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IDENTIFICATION OF SEAWATER INTRUSION USING GEOPHYSICAL METHODS IN THE MANDALIKA, LOMBOK, INDONESIA

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ABSTRACT: Seawater intrusion is an event of infiltrating seawater into aquifers caused by constituent rocks that have high porosity, such as alluvial rocks. The Mandalika Lombok Indonesia is located on an alluvial plain that is very vulnerable to the occurrence of seawater intrusion. This study aims to identify areas that have been potentially affected by seawater in the Mandalika and surrounding areas. The method used is a geophysical method that combines geoelectric resistivity and gravity methods. For the data processing, we used several computer programs, namely Res2Dinv and Oasis Montaj for geoelectric data and Oasis Montaj and Grav3D for gravity data. The results of data processing are resistivity values of (0. 2 – 1022.9) Ωm, residual anomaly values of (-2.7 – 2. 3) mGal, and 3D model density values of (1 – 3) gr/cm^3. Based on a cross-section of 2D resistivity, the aquifer is at a depth of (2 – 12) meters. There are three main layers consisting of the upper layer (Alluvium) with resistivity (18 – <100) Ωm and density value of 1.2 gr /cm^3, the middle layer (clay sand as a shallow aquifer layer) with resistivity <18 Ωm and density value of 1.7 gr /cm^3, then the lower layer (basement) clay with resistivity (100 – 3000) Ωm and density value of 2.0 gr/cm^3. The potential intrusion areas are located in the western part, which includes the coast of Kuta Beach and Seger Beach, and the eastern part includes the coastal area of Tanjung Aan, the Gerupuk hamlet, and the Mertak village.

Keywords: Geoelectric resistivity method, Gravity method, The Mandalika, Seawater intrusion

1. INTRODUCTION

Tourism is one of the important economic sectors in Indonesia. A priority project to support the tourism sector is the development of a special economic zone called Kawasan Ekonomi Khusus (KEK) The Mandalika, located in Lombok Island, Indonesia. The Mandalika is a southern coastal area of Lombok Island that is directly opposite the Indian Ocean, and has a stretch of them in the form of coastal plains. This area is a subduction zone between the Indo-Australia plate that plunges down the Eurasian plate. The coastal plain of The Mandalika is composed of alluvial layers surrounded by hills of intrusion rocks that have high permeability [1, 2]. Seawater intrusion is a common problem in coastal areas and alluvial plains [3–5].

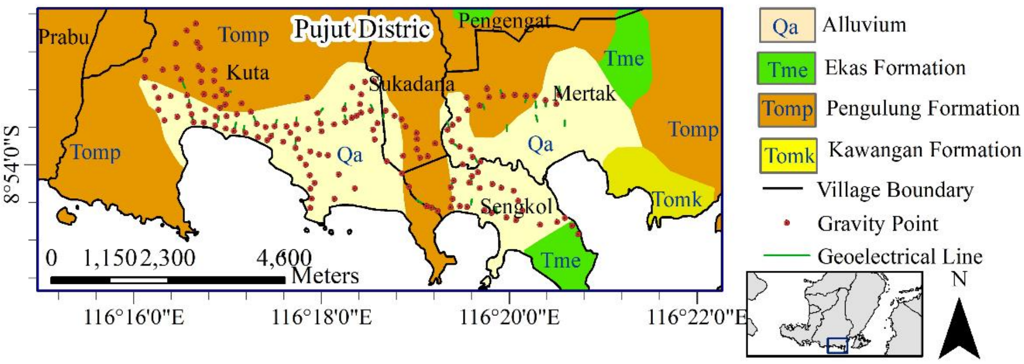


Fig. 1 Geological and location map with Survey Design (Modified from [2])

Based on the geological condition of Lombok, the stratigraphy of The Mandalika is composed of The Scavenger Formation *(Tomp)*, composed of tuff lava breccia with limestone lenses containing sulfide minerals and quartz veins. This formation is located to the north of The Mandalika and around the hills between the Mandalika circuit and the pond plains on the coast of Tanjung Aan to Merese hill. The Ekas *(Tme)* formation is composed of local limestone and crystalline, located on the peninsula of Gerupuk Village. The Scavenger *(Tomp)* and The Ekas *(Tme)* formations were formed from the early to late Miocene. Alluvium *(Qa)*, coastal deposits composed of crustal, gravel, sand, clay, peat, and coral fragments and scattered almost throughout the research area and was formed during the Holocene, which was the youngest rock at this location [2]. Thus, the compactness between the rocks is rather weak and allows for intrusion. The research site with the design of the research survey can be seen in Fig. 1.

Seawater intrusion is an event of seawater entering the body of freshwater. The intrusion can change the quality and quantity of water. Based on research that has been done, the intrusion of seawater is influenced physically by several factors, namely: density, resistivity, salinity, and a viscosity [6]. The estimation of seawater intrusion below the surface can be done by geophysical methods. In the event of an intrusion, this increases salinity which has an impact on increasing electrical conductance. One geophysical method that uses the properties of subsurface electricity is known as the geoelectric resistivity method [7]. The geoelectric resistivity method determines the resistance of rock units by injecting electric currents [8]. The geoelectrical method is a popular method for investigating aquifers, intrusion of seawater, and environmental issues [7 - 11].

In addition to the electrical properties, one of the physical properties of the material that can distinguish water and seawater is density. Geophysical methods that take advantage of density differences due to changes in subsurface mass are known as gravity-based methods. The gravity method is one of the passive geophysical methods that utilize variations in subsurface density. There is a difference between the density of seawater and freshwater, where the value of freshwater density is 1.000 gr/cm^3, and the density of seawater is 1.025 gr/cm^3 [7]. Therefore, naturally, the seawater density is under the freshwater density. The gravity-based method is used to review very small gravity differences/contrasts in density between high-porosity semi-arid sedimentary rocks such as aquifers and low-porous hard/compact bedrock [12]. Measurement of gravity is very good for the investigation of shallow aquifers and bedrock so that it can be used for the investigation of seawater intrusion in aquifers [8].

Geoelectric methods can provide information on the hydrology, changes, and distribution of resistivity of aquifers that have the potential to be intruded by seawater. Meanwhile, the gravity method can describe subsurface states based on bedrock configuration (basement) and the distribution of aquifer layers as well as water flows [13 – 15]. The combination of measurements of the two methods can be used to determine the distribution of aquifers as well as the possibility of seawater intrusion into the water. [8, 14].

The combination of the two methods is very good to be used to minimize ambiguity caused by the similarity of subsurface response forms by different structures and materials. This method can effectively interpret the approximate condition of the aquifer. Based on this, it is necessary to do subsurface identification using a combination of geoelectric resistivity and gravity methods to find out the areas that allow the intrusion of seawater around Mandalika Lombok, Indonesia.

2. RESEARCH SIGNIFICANCE

Land conversion for the construction of The alika might have several negative impacts on the environment. One of the inevitable effects is the availability of groundwater in the aquifer due to the massive groundwater exploitation. The void space in the aquifer will be easily filled by sea wateseawaterter intrusion will possibly change the water quality in the aquifer to become brackish and even salty, leaving the non-consumable water. Thus, it is necessary to identify the potential areas for seawater intrusion using geophysical methods as a preliminary study for disaster mitigation in The Mandalika area.

3. METHODS

The research was conducted in during the dry season of 2021 using a combination of geophysical methods, namely the geoelectric resistivity method and the gravity method. There are 38 resistivity geoelectric lines with a length of 120 meters each. In comparison, the measurement of gravity used 151 positions. The research site covers four villages, among others; Kuta Village, Sukadana Village, Sengkol Village, and Mertak Village are mostly included in The Mandalika area. The priority of data retrieval is spread throughout the area, which includes The Mandalika, which is focused on investigating shallow aquifers.

3.1 Geoelectric Resistivity

The study used the G-Sound Geocis 2x12 Volt geoelectric device. The dipole-dipole configuration is used because it is excellent for shallow aquifer investigation and lateral dispersion [3]. Measurements are made above ground level with the help of current injection through two current electrodes (C1 and C2), then measured the difference in potential at two potential electrodes (P1 and P2) [16]. The study used the distance between an electrode of 5m, n (1-10), and the position of the dipole-dipole configuration electrode can be seen in Fig. 2.

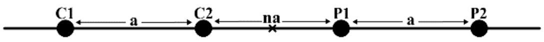


Fig. 2 Positions of electrodes for dipole-dipole configuration

Measurement output from the geoelectric resistivity method is in the form of pseudo-resistivity values. Pseudo-resistivity $\boldsymbol{\rho_a}$ is defined as:

$$\boldsymbol{\rho_a} = \frac{\Delta \boldsymbol{V}}{\boldsymbol{I}} \boldsymbol{K_d} \tag{1}$$

Where $\boldsymbol{\rho_a}$ is pseudo-resistivity (Ωm), I is current (ampere), $\Delta\boldsymbol{V}$ is the potential difference (volt), $\boldsymbol{K_d}$ is geometrical factor of configuration used.

Data processing uses Res2Dinv to transform pseudo-resistivity into a real resistivity by the inversion. The outcome of software processing is a 2D cross-section of actual data resistivity as a function of distance and depth displaying a color image that represents the resistivity value. Interpretation of an area intruded by seawater is shown in the form of a color image with a low resistivity value (≤ 10 Ωm) [11,14]. Furthermore, the Oasis Montaj is used to interpolate the actual resistivity data of 38 trajectories based on different depths, thus forming a lateral distribution map of resistance values for the entire research site. Interpretation is made by referring to the data in Table 1.

Table 1 Material Resistivity Value [16]

No	Material	Resistivity (Ωm)
	Sedimentary Rock	
1	Sandstone	$8 – 4x10^3$
2	Flakes	$20 – 2x10^3$
3	Limestone	$50 – 4x10^2$
	Soil and Water	
4	Clay	1 – 100
5	Alluvium	10 – 800
6	Groundwater	10 – 100

3.2 Gravity

The measurement of gravity is carried out by the Gravimeter Scintrex CG-5 Autograv tool with a reading resolution of 1 microGal. The looping method is used in field measurements consisting of 151 data points, and GPS assists in measuring positions. Then to validate the measurement data using satellite image data. Currently, there is a lot of gravity data from satellite images, including Topex [17] and GGMPlus (Global Gravity Model Plus) [18], but in this study, validation uses GGMPlus data. Validation of field measurement data with GGMPlus uses as many as 151 data points whose positions are adjusted so that it almost coincides with the coordinates of field data.

The theory underlying the gravity survey is Newton's law of attraction between two objects, where the magnitude of the gravitational force between two masses m_1 and m_2 separated by a distance of r is formulated as follows:

$$\vec{\boldsymbol{F}} = -\boldsymbol{G}\frac{\boldsymbol{m_1 m_2}}{\boldsymbol{r^2}}\hat{\boldsymbol{r}} \tag{2}$$

Where $\boldsymbol{F}$ is the force (N), $\boldsymbol{m_1}$ and is the mass of the first object and the mass of the second object (kg), r is the distance between two objects, $\hat{\boldsymbol{r}}$ is the unit vector from $\boldsymbol{m_1 to\, m_2}$, G is the universal gravitational constant (6.67 x 10-11 m^3 kg^{-1} s^{-2}) [16].

The results of the Gravity measurements are in the form of Bouguer's gravitational anomaly data. Bouguer gravity Anomaly (formulated $\Delta\boldsymbol{g_b}$) as:

$$\Delta\boldsymbol{g_b} = \boldsymbol{g_{obs}} - \boldsymbol{FA_{corr}} - \boldsymbol{B_{corr}} - \boldsymbol{T_{corr}} \tag{3}$$

Where $\boldsymbol{g_{obs}}$ is measurable data, $\boldsymbol{FA_{corr}}$ is correction-free air, $\boldsymbol{B_{corr}}$ is Bouguer correction, and $\boldsymbol{T_{corr}}$ is field correction. Gravity data obtained after this correction is known as the Bouguer anomaly. Bouguer anomalies are usually presented in the form of maps of contour lines or both, with anomalies describing subsurface sources causing differences in gravity values.

Data processing begins by creating Bouguer anomalous map using Oasis Montaj *software.* The complete Bouguer Anomaly map still consists of a regional anomaly caused by an internal object and a residual anomaly caused by a shallow object, so it needs to be separated. One method of separation is continuation upwards [19].

The next process is 3D inversion modeling with the help of Grav3D software. In this process using an inversion algorithm, which performs the creation of a subsurface model based on the data measured at the Earth's surface, the Earth is modeled using a large number of rectangular cells with constant density and the final density distribution is obtained with the model objective function adjusted to the data observed in the field. The application of synthetic and field data produces a density model that represents the actual structure [20]. Output assessment can ascertain, quantitatively, whether the geological conceptual model is consistent with the geophysical data measured at the surface. Otherwise, the geological conceptual model and/or geophysical interpretation will need to be changed to achieve a better fit.

Because the research target is shallow depth, for further processing residual anomalies are used. The Oasis Montaj and Grav3D were used for obtaining 2D models and 3D models with the density of rock and aquifers based on gravity anomalies, respectively. Modeling uses a reference density of 1.9 gr/cm^3, where the value is the average density value of the research site (Alluvial plain) based on the Parasnis method. Interpretation of density values is made by referring to Table 2.

Table 2. Rock Density Value [16]

Rock type	Density range (gr/cm^3)	Average (gr/cm^3)
Sedimentary rocks		
Overburden	-	1,92
Soil	1.20-2.24	1.92
Clay	1.63-2.60	2.21
Gravel	1.70-2.40	2
Sand	1.70-2.30	2
Sandstone	1.61-2.76	2.35
Shale	1.77-3.20	2.4
Limestone	1.93-2.90	2.55
Dolomite	2.28-2.90	2.7

3.3 Combination of Geoelectric Method with Gravity Method

A combination of geoelectric resistivity and gravity methods was done to see the similarity of coating between 2D cross-sections of geoelectric resistivity trajectories resulting from inversion using Res2Dinv software with a 2D cross-section of gravity using Oasis Montaj. The use of this combination of methods is also to see the similar distribution of rock resistance values at a certain depth using the Oasis Montaj with the distribution of rock density values using Grav3D software. Based on the results of both methods, interpretation will be carried out to determine the areas indicated to experience seawater intrusion in The Mandalika area and surrounding areas.

4. RESULTS AND DISCUSSION

4.1 Geoelectric Resistivity

The 2D cross-section of the pseudo-section of Res2Dinv shows the length of the line and the depth of strata and rock structures (Fig. 3). The distribution of geoelectric measurement trajectories can be seen in Fig. 1. The measurement line amounts to 38 measurement lines, but the cross-sectional interpretation is carried out on several cross-sections that can represent the cross-section of the line around it. Some of the cross-sections selected include cross-sections of lines 2 and 3 representing the western region around Kuta Beach, cross-sections of lines 17 and 18 representing the measurement area next to the North of The Mandalika Circuit, cross-sections 23 and 25 representing the measurement area in the South around Tanjung Aan Beach and cross-sections of lines 36 dan 37 representing the eastern region, namely in Mertak.

The cross-sectional interpretation of the western region is represented by Line 2, shown in Fig. 3(a). Line 2 has a range of resistivity values ranging (1.2 – 1022.9) Ωm. Based on the cross-sectional resistivity value concerning Table 1, there are three main layers in the location which are composed of Alluvium and slightly clay with resistivity (17 – 200) Ωm. The second layer is sandstone with resistivity <17 Ωm, this layer has a sharp resistivity contrast with the layer around which is thought to have a lot of water content. The bottom layer is clay and limestone as a shallow aquifer basement with resistivity (156 – 1022.9) Ωm. Some points on this layer are detected intruding by seawater because it has a resistivity of <10 Ωm.

Line 2 has a resistivity-dominated aquifer. According to the positions of the Line, it is closer to the shoreline and shows that there has been a significant seawater intrusion. The height of the water level on both cross-sections is about (2.1 – 4) meters. This is in accordance with the height of the water level based on direct observations on the ground at the nearest citizen well with both lines, which is 2.1 meters.

The cross-sectional interpretation of the northern region of the circuit is represented by Line 17, which can be seen in Fig. 3(b). Line 17 has a range of resistivity values ranging (0.8 – 112.7) Ωm. Based on the cross-sectional resistivity value, there are three main layers referring to Table 1, and it is composed of the top most layer in the form of Alluvium with resistivity (5 – 54.7) Ωm. The middle layer is in the form of sandstone with resistivity <7 Ωm, and the bottom layer is interpreted as clay as a shallow aquifer basement with resistivity (17.2 – 112.7) Ωm. This location detected that there is an intrusion of seawater because it has a resistivity <10 Ωm.

The height of the water level in the cross-section is about (3.5 – 4) meters. This is in line with the height of the water level based on direct observations on the ground at the well of the residents, namely at a depth of 4 meters. Based on the function of distance to the shoreline, Line 17 is very far from the beach but has a resistivity value that indicates the aquifer has been intruded by seawater.

Cross-sectional interpretations of the coastal region of Tanjung Aan are represented by Line 23 (Fig. 3(c)). It has a range of resistivity values ranging (0.5 – 345.1) Ωm. Based on the 2D cross-sectional resistivity value in Table 1, there are three main layers. The upper layer is composed of Alluvium with resistivity (6 – 132) Ωm. The middle layer is in the form of sandstone and gravel with resistivity <10 Ωm. The lowest layer is clay as a shallow aquifer basement with resistivity >61 Ωm. The water level around the cross-section is 2 – 4.5 meters.

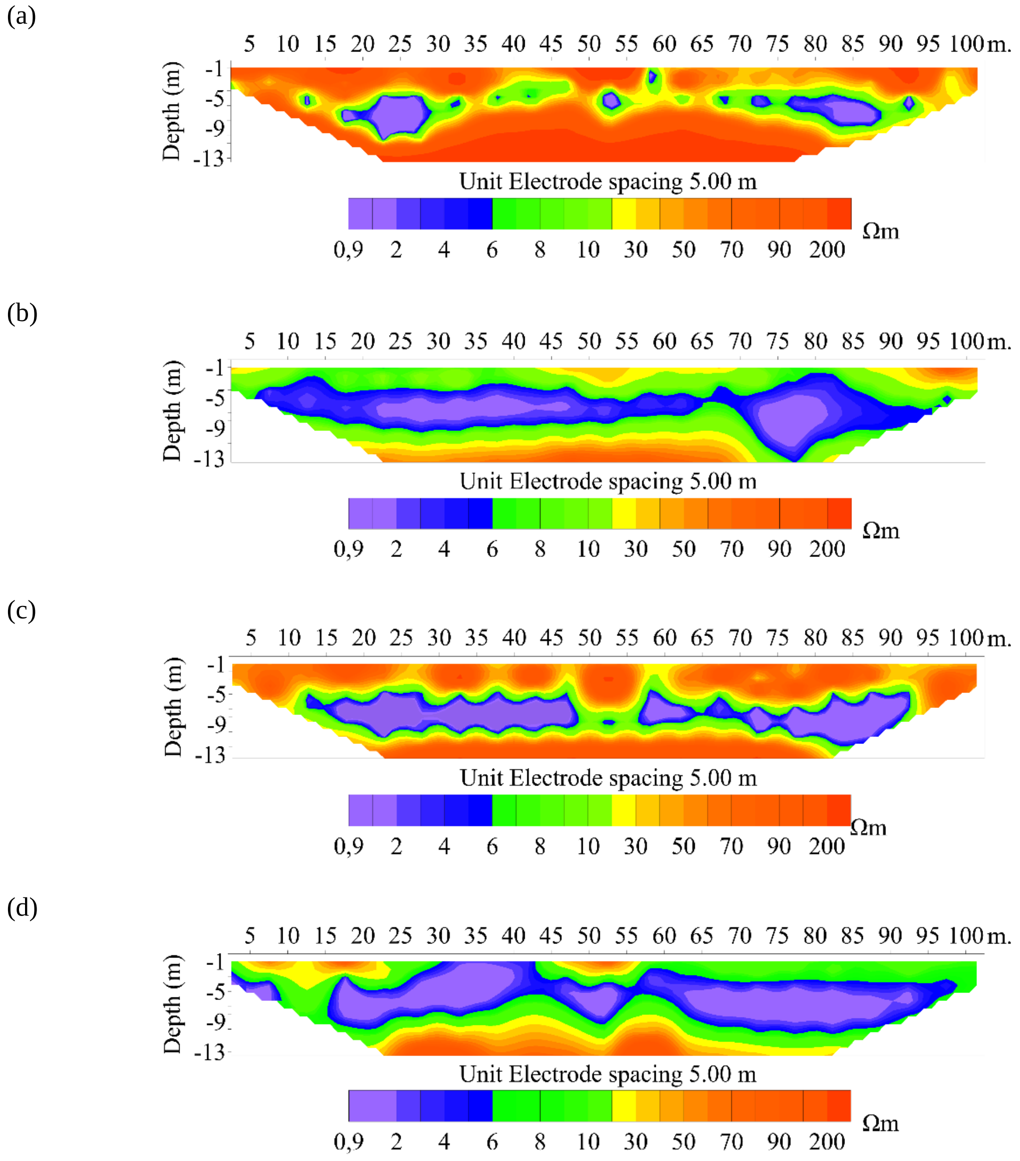


Fig. 3 The 2D Cross-section of (a) Line 2, (b) Line 17, (c) Line 23, and (d) Line 36

Line 23 shows the resistivity values of the upper layer and the low dominant bottom layer. This illustrates the location of this rock is quite compact, and the aquifer layer (sandstone and gravel) has a very low resistivity value which indicates very saturated with water and intruded by seawater.

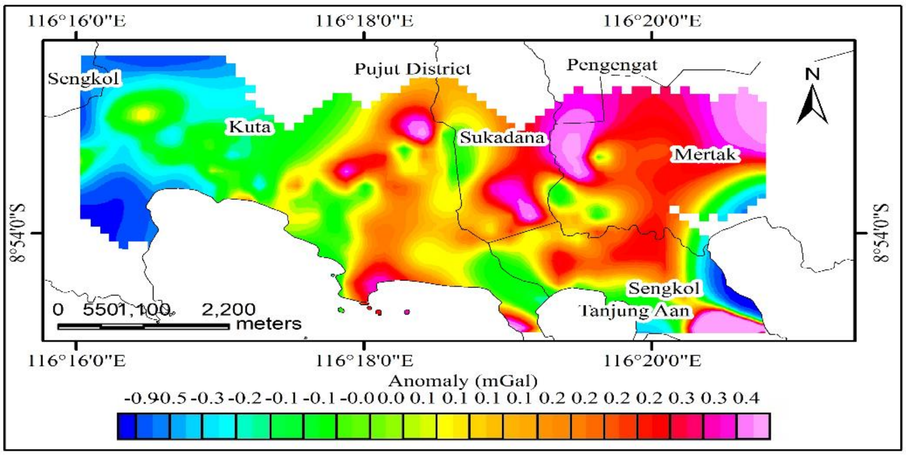
Fig. 3(d) is a cross-section of the eastern region, represented by Line 36. It has a range of resistivity values ranging (0.4 – 222.6) Ωm. Based on the 2D cross-sectional resistivity value of the line, there are three main layers. The first layer is Alluvium with resistivity in the value range (0.4 – 100) Ωm. The second layer in the form of sandstone is an aquifer with resistivity <5 Ωm, and the lowest layer in the form of clay which is a shallow basement aquifer with resistivity (20 –222.6) Ωm. This location has a very small resistivity value compared to other cross-sections of the line. The water level on cross-sections ranges from (2 - 3.5) meters.

Based on the cross-section of resistivity, Fig. 3 shows that the layer model on the entire research Line is quite uniform, consisting of three main layers, and the height of the water level in the research area ranges from 2 meters to 4.5 meters. This is in accordance with water level data based on direct observations in the field at the wells of residents. Thus, it can be interpreted as the most intrusion location based on a very small resistivity value, namely in the eastern area (Mertak village area). As for other locations intrusion, but not as wide as in the eastern region (Mertak village).

4.2 Gravity

The distribution of residual anomalies between GGMPlus data and field data in Fig. 4 shows the equality and similarity of anomalous distribution, so it can be concluded that field measurement data is good enough for further processing. Based on the distribution of residual anomalies, both maps show some regions have anomalies that tend to be the same, but the range of anomalous values in GGMPlus data ranges from (-1.5 – 0.5) mGal. Meanwhile, gravity measurements of 151 field data points showed anomalous residual values ranging from (-2.7 – 2.3) mGal.

(a)



(b)

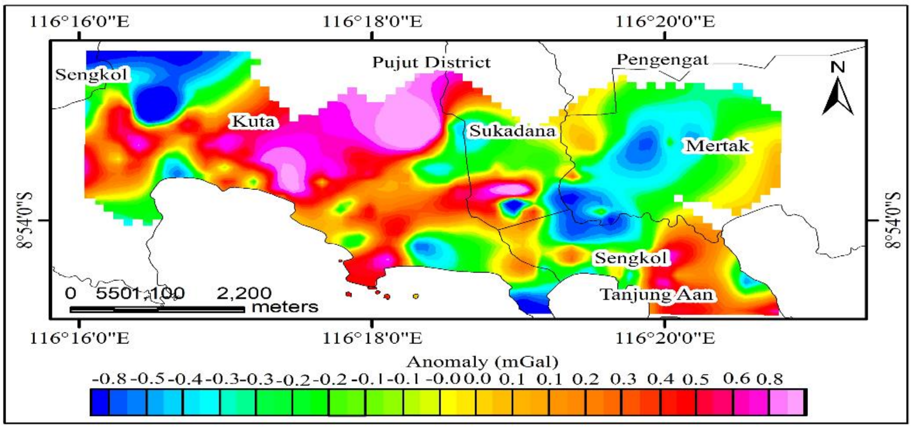


Fig. 4 (a) GGMPlus Residual Data Anomaly Map, (b) Field Data Residual Anomaly Map

Residual anomaly maps show the distribution of rocks relatively close to surfaces that are more affected by variations in the lateral density of bedrock [20]. Low anomalies (blue) range (-2.7 – -0.3) mGal is indicated as the location of aquifers, moderate anomalies (green to yellow) range (-0.2 – 0) mGal is indicated as semi-arid aquifers, and high anomalies (red to purple) range (0.1 – 2.3) mGal interpreted as locations with dominant hard rocks.

Based on residual anomaly maps, high anomalies are spread across the east coast of Kuta to the central area, slightly in the Seger area. In addition, high anomalies were seen in the eastern region on the Gerupuk peninsula towards the

Mertak coast to the eastern end of the research area. Moderate and low anomalies are seen in the western region, including the north of Kuta Village, the area at Northern Circuit, which is a rice field than in the area of Tanjung Aan coastal circuit and pond area to the hills of Nandus hamlet and Serenang hamlet

Based on local geological maps, Bouguer's relatively high anomalous value is a representation of lava, breccia, and tuff rocks that are scavenger or massive. Moderate to low anomalies are representations of sandstone, clay, and limestone, as well as potential alluvial plains as locations for seawater intrusion

4.3 Correlation of Geoelectric and Gravity Data

The results of resistivity and density data are combined with being interpreted together with local geological data based on geological maps of Lombok sheets as well as with data on resistivity and rock density based on Table 1 and Table 2. Thus, the combination of these two methods can be relied upon for the proper interpretation of subsurface structures [22].

Furthermore, interpretation is made by creating a density model that refers to the cross-section of resistivity. Based on Fig. 5, the entire layer has a layer with a uniform resistivity and density value with three main layers.

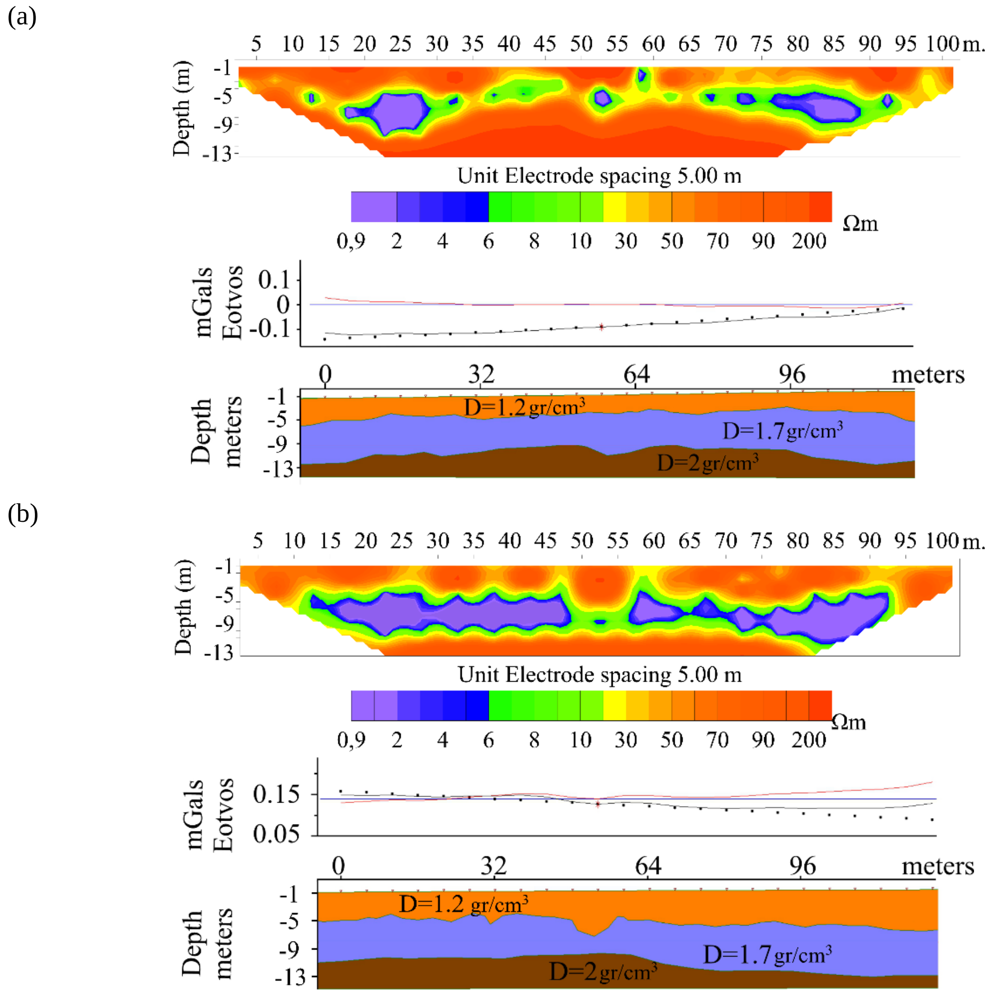


Fig. 5 Comparison of Geoelectric Value Cross-Section with Density Value Cross-section of (a) Line 2, (b) Line 23

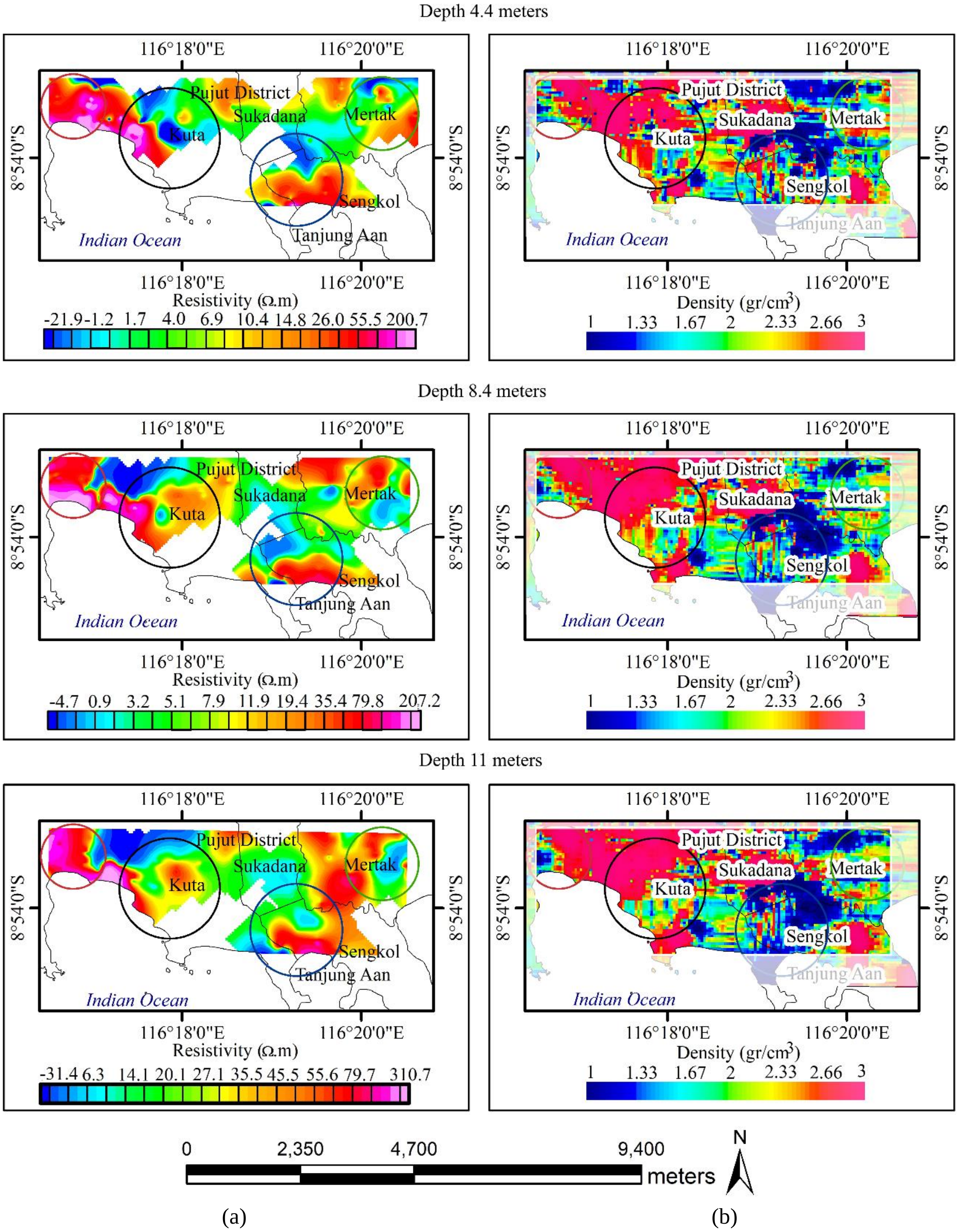


Fig. 6 (a) Distribution Map of Resistivity Value, (b) Distribution Map of Density Value

Furthermore, the distribution map of the value of resistivity and density of rocks in Fig. 6 shows the distribution of aquifers and the location of intrusions based on depth. Some of the depths used include 4.4 meters, 8.4 meters, and 11 meters. The depth of 4.4 meters is taken because the depth is closest to the location of the tide. For 8.4 meters, it is because that depth is in the middle of the aquifer layer. Also, the 11 meters has a similar method as it was located close to the aquifer basement.

Based on the distribution of resistivity and density values (Fig. 6), there is a similar distribution of aquifer areas that are suspected to be intruded by seawater. Intrusion aquifers have less resistance and density value than areas without intrusion. A low resistivity value indicates the effect of saltwater mixtures on water [14]. The resistivity value of the saline water is <10 Ωm with a density value of about 1.7 gr/m^3. The nature of aquifer rocks has a low resistivity value because it has a high porosity, so the void of the groundwater will be filled by seawater. Generally, rocks with high porosity also have low-density values and are geologically eroded by sandstone and gravel.

Table 3. Resistivity and Layer Density Values

Layer	Resistivity (Ωm)	Density (gr/m^3)	Rock
1	18 - <100	1.2	Alluvium
2	0.2 – <18	1.7	Sand, Gravel, Limestone
3	100 – 3000	2.0	Clay

The location of the spread of aquifers suspected to be intruded, among others: The western Region (the shore of Kuta Beach), led by red circles, the greater the depth, the greater and expand the value of resistivity. Also the density value, based on the density value of this region is very potential to be the location of intrusion. The western region around the circuit (dark circle) is located at a depth of 11 meters with a low resistivity value and is on the edge of the beach with its northern region far from the beach is a rice field saturated with water.

Then the Eastern South (blue circle) covering the coast of Tanjung Aan has a low resistivity value that is quite wide compared to other places, especially at a depth of 8.4 meters. This is because, indeed, in that region, the constituent rocks are in the form of dry sand that is very loose and in the form of pond areas that are indeed submerged by seawater. So, it's no surprise the region has a very low resistivity value, especially at depths of 4.4 meters and 8.4 meters. Meanwhile, a depth of 11 has a resistivity value that is already high and indicates at that depth is already clay rock. Based on its density value, this region has a low dominant rock density value compared to other locations.

The Northern Eastern Region (green circle) covering Mertak village has an area with low resistivity that is wide enough to signify this location is also intrusion at a depth of 8.4 meters and 11 meters. The eastern region does have a low-density value that is quite wide and geologically composed of sandstone and gravel. In addition, this location has a low and flat average ground surface, so it has the potential to be intruded by seawater.

The correlation of resistivity value to density value is also tied to the proportion of its rock material [23]. For example, the coast of Tanjung Aan has a high resistivity value but low density. This is possible because the building material of the area is dry sand with high porosity, thus making the resistivity value large and the density small. Then in the pond area around Tanjung Aan, the rocks are in the form of sand but have a low resistivity value because the location tends to be saturated with water, especially filled with seawater. The presence of seawater in low-porous rocks causes them to experience a greater decrease in resistivity [23].

5. CONCLUSION

The aquifer at The Mandalika is at a depth of (2 –12) meters with a water level ranging (2.1 – 4.5) meters. There are three main layers, the upper layer in the form of Alluvium with resistivity (18 – <100) Ωm and a density value of 1.2 gr/cm ^{3}, the middle layer in the form of sandstone as a shallow aquifer layer with resistivity <18 Ωm and a density value of 1.7 gr/cm^3, and the lower layer of the basement clay with resistivity (100 – 3000) Ωm and a density value of 2.0 gr/cm^3. Then, the potential intrusion area is located in the western part of Kuta and Seger beach. The Eastern part covers the coastal areas of Tanjung Aan, the Gerupuk hamlet, and the Mertak village.

6. ACKNOWLEDGMENTS

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