The Susceptibility of Seawater Intrusion Based on Resistivity at Banda Aceh City, Indonesia

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Abstract. The research has been conducted to analyze the susceptibility of seawater intrusion based on resistivity values in Banda Aceh city. In geomorphology, the mainland Banda Aceh extend to southeast (around Krueng Aceh River) in Aceh Besar district (western and eastern coastal areas) and Pidie district. This research aimed to determine the lithology of the susceptibility of seawater intrusion areas by using 2D resistivity Wenner-Schlumberger configuration. This method is also used to interpret the subsurface layer structure of the susceptibility of seawater intrusion in Banda Aceh with five measurement lines. The results in this research showed that the resistivity value of susceptibility of seawater intrusion in the research area is below 1.45 Ωm with intrusion depth varies from 0 to 34.1 meters. Based on the analysis and interpretation data, the subsurface structure of the region composed of clayey sand, sandy clay and clay that spreads laterally. The deployment of seawater intrusion occurs at the northern part of Banda Aceh directly related to the coastal area.

1. Introduction

Banda Aceh is the capital province of Aceh, Indonesia. Banda Aceh city is also one of the most seriously affected areas of the clean water crisis in Aceh Province. Increased physical development needs the aftermath of devastating earthquake and Tsunami (26 December 2004) in Banda Aceh city which has affected the pattern of pressure on the city's water resources. The clean water crisis occurring in the city was caused by saltwater breakthrough into freshwater aquifers and substantial groundwater degradation resulted in seawater intrusion. The inland migration of seawater in coastal aquifers, known as seawater intrusion (SWI), can be categorised as passive or active, depending on whether the hydraulic gradient slopes downwards towards the sea or the land, respectively [1]

In principle, groundwater in the land flows into the sea through aquifer media, while seawater also seeps into the land due to hydrostatic pressure of seawater [2]. There are two main causes of saltwater intrusion into freshwater aquifers that is due to the aquifer is directly related to freshwater and the substantial groundwater degradation resulted in the entry of seawater. On the other hand, the mixing of freshwater with salt water in a well can occur due to three conditions: (a) the bottom of the well lies beneath the border between saltwater and freshwater; (b) the water surface in the well during pumping.
becomes lower than sea level; (c) the balance of the border between saltwater and freshwater cannot be maintained [3]. The conditions had occurred in Banda Aceh city, geomorphologically the city has Alluvial deposit with an average elevation of 0-10 meter above sea level (asl), and the residential center in coastal areas parallel to coastal directions as well. It is estimated that the groundwater of Banda Aceh city is influenced by seawater activity, even found groundwater in several areas of the city that are brackish due to seawater intrusion [].

1.1. Geological Setting
Based on the geological map of Banda Aceh, the area contains alluvium with sediment deposits consisting of mud, sand and gravel. Around the research area, there are also Lam Teuba Volcanic Rock consisting of andesites, dacids, brecciated breccias, tuffs, agglomerates, and volcanic ash flows [2]. The age of rocks in Banda Aceh formed during the Holocene. Geomorphology of the research area was an alluvial coastal area with average elevation of 0-10 meter above sea level (asl) and slope of 0-10%.

1.2. Study Area
The location of research areas is in Banda Aceh city. Administratively, this area belongs to the Province of Aceh, Indonesia (Figure 1). Geographically, Banda Aceh is located in the northern part of Aceh Province which is located at coordinates 05°32'0"N - 95°17'0"E and 05°37'0"N - 95°23'0"E.

![Figure 1. Location map of the research area in Banda Aceh](image)

2. Methods
Data acquisition in this study used the resistivity method of Wenner-Schlumberger configuration in Banda Aceh city.

2.1. Field Measurement
The preliminary survey was conducted to determine the location of lines in the research area using GPS coordinates. The measurements were conducted along five lines of perpendicular orientation to
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the coastline. Resistivity measurements were performed using resistivity meter (ARES Instrument) with Wenner-Schlumberger configuration. The rule of electrode placements in the resistivity method called the electrode configuration. The configuration causes the geometry factor of each configuration to be different.

\[ K = \pi n(n+1)a \]  
(1)

Where \( n \) is a spacing factor and \( a \) is distance between electrodes.

2.2. Data Processing Technique
The data analysis involves the electric potential difference (\( \Delta V \)) and electric current (\( I \)) obtained from the field measurement used to calculate the value of the apparent resistivity (\( \rho_a \)). The apparent resistivity can be calculated based on the formula [6] [10]:

\[ \rho_a = K \frac{\Delta V}{I} \]  
(2)

Where \( K \) is a geometric factor, \( \Delta V \) the measured potential difference, and \( I \) the electric current. The magnitude of the apparent resistivity (\( \rho_a \)) was grouped according to the layer depths. Then the data inversion procedure used Res2dinv software that produces 2D images of subsurface conditions based on different resistivity values.

The resistivity data of the inversion have an error value called RMS (Root-Mean-Square) error expressed as a percentage. The RMS error represents the difference between measured apparent resistivity values and calculated apparent resistivity values. In principle, the resistivity model with smaller RMS error value has higher reliability [5]. The following Table 1 gives several values of the resistivity from earth materials:
Table 1. Resistivity of rocks [9][3]

| Materials                                                   | Resistivity (Ωm) |
|-------------------------------------------------------------|-------------------|
| Sand                                                        | 1 – 1.000         |
| Clay                                                        | 1 – 100           |
| Alluvium                                                    | 10 – 800          |
| Sand and gravel are submerged in fresh water                | 10 – 100          |
| Sand and gravel are submerged in seawater                   | 0,5 – 5           |
| Surface water (in rock)                                     | 0,1 – 3 x 10³     |
| Surface water (in sediman)                                 | 10 – 100          |
| Groundwater (in rock)                                      | 0,5 – 150         |
| Groundwater (in sedimen)                                   | 1 – 100           |
| Sea water                                                   | 0,2               |
| Salinity (3%)                                               | 0,15              |
| Salinity (20%)                                              | 0,05              |

3. Results and discussion
The analysis of seawater intrusions in Banda Aceh city was focused on 5 measurement lines. Each of them has length 165-224 meter and space between adjacent electrodes is set as 3-5 meter. The following Table 2 is the coordinates of measurement lines that was set on several locations in Banda Aceh city.

Table 2. The position and coordinate of lines

| No  | Lines | Area       | Length of lines (m) | Coordinates                                             | Elevation (m) |
|-----|-------|------------|---------------------|--------------------------------------------------------|---------------|
| 1   | LAM 1 | Lamnyong   | 0 - 224             | 5°34'15.10"N-95°21'32.80"E                             | 5             |
| 2   | LINGKE 3 | Lingke   | 0 - 165             | 5°35'19.7"N-95°20'25.1"E                               | 1             |
| 3   | TPA 4   | Kampong Jawa | 0 - 195         | 5°34'48.23"N-95°18'55.50"E                             | 3             |
| 4   | MR 5   | Meuraksa   | 0 - 195             | 5°33'13.28"N-95°17'41.64"E                             | 3             |
| 5   | JB 6   | Jaya Baru  | 0 - 195             | 5°32'17.66"N-95°17'32.67"E                             | 8             |

The following figure is the resistivity structure models of the research area in Banda Aceh city:

3.1. Measurement of line LAM 1
The result of data modeling with RMS error of 3.0% (Figure 3), LAM 1 was generally found three subsurface layers. The first layer has resistivity value ranged from 2.91 to 21.6 Ωm at depth of 0-8 meter which was topsoil layer and dominated by clayey sand. The second layer has resistivity value ranged from 0.64 to 2.91 Ωm at depth of 0-27 meter which was considered sandy clay and found brackish water. The third layer has resistivity value ranged from 2.91 to 9.5 Ωm at depth of 14-34.5 meter which was dominated by clayey sand.
Figure 3. 2D resistivity model of line LAM 1

The survey result at line LAM 1 directly obtained the lowest resistivity value was below 1.45 m which was the area affected by seawater intrusion. The seawater intrusion was located at length of line from 94 to 224 meter with depth of 0-21 meter.

3.2. Measurement of line LINGKE 3
The result of data modeling with RMS error of 3.2% (Figure 4), LINGKE 3 was generally found two subsurface layers. The first layer was soil layer which has resistivity value ranged from 1.48 to 3.45 m at depth of 0-3 meter. The second layer was topsoil layer which has resistivity value ranged from 0.47 to 1.48 m at depth of 0-29.9 meter. Generally, these layers were unconfined aquifer which were dominated by sandy clay and clay.

Figure 4. 2D resistivity model of line LINGKE 3

The survey result at line LINGKE 3 directly obtained the lowest resistivity value was below 1.45 m which was the area affected by seawater intrusion. The seawater intrusion was located at length of line from 0 to 165 meter with depth of 0-29.9 meter.

3.3. Measurement of line TPA 4
The result of data modeling with RMS error of 7.9% (Figure 5), TPA 4 was generally found three subsurface layers. The first layer has resistivity value ranged from 3.68 to 7.71 m at depth of 0-3
meter which was dominated by soil. The second layer has resistivity value ranged from 0.57 to 3.68 m at depth of 1.25-36.9 meter which was considered sandy clay and found brackish water. The third layer has resistivity value ranged from 3.68 to 7.71 m at depth of 13.4-36.9 meter which was dominated by clayey sand.

Figure 5. 2D resistivity model of line TPA 4

3.4. Measurement of line MR 5
The result of data modeling with RMS error of 15.0% (Figure 6), MR 5 was generally found three subsurface layers. The first layer has resistivity value ranged from 4.38 to 34.7 m at depth of 0-21.5 meter which was dominated by clayey sand. The second layer has resistivity value ranged from 0.1 to 4.38 m at depth of 6.76-31.3 meter which was considered sandy clay. The third layer has resistivity value ranged from 4.38 to 144 m at depth of 21.5-31.3 meter which was dominated by clayey sand.

Figure 6. 2D resistivity model of line MR 5

The survey result at line MR 5 directly obtained the lowest resistivity value was below 1.45 m which was the area affected by seawater intrusion. The seawater intrusion was located at length of line from 70 to 157 meter with depth of 6-31.3 meter.

3.5. Measurement of line JB 6
The result of data modeling with RMS error of 4.6% (Figure 7), JB 6 was generally found only one subsurface layer. This layer has resistivity value ranged from 0.77 to 3.32 m at depth of 0-36.9 meter which was dominated by sandy clay. The survey result at line JB 6 directly obtained the lowest
resistivity value was below 1.45 m which was the area affected by seawater intrusion. The seawater intrusion was located at length of line from 0 to 165 meter with depth of 0-17 meter.

Overall, the areas affected by seawater intrusion in Banda Aceh was dominated by sandy clay which has the lowest resistivity value (highest conductivity). The sand-textured soils will have a higher hydraulic conductivity compared with the fine-textured soil, since the soil with coarse textures (large sand particles) has macro pores and better-aerated pores [7]. The spreading of seawater intrusion in the research area of Banda Aceh started from LINGKE 3, TPA 4, MR 5, LAM 1 to JB 6. The highest measurements of seawater intrusion at varying depths of 0-33 meter were MR 5, TPA 4 and LINGKE 3, began to decrease at depth of 0-20 meter on JB 6 and LAM 1.

4. Conclusion
Based on the data interpretation, it can be concluded that the intrusion of seawater into the surface of Banda Aceh occurred through two ways: (1) The Seawater entered the surface through coastal areas. This was shown by the data obtained on the line MR 5, TPA 4, and LINGKE 3. (2) The seawater entered the soil through the outfall that was directly related to seawater, based on line JB 6 and LAM 1.

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