use of 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 [22]. The resistivity of geological materials varies with the type of rock, the constituent minerals, and the fluids in the rock [23, 24]. 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 when compared to freshwater, so there will be differences in the resistivity values of rocks saturated by the two types of fluids. In addition, the use of Electrical Resistivity Tomography (ERT) in four paths aims to map the presence of aquifers and the effect of saline water filling the pores. The Vertical Electrical Sounding (VES) data distribution is used to get deeper information. Another objective is to find the linkage of coastal aquifers with parts farther inland. All geoelectric measurements were carried out using the ARES GFZ instrument.

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. The ERT profile is obtained by inversion of the measured data and converted into actual resistivity using the Res2DInv programs [25, 26]. In this study, ERT investigations were carried out in 4 coastal passes to map aquifers and the presence of seawater intrusion accurately. Measurements using the Wenner-Schlumberger array with an electrode distance of 6 m and a track length of 160 m.

VES measurements provide the advantage of examining resistivity changes vertically [27, 28]. 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 outside 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 [29]. Data 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. There are 6 VES points to examine aquifers on the coast, while 8 VES points are away from the coast (Figure 1). 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. To reduce these problems, soil Penetration Test (SPT) analysis was carried out at four drilling points located in coastal areas. This analysis serves as a binder of the resistivity value of the modeled layer with the actual subsurface constituent.

2.3. 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 dry season, namely in August 2021. The measurement results were mapped to show the distribution of groundwater salinity values, as shown in Figure 8.

3. Results and Discussion

The results of mapping the closest aquifer to the coast in detail based on electrical resistivity tomography (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 results are in line with the composition of the geological material found in Table 1. Prospects of groundwater are at a depth of 2 – 24 m. The aquifers are marine sedimentation composed of interbedding sand, silt, and clay with coral reefs. The four ERT profiles were unable to distinguish in detail the interbedding sand, silt, and clay with coral reef. These were read as one conductive layer with a resistivity value of 10 – 70 ohm m. However, the influence of saline water that fills the aquifer produces a resistivity value of 9 - 20 ohms m.

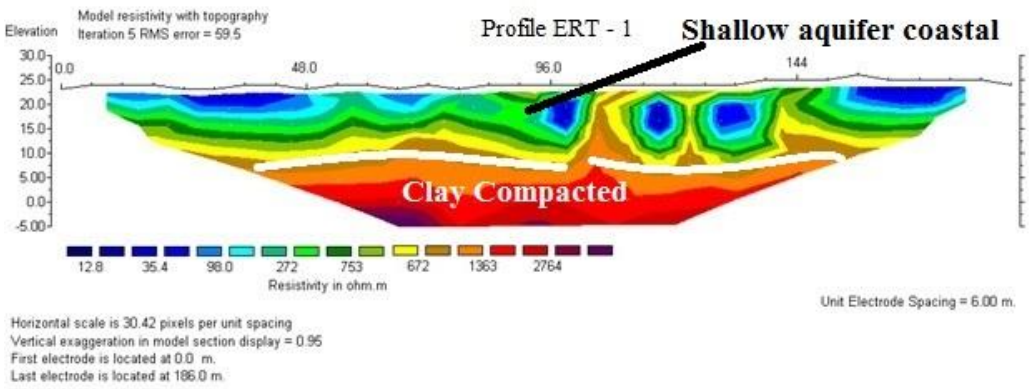

Figure 2 ERT profile on line 1

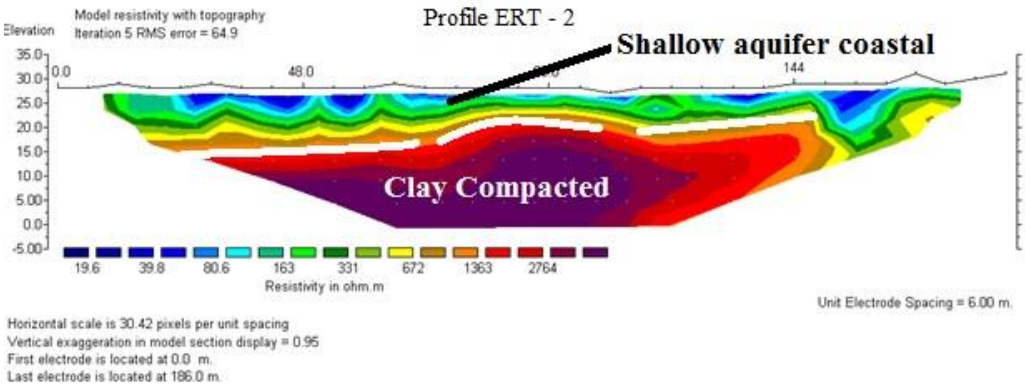

Figure 3 ERT profile on line 2

The 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, as shown in Figure 1. However, the drilling results indicated the presence of a claystone layer as a constituent of the Lampung Formation (QTI). The compressive test results on this claystone layer have an N-SPT value of 60, which is strengthened by the difficulty of the drilling process to penetrate this layer.

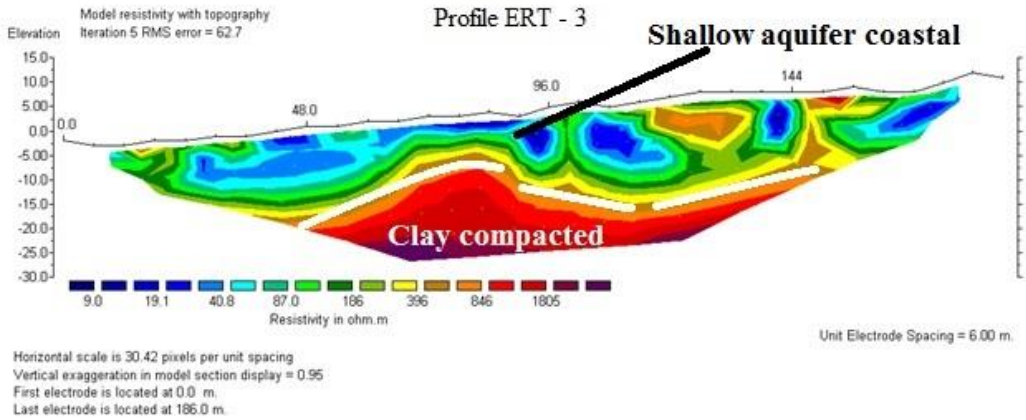

Figure 4 ERT profile on line 3

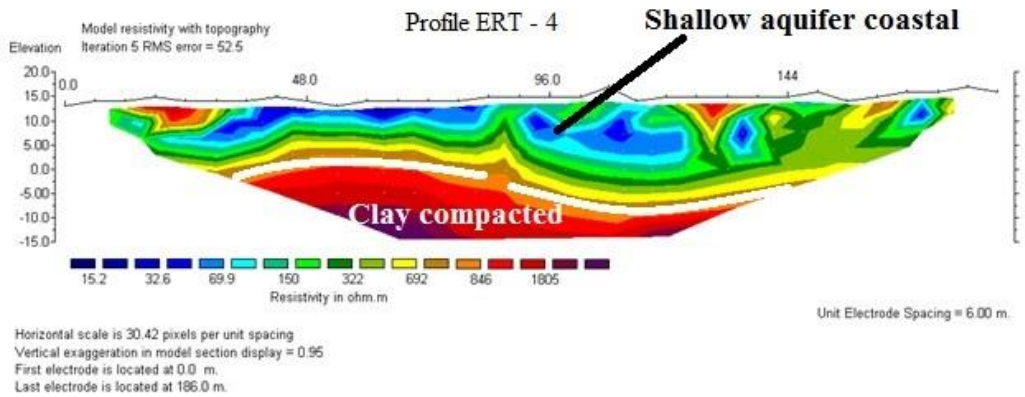

Figure 5 ERT profile on line 4

The interpretation of the ERT profile (Figures 2, 3, 4, and 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 formed during the Holocene period, which resulted in the Coastal Alluvial Formation [21]. The existence of coral reefs is a reinforcement for sedimentation on the continental shelf with a tropical climate on the coast of Lampung Bay. 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, SPT-2, and SPT-4) and 30 m in the sea (SPT-4).

Table 1. Subsurface geological materials on 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

The results of the ERT on the coast of Bandar Lampung are in line with the results of VES data modeling, which are shown in Figure 6. The presence of claystone indicates a thick basement which is the base for a thin layer of Alluvial Formation. In contrast, the VES model away from the coast (Figure 7) shows changes in the sedimentation environment, which are interpreted as

fluvial and flood plain environments. Aquifers away from the coast were found at varying depths, corroborated by the presence of wells that were 45 – 60 m deep and more than 100 m deep (Figure 1). 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 Tarahan Formation (Tpot) and Lampung Formation (QTI).

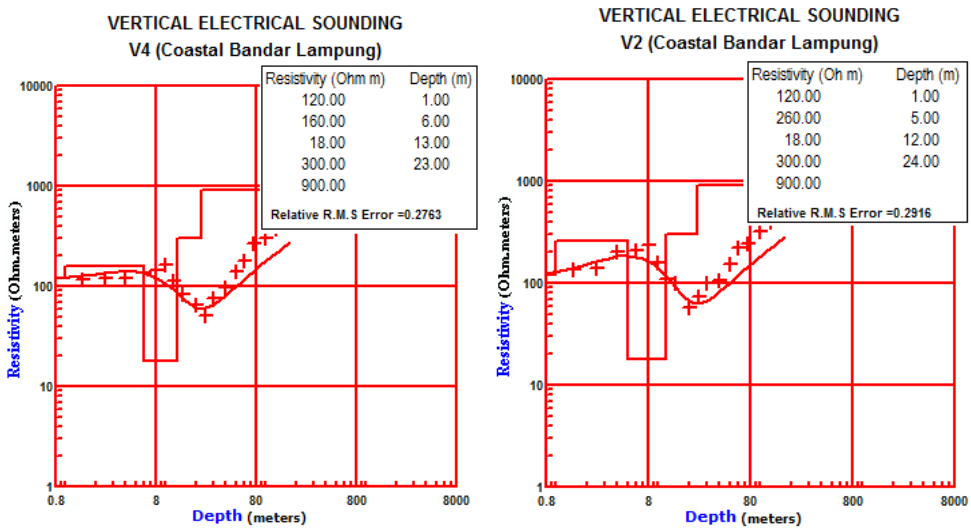

Figure 6 Interpretation of VES data at points V4 (left) and V2 (right) on the coast of Lampung Bay

A blue distribution as a conductive layer with a resistivity of fewer than 20 ohms m was found in shallow aquifers in all ERT profiles and VES models. The results obtained from the four ERT profiles are corroborated by the measured salinity of groundwater test results from the well (black dot) with the distribution shown in Figure 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 subdistricts, seawater intrusion is located at a radius of less than 1.0 km from the coastline.

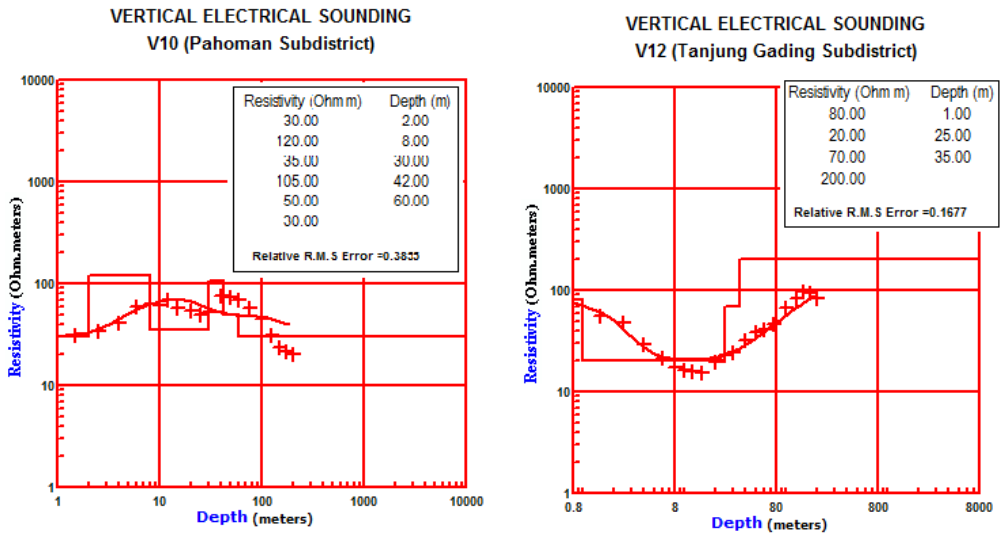

Figure 7 Interpretation of VES data at points V10 (left) and V12 (right) on the coast of Lampung Bay

Bumiwaras subdistrict is a zone with high contamination where the measured salinity value reaches 3100 ppm. Meanwhile, the Way Lunik village, with salinity in groundwater reaching 1500 ppm, takes second place. Bumiwaras sub-district and Way Lunik sub-district are centers of trade, various industries, and warehouses related to the presence of the port, causing an extensive use of groundwater. These results indicate that the high level of groundwater salinity in Lampung Bay has reached a radius of > 1 km from the shoreline. These conditions are mainly in the Bumiwaras sub-district and Way Lunik village. 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 < 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 of land subsidence in this area [30].

Furthermore, groundwater testing results from wells away from the shoreline managed to get a picture of the effect of seawater intrusion into more distant lands. The well distribution with the aquifer at a depth of 45 – 60 m (yellow point) and more than 100 m (red point) in Figure 1 is assumed to align with the coastal aquifer. The results of salinity testing on groundwater samples indicate that they have not been exposed to marine intrusion with a value less than 200 ppm. However, groundwater extraction by household needs, and the presence of hotels, can undoubtedly pose a threat to 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. For further research, it is necessary to study the infiltration capacity of the hills around the Tmgr Formation (Figure 8). It is also needed to study groundwater flow from the mainland to the coast, which can prevent seawater intrusion.

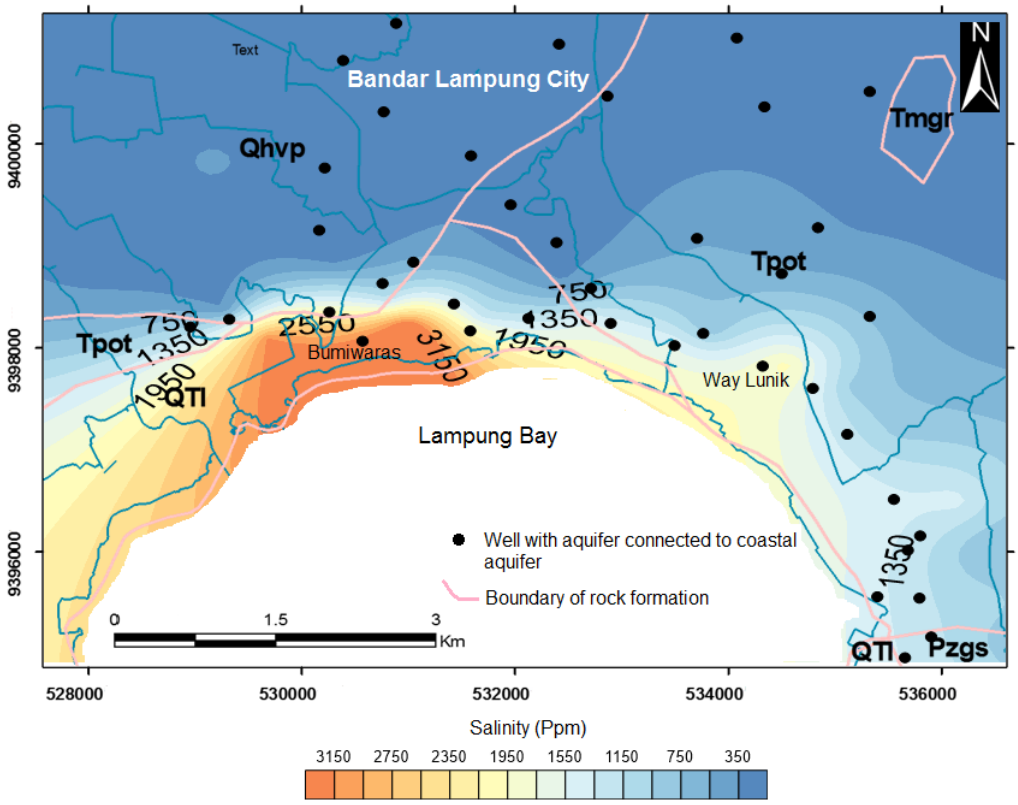

Figure 8 Map of saline groundwater on the coastal aquifer of Lampung Bay.

4. Conclusions

Using the geoelectrical resistivity method through a combination of ERT and VES and supported by lithological data from SPT measurements is very good in mapping the thickness of the coastal alluvial formation in Lampung Bay. The four ERT profiles accurately distinguish the basement between the marine sedimentary and resistive layers. The coastal aquifer in Lampung Bay is part of the Holo-Quaternary Formation layer, which is from a depth of 2 - 24 m in the form of interbedded sand, silt, and clay from marine sedimentation. Groundwater is only in shallow aquifers with a depth of fewer than 24 m but has experienced seawater intrusion, which causes low resistivity values between 9 – 20 ohms m. The main factor for taking large amounts of groundwater is indicated as the main factor causing seawater intrusion to have reached 1 - 1.5 km from the shoreline. The ERT results support this finding, especially in lines 1 and 3, which show low resistivity values up to <10-ohm m in the shallow aquifer zone. VES data reinforce this result (point V2 and point V4), which detects low resistivity values (18-ohm m) at a depth of 12 - 13 m.

The resistive layer composed of claystone is found as a constituent of the Lampung Formation and becomes a basement in Lampung Bay. Claystone is located at a depth of 24 – 80 m due to the interpretation of data from ERT, VES, and four drilled points for soil mechanics analysis. The presence of very thick claystone makes the prospect of groundwater on the coast of Lampung Bay in a shallow layer with a depth of less than 24 m. 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.

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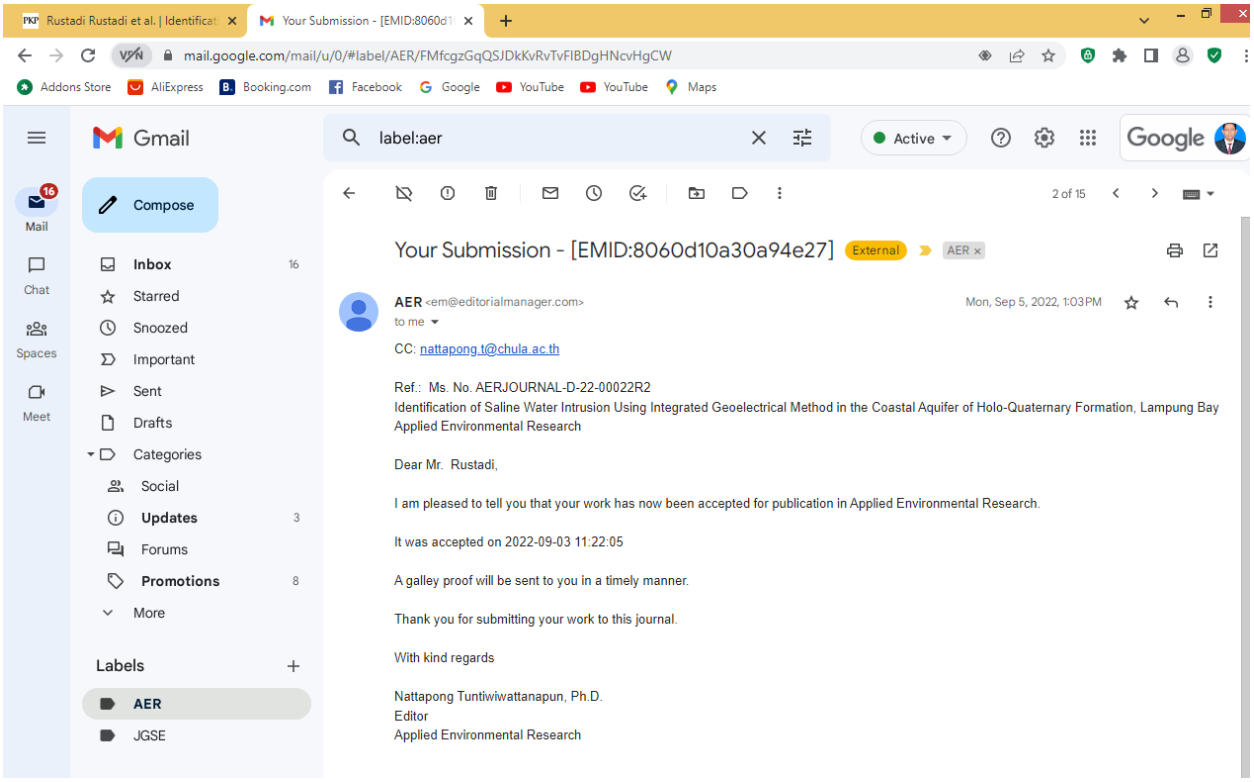

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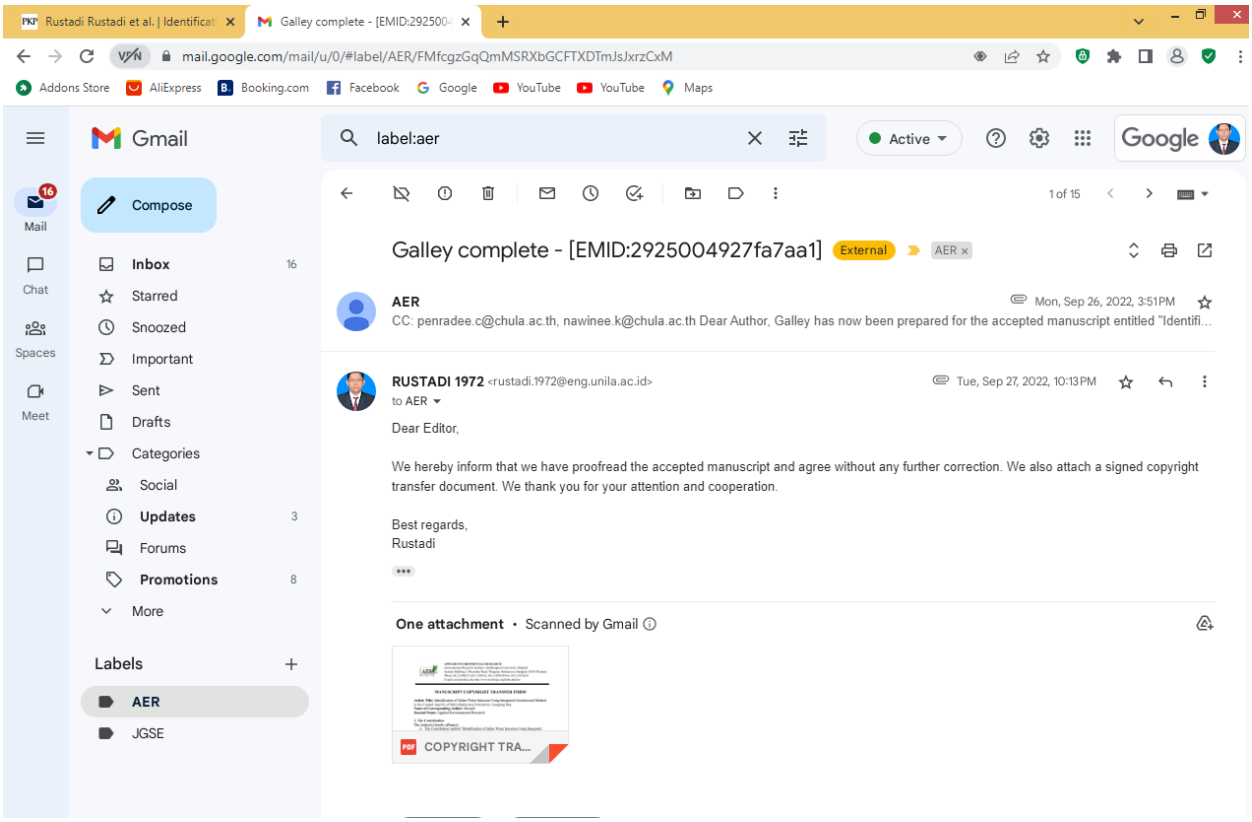

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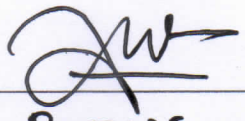
Signature 

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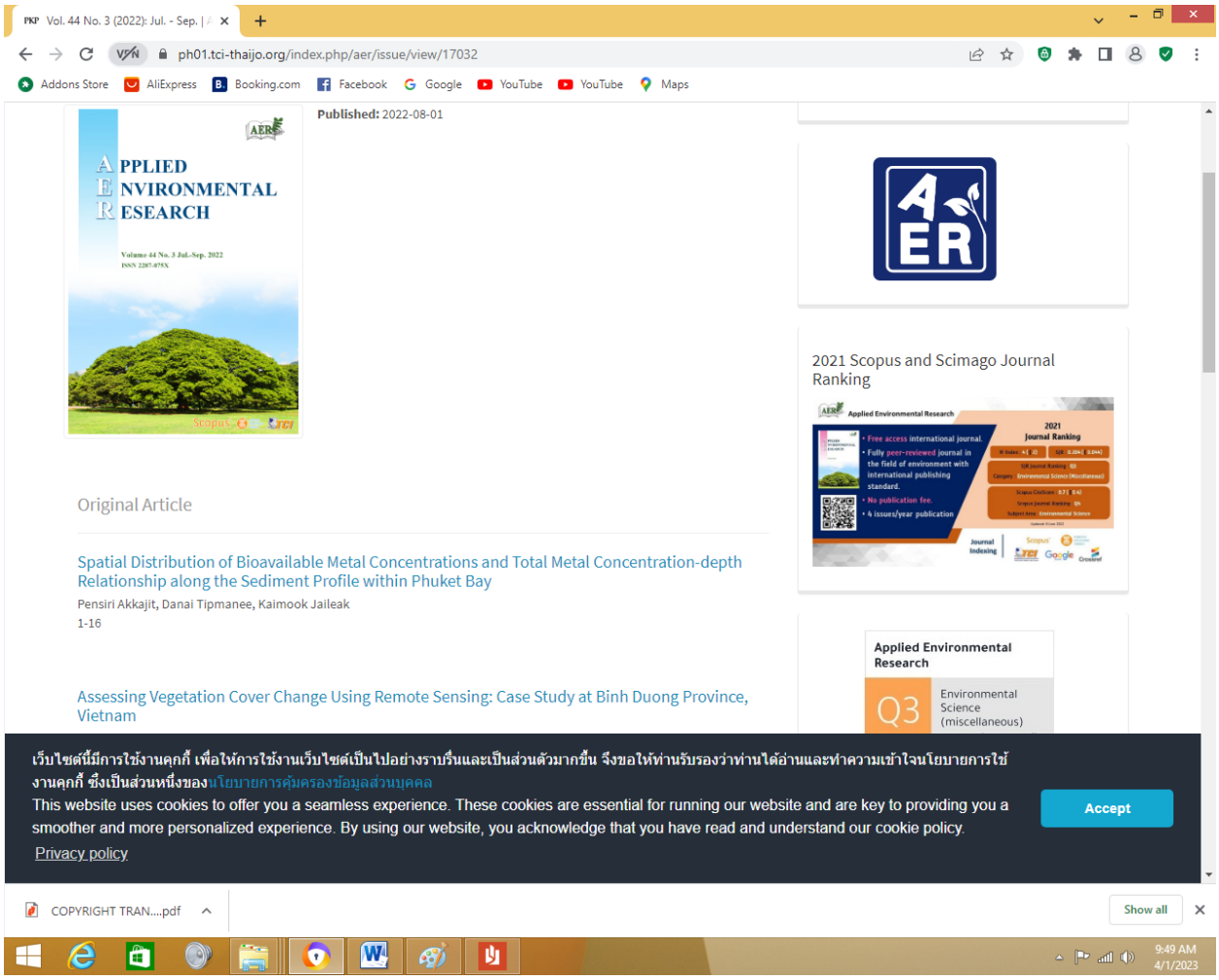

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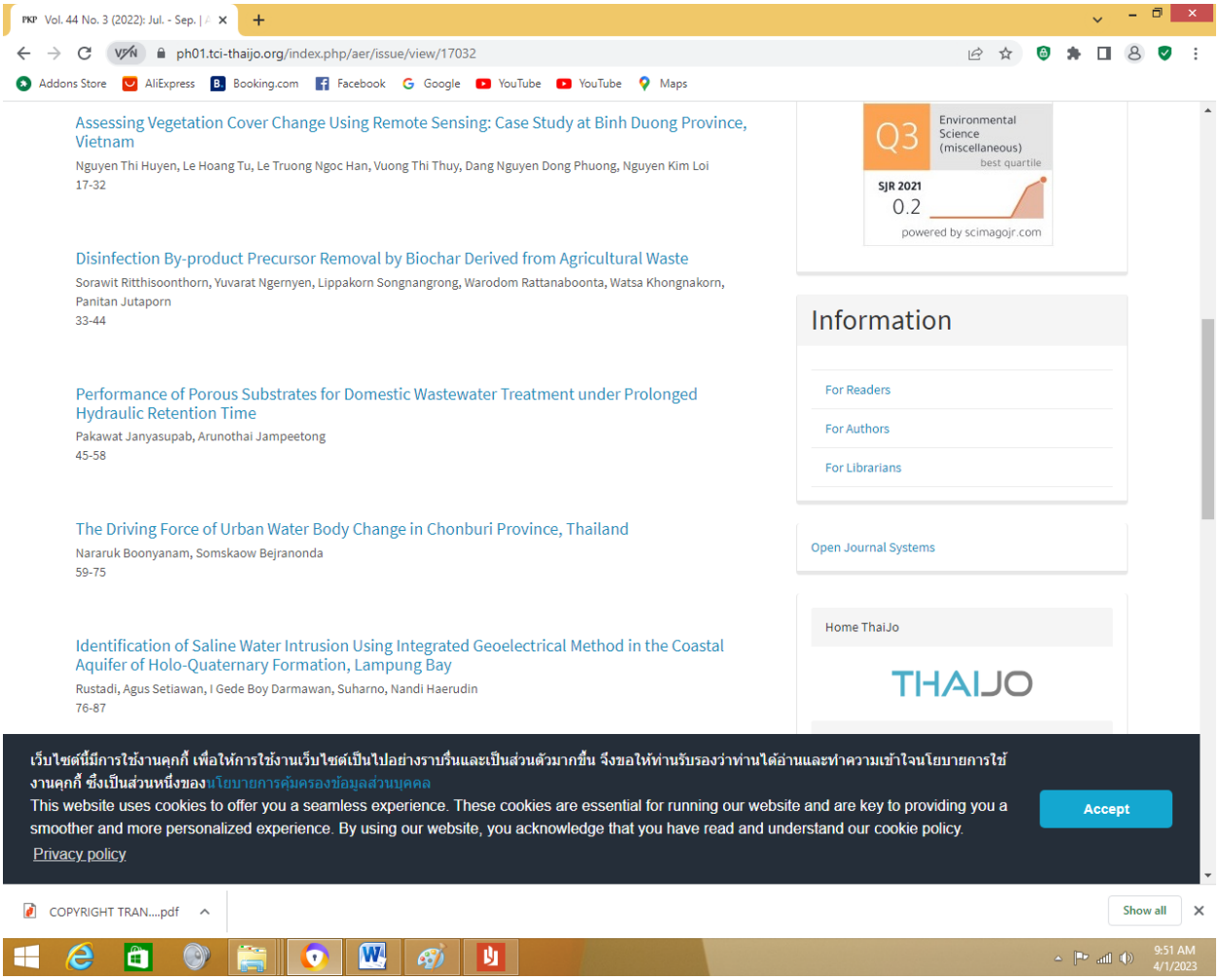

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