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RESEARCH ARTICLE

Investigation of Groundwater Quality using Vertical Electrical Sounding and Dar Zarrouk Parameter in Leihitu, Maluku, Indonesia

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Abstract

The goal of this research is to obtain information related to aquifer quality, including aquifer protection capacity, transmissivity, and aquifer thickness based on vertical electrical sounding (VES) data and Dar-Zarrouk parameter analysis. The research area is located in Leihitu District, Ambon with 8 measurement points. The Leihitu region is included in the geological map of the Ambon sheet, Maluku, which consists of Late Pliocene - Holocene lithology, specifically Ambon volcanic rocks, reef limestones, and alluvial deposits. The rock resistivity measurements and layer thickness information were obtained using the VES method and analyzed with IP2WIN software. Based on VES data, aquifer properties were identified using Dar-Zarrouk parameters. That parameter consisted of longitudinal conductance, transfer resistance, longitudinal resistivity, and transfer resistivity. Longitudinal unit conductance is applied to evaluate the protective capacity class of the aquifer, the transfer resistance is beneficial for analyzing rock type and aquifer transmissivity. Based on the Dark-Zarrouk parameters, the longitudinal conductance (S) ranged from 0.0278 to 5.1213 mho and was classified as moderate to good protective capacity. The high S value results from a thick layer of clay at the observation point. This area also has a high enough transverse resistance (T) and then if related to aquifer transmissivity, this area is classified as a good transmissivity aquifer, especially at VES 2, VES 5, VES 6, VES 7, and VES 8. If correlated to rock formations, areas with limestone and volcanic rocks have better transmissivity than areas with alluvial deposits.

Keywords: Dar Zarrouk Parameter, Groundwater, Leihitu District, Resistivity, VES

1. Introduction

Indonesia is one of archipelagic country, where most of the people live along the coastal area with the source of drinking water coming from coastal aquifers (Djunarsjah & Putra, 2021). The need for fresh water in coastal areas continues to increase as the population increases (Miharja & Arsallia, 2017). Apart from domestic needs, coastal aquifers are also exploited for agricultural and industrial purposes (Mukate et al., 2019). Continuous and unplanned extraction can cause aquifer quality problems such as seawater intrusion (Moore & Joye, 2021). Changes in climate, topography, and rising sea levels also affect the rate of seawater intrusion into aquifers (Abd-Elhamid et al., 2016, 2019). The mixing of saltwater with fresh water, even in small amounts, makes groundwater unsuitable for domestic, agricultural, and industrial uses (Kazakis et al., 2016). Prevention of coastal aquifer salination can be done by making an appropriate aquifer pumping management plan. Implementation of a management plan requires an understanding of aquifer conditions and brine distribution. Measurement of salinity distribution and hydrological modeling are the most efficient methods for studying seawater intrusion for the sustainable development of groundwater resources in an area (Shinawi et al., 2022).

Traditionally, the fresh-saline interface of an aquifer has generally been described using the boreholes method including laboratory water tests. However, this method has drawbacks such as expensive, complicated, intrusive, and time-consuming handling costs (Gao et al., 2018). Non-intrusive methods that can be used to describe subsurface conditions are 1D vertical electrical sounding (VES) and 2D electrical resistivity tomography (ERT). The VES and ERT methods are methods that are widely used in mapping aquifer zones, groundwater conditions, and monitoring seawater intrusion (Bahri et al., 2022; Hasan et al., 2020). ERT can provide a two-dimensional description of subsurface conditions and has sensitivity to spatial lithology variations (Holmes et al., 2022; Porras et al., 2022). The VES method can provide information on the groundwater resistivity distribution in the vertical direction. This method has been used to study seawater intrusion in coastal areas of Saudi Arabia (Alhumimidi, 2020), coastal areas of Nigeria (Ekwok et al., 2022; Folorunso, 2021; Obakhume, 2022), and deltaic areas in Spain's Velez-Malaga (Martínez et al., 2009). In general, geoelectrical methods are combined with hydrochemical data to study seawater intrusion phenomena effectively (Ezekiel & Lasisi, 2020; Wilopo et al., 2018). Aquifers contaminated with seawater are characterized by high TDS (Total Dissolved Solids) and chlorine ion values.

Geoelectrical data sometimes has ambiguity when there are similar lithologies. Dar-Zarrouk parameters are used to decrease this ambiguity and significantly resolve the boundary zones of fresh and saltwater aquifers (Mahmud et al., 2022). The D-Z parameters consist of longitudinal unit conductance (S), transverse unit resistance (T), longitudinal resistivity (R_S), and transverse resistivity (R_T) (Singh et al., 2004). This parameter has been widely used to obtain aquifer information related to the protective capacity zone and aquifer transmitivity (Ahamefula et al., 2012). Estimation of D-Z parameters from resistivity data increases confidence and is realistic by up to 80-90% in determining zones of fresh, brackish, or salt groundwater (Hasan et al., 2020).

Groundwater assessment is the important in Leihitu, where groundwater exploration requires optimal planning. The aim of this research is to obtain information related to aquifer quality, including aquifer protection capacity, transmissivity, and aquifer thickness based on VES data and Dar-Zarrouk parameter analysis.

2. Regional Geology of Research Area

Ambon Island was formed from the interaction of three plates, namely the Eurasian, Pacific, and Australian plates. Based on geological data, Ambon Island consists of two main parts, namely Hitu in the north and Laitimor in the south. Hitu is dominated by volcanic rock in the form of dacite composed of cordierite and a small amount of garnet known as Ambonite, over which coral limestone and alluvium deposits are exposed (Pownall et al., 2013). Laitimor consists mostly of Upper Triassic greywackes and metamorphic limestones that are tectonically overlain by ophiolitic rocks (Honthaas et al., 1999).

The research area is located in Leihitu District, Central Maluku Regency. The VES measurement and data collection points are spread across 8 points as shown in Figure 1. Based on the regional geological map, the Leihitu area is included in the Geological map of the Ambon Sheet, Maluku (Tjokrosaputro et al., 1993) which is composed of two rock groups, namely volcanic rocks and coral limestone. The stratigraphic unit from young to old is described as follows:

a. Alluvial Deposits (Qa)

This deposit consists of sedimentary material such as gravel, silt, sand, clay, and plant remains.

b. Coral Limestone (Ql)

This rock formation consists of colonies of coral, algae, and bryozoa. This rock formation has a distribution of about 25% in the study area. The age of coral limestone is Late Pleistocene to Holocene.

c. Ambon Volcanic Rock (Tpav)

Ambon Volcanic rock formations consist of andesite, dacite, breccia and tuff. This formation has a very wide distribution and occupies almost 75% of the study area. Ambon volcanic shows the age of the Late Pliocene to Early Pleistocene. Dacite lithology is also known as Ambonite, this is due to the presence of xenolith which composes the lithology, in the form of the minerals garnet and cordierite.

The aquifer layer on Ambon Island consists of aquifers that pass through inter-grain spaces with moderate productivity and wide distribution; aquifers flowing through the gaps between grain spaces; aquifers with flows through fracture and channels; and aquifers with low productivity and scarce groundwater areas (Sukrisno, 1994). Based on these data, the aquifer of the study area is a moderate productivity aquifer and wide distribution.

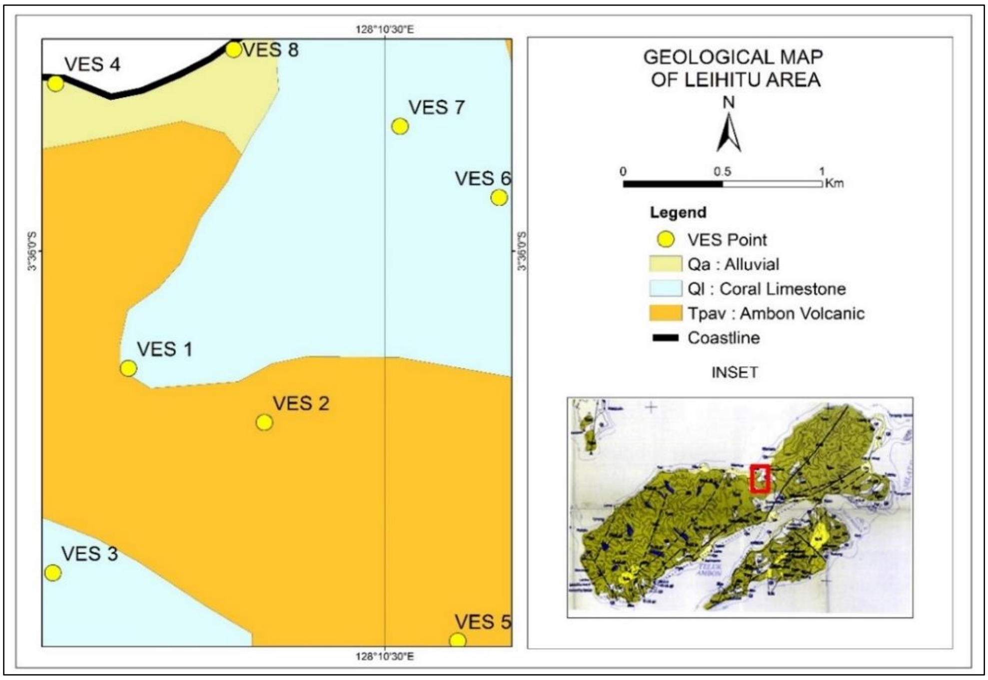

Fig 1. Geological map of study area in Leihitu

3. Methods

3.1 Vertical Electrical Sounding (VES)

Vertical Electrical Sounding (VES) technique is used in the research area to obtain information on the resistivity of the rock beneath the surface. Several factors such as mineralization, porosity, permeability, and fluid properties in the pore space have an impact on the resistivity value of the rock (Gao et al., 2018). This measurement is made with the assumption that the subsurface layer is almost horizontal and has little lateral variation. The resistivity value of the rock increases with grain size and also increases with compact rocks that have a fine grained texture (Mahmud et al., 2022). The resistivity value in brine formations also has a low value, besides that the resistivity also decreases due to an increase in clay content. Therefore, geoelectrical methods can effectively delineate salt zones or high clay content. Several types of materials and their resistivity range values can be seen in table 1. This value will be used to interpret the lithology of the VES measurement results.

Table 1. The range of resistivity values of several types of materials (Everett, 2013).

Material Type	Resistivity Value Range (Ωm)
Clay	1 – 20
Sand, wet to moist	20 200
Shale	1 - 500
Porous Limestone	100 - 10^3
Dense Limestone	10^3 - 10^6
Metamorphic Rock	50 - 10^6
Igneous Rock	10^2 - 10^6

The apparent resistivity calculation is based on Ohm's law as in equation (1):

$$\vec{E} = \rho\vec{J} \qquad (1)$$

The electric potential under direct current conditions is obtained based on the second order Laplace differential equation, as in equation (2),

$$\frac{\partial^2 V}{\partial r^2} + \frac{1}{r}\frac{\partial V}{\partial r} + \frac{\partial^2 V}{\partial z^2} + \frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2} = 0 \qquad (2)$$

By using the variable separation technique, equations (1) and (2) are solved to obtain the equation expression for the apparent resistivity ρ_a, as shown in equation (3).

$$\rho_a(l) = l^2 \int_0^\infty T(\beta) J_1(\beta l)\beta \, d\beta \qquad (3)$$

Where l is the length of half the current electrode, *T(β)* is a transformation function derived based on the recursion relationship, J_1 is a first-order Bessel function of a kind, and β is an integral variable constant.

Electrical resistivity data is obtained by injecting a direct electric current (*I*) into the ground with two current electrodes, then measuring the magnitude of the electric potential (∇V) measured at the two potential electrodes, with the earth as the resistor. Four electrodes are installed based on a certain configuration and have a geometric factor (*K*), resulting in an apparent resistivity as shown in equation (4) (Telford et al., 1990),

$$\rho_a = K\frac{\nabla V}{I} \qquad (4)$$

The commonly used four-electrode configuration is; Schlumberger, Wenner, Pole-Dipole, and Pole-Pole. In this investigation using the Schlumberger array. This array is quite simple, fast, and provides good resolution of subsurface geological layers (Koefoed, 1979). The arrangement of the electrodes in the Schlumberger configuration can be seen in Figure 2.

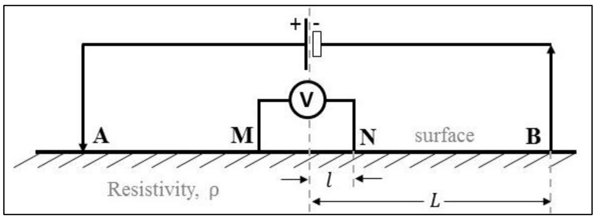

Fig 2. Electrodes arrangement in Schlumberger configuration (Everett, 2013)

The value of the geometric factor in the Schlumberger configuration is shown in equation (5).

$$K = 2\pi\left(\frac{L^2 - l^2}{2l}\right) \qquad (5)$$

The geoelectrical survey was carried out with a minimum and maximum current electrode distance of 1 and 300 meters, respectively. The estimated depth achieved is 50 meters, which is sufficient to detect the location of the aquifers. The distance between pairs of current electrodes is increased progressively, while the potential electrode distance remains relatively constant. Apparent resistivity values and rock layer thickness are interpreted using software *IP2WIN*.

3.2 Dar Zarrouk Parameters

Additional information from VES data can be obtained by applying the Dar-Zarrouk parameters introduced by Maillet in 1947 (Maillet, 1947). These parameters consist of longitudinal unit conductance (S), transverse unit resistance (T), longitudinal resistivity (R_S), and transverse resistivity (R_T), which are very important for identifying the saline and freshwater zones in coastal areas. The equation for each of these parameters can be seen in equations (6-9). This calculation can remove the ambiguity of geoelectrical data about the presence of brines in subsurface aquifers. For a section that has n layers with thicknesses $h_1, h_2, \ldots, h_n$, and rock resistivity $\rho_1, \rho_2, \ldots, \rho_n$. While the total thickness is the sum of $h_1 + h_2 + \cdots + h_n = H$.

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (6)$$

$$T = \sum_{i=1}^{n} h_i \, \rho_i \qquad (7)$$

$$R_S = \frac{H}{S} \qquad (8)$$

$$R_T = \frac{T}{H} \qquad (9)$$

Longitudinal conductance refers to the ability of a material to conduct electric current along its longitudinal axis. This parameter is used to determine the protective capacity rating of an aquifer. Table 2 shows the categories of aquifer protective capacity based on longitudinal conductance values, including excellent, very good, good, moderate, weak, and poor. Meanwhile, tranverse resistance is the result of multiple between layer thickness and resistivity value. This parameter correlates with transmissivity. (Ahamefula et al., 2012; Patil et al., 2018).

Table 2. Protective capacity rating based on longitudinal conductance (Odalapo & Akintorinwa, 2007).

Longitudinal Conductance (mho)	Protective Capacity Rating
>10	Excellent
5 - 10	Very Good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
<0.1	Poor

4. Result and Discussion

4.1 Geoelectrical Resistivity Data of Study Area

The electrical resistivity method of the VES technique is very suitable for observing groundwater reservoirs. Measurements were taken in August 2022 during the rainy season in Leihitu District, Maluku and there were 8 measurement points. The distribution of measurement points can be seen in Fig 1.

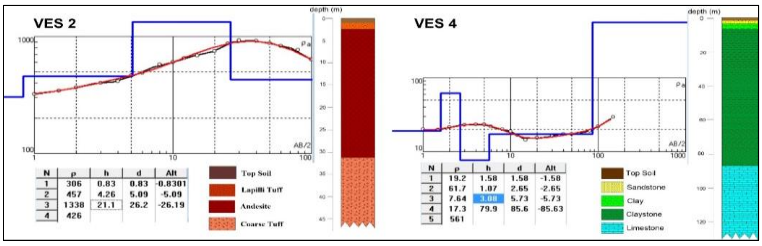

Fig. 3. Resistivity curves, tables showing thickness, and litological interpretation of VES 2 and VES 4

Electrical resistivity measurements use the Schlumberger configuration, which has good ability in vertical interpretation. A summary of the results of the resistivity and thickness values at each point can be seen in Table 3. The inversion result of the IP2WIN software for several stations can be seen in Figure 3. The lithology interpretation is carried out based on the range of resistivity values in table 1 and the rock formations on the geological map.

Table 3. Geoelectrical Layer Distribution and Aquifer System.

VES No	Coordinates	Layer No.	Resistivity (Ωm)	Thickness (m)	Inferred lithology	Aquifer System
1	-3.6060881/ 128.1629985	1	2.93	0.141	Top soil	Claystone
		2	19.5	0.286	Claystone	
		3	0.853	0.174	Wet clay	
		4	18.9	31.6	sandstone	
		5	8.39		Claystone	
2	-3.6079722/ 128.1695556	1	306	0.831	Top soil	Coarse Tuff
		2	457	4.26	Lapilli Tuff	
		3	1338	21.1	Andesite	
		4	426		Coarse tuff	
3	-3.614966/ 128.159996	1	114,7	2,516	Top soil	Sandstone
		2	270,5	1,052	Limestone	
		3	83,97	6,266	Sandstone	
		4	37,07	70,43	Claystone	
		5	76,65		Sandstone	
4	-3.591905/ 128.160127	1	19,2	1,58	Top soil	Claystone
		2	61,7	1,07	Sandstone	
		3	7,64	3,08	Clay	
		4	17,3	79,9	Claystone	
		5	561		Limestone	
5	-3.6181351/ 128.1783005	1	167,72	3,21	Top soil	Coarse tuff
		2	471,63	2,385	Lapilli tuff	
		3	5,46	2,9	tuff	
		4	28,79		Coarse tuff	
6	-3.597517/ 128.180171	1	149	0,874	Top Soil	Sandstone
		2	253	6,29	Limestone	
		3	92,9	25,1	Sandstone	
		4	40,8		Claystone	
7	-3.5942031/ 128.1756885	1	244	5,7	Top soil	Sandstone
		2	800	14	Limestone	
		3	21	4,65	Claystone	
		4	131		Sandstone	
8	-3.588822/ 128.166821	1	37,21	1,902	Top soil	Sandstone
		2	27,29	3,79	Claystone	
		3	76,65	25,79	Sandstone	
		4	16,75		Claystone	

Based on data from 1D true resistivity and lithological interpretation, the subsurface cross-sectional profiles were successfully created as shown in Figure 4. These hydrogeological sections can provide information regarding aquifer thickness and map geological structures that can affect groundwater quality and movement. This profile consists of an arrangement of 3 VES points (VES 8, VES 7, and VES 6) which are in the transition area between the alluvium formation and the limestone formation. In the top soil layer, the resistivity value of VES 8 which is an area with alluvium formation has a lower resistivity value when compared to VES 7 and VES 6 which are in limestone formations. The water-carrying rock types in this profile are sandstones followed by a layer of clay below. The clay layer acts as an aquiclude which separates the aquifer layer from the underlying layer.

Then the second profile consists of 3 VES points (VES 5, VES 2, and VES 1) can be seen in Figure 5. This section is a transition area between limestone formations and Ambon volcanic rock formations. The aquifer layers in this area are Coarse Tuff and Claystone. At the VES 1 point, there are thick enough deposits of sand and clay when compared to other VES points with the same limestone formations as VES 6 and VES 7.

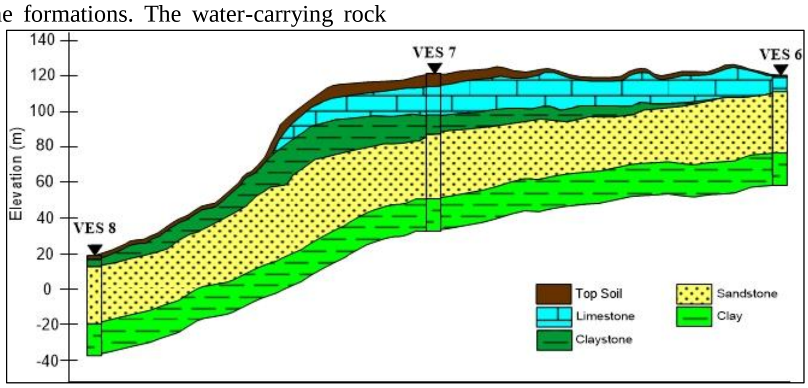

Fig. 4. Hydrogeological cross section of VES 8, VES 7, and VES 6

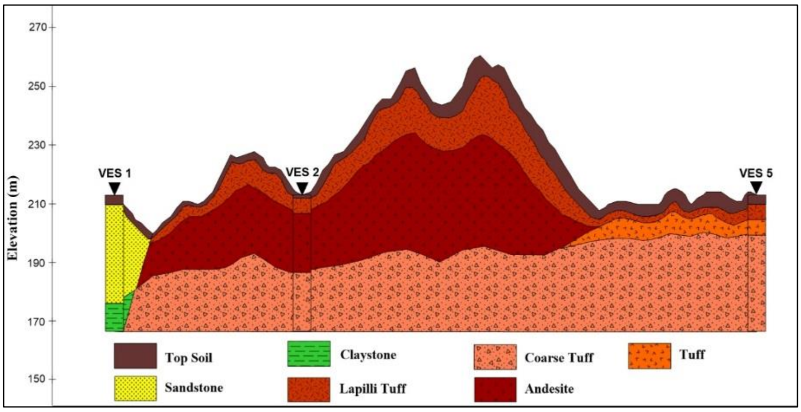

Fig. 5. Hydrogeological cross section of VES 5, VES 2, and VES 1

4.2. Groundwater Analysis with Dar Zarrouk Parameters

Dar Zarrouk parameters are used to identify aquifer properties and groundwater conditions. These parameters consist of total longitudinal conductance, total transverse resistance, longitudinal resistivity and transverse resistivity. This parameter helps in removing ambiguity or uncertainty in interpretation (Singh et al., 2004). Table 4 illustrates the results of the distribution of Dar-Zarrouk parameters for the study area.

Table 4. Analysis of Dar-Zarrouk Parameters based on VES inversion data.

VES Points	Total Longitudinal Conductance (mho)	Total Transverse Resistance (Ωm^2)	Longitudinal Resistivity (Ωm)	Transversal Resistivity (Ωm)	Protective Capacity Class
S1	1.9387	603.378	16.6088	18,7385	Good
S2	0.0278	30432.9	941.8799	1161,96	Poor
S3	2.0003	3710.15	40.1227	46,2266	Good
S4	5.1213	1502.15	16.7146	17,5485	Very Good
S5	0.5553	1679.05	15.2971	197,651	Moderate
S6	0.3009	4053.38	107.3409	125,492	Moderate
S7	0.2623	12688.5	93.0271	520,018	Moderate
S8	0.5264	2151.01	61.3154	66,6358	Moderate

4.2.1. Total Longitudinal Conductance (S)

The total value of longitudinal conductance in the study area varied from 0.0278 mho to 5.1213 mho. The distribution of longitudinal conductance values can be visibly in Figure 6a. This parameter value is then used to evaluate the protective capacity class of the aquifer based on the protective capacity rating in Table 2. In the study area there are 4 stations with moderate protective capacity class (S5, S6, S7, and S8), then 2 stations with good protective capacity class (S1 and S3), S2 station with poor protective capacity class, and S4 station which has very good protective capacity. Protective capacity is a geological layer's ability to withstand aquifer contamination from the surface or subsurface which is useful for developing potential groundwater quality (Bayewu et al., 2018). A good protective capacity value is indicated by the presence of an impermeable protective layer such as a thick layer of clay, so that water from the surface can be filtered naturally by this layer. If related to regional geology, alluvial deposit areas have a higher value than limestone and volcanic formations. That is because the site has a thick layer of silt or silty sand, for more details, look at the 1D sections on VES 4 and VES 2. Overall the study area has a moderate to good aquifer protective capacity.

4.2.3. Total Transverse Resistance (T)

The total transverse resistance varies from 603.378 Ωm^2 (S1) to 30.432.9 Ωm^2 (S2) with an average value of 7.102.565 Ωm^2. The distribution of these parameter values can be visibly in Figure 6b. The transverse resistance value is inversely proportional to the longitudinal conductance. Low T values are associated with rock types with low resistivity values such as clay formations. At VES points with high T values such as S2, S5, S6, S7, and S8 associated with rock types with high resistivity values such as limestone and volcanic rocks. High total transverse resistance (>3,000 Ωm^2) can also indicate high aquifer transmissivity, namely the ability of a layer to transport water through a vertical line (Tahama et al., 2022). Transmissivity values are also associated with rock formations, where VES points in volcanic rock and limestone formations (S2, S3, and S7) have better transmissivity than points in alluvium deposit areas (S4 and S8). Limestone, Volcanic Rock, and Sandstone have larger cavities between grain particles than clay, so they can pass water better (Domenico & Schwartz, 1998).

4.2.3. Longitudinal Resistivity (R_S)

In Figure 6c can be seen the distribution map of the longitudinal resistivity values ranging from 15.2971 Ωm to 941.8799 Ωm. At VES station S2 has the highest value due to the presence of andesite layers that has a high resistivity value. This area tends to have a low longitudinal resistivity value. That is dominated by the low resistivity rock layers such as clay, silt, tuff, and sand.

4.2.3. Transverse Resistivity (R_T)

The distribution of transverse resistivity values in the study area ranges from 17.5485 Ωm to 1161.96 Ωm. If seen in Figure 6d, the distribution of values for this parameter tends to be similar to the longitudinal conductance value. The VES measurement point at station S4 has a small value because there is a thick layer of clay.

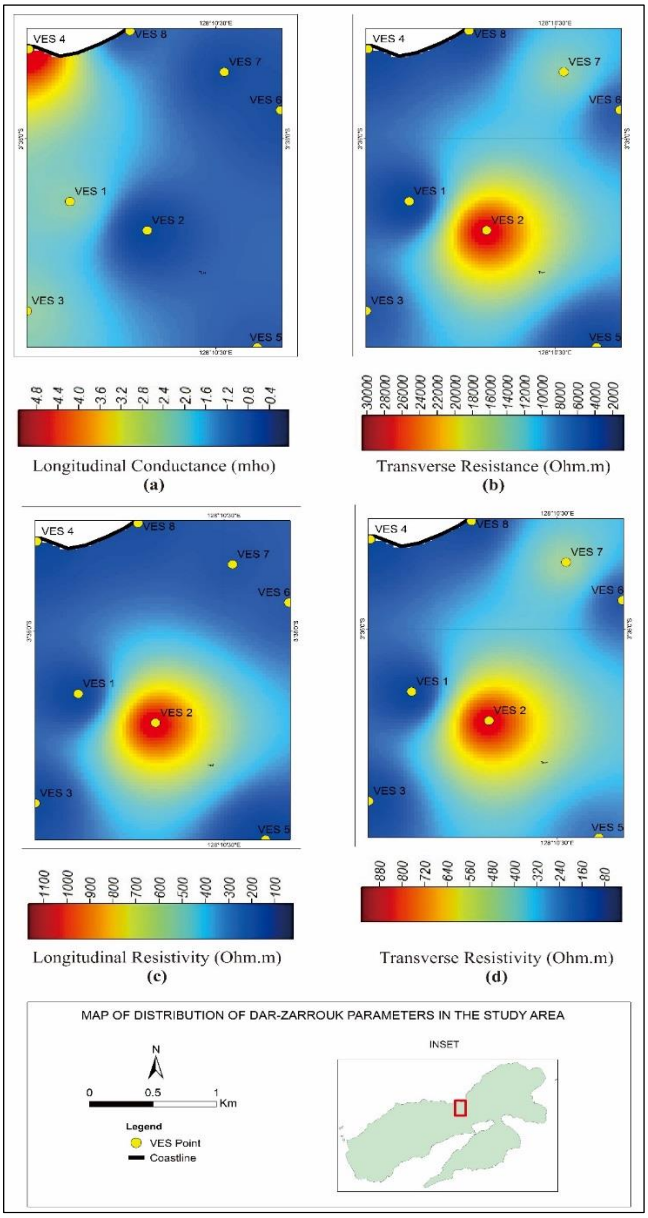

Fig. 6. Map of the Distribution of Dar-Zarrouk Parameters in the Study Area. (a) Longitudinal Conductance (b) Transverse Conductance (c) Longitudinal Resistivity (d) Transverse Resistivity.

5. Conclusion

This study characterizes and describes the condition of groundwater aquifers in Leihitu District, Ambon based on 8 vertical electrical sounding (VES) data points. The geoelectric measurement technique uses the Schlumberger configuration with an electrode spacing of 100 – 150 meters. VES data is interpreted using IP2WIN software to obtain actual subsurface thickness and resistivity information. Dar-Zarrouk parameters are used to estimate the hydraulic properties, transmisitivity and protective capacity of aquifers based on VES data. Based on the aquifer protective capacity, there is 1 point (VES 2) which is in the poor category, 4 points (VES 5, VES 6, VES 7, and VES 8) which is in the moderate category, 2 points (VES 1 and VES 3) which are in the good category, and 1 point (VES 4) which is in the very good category. This value is associated with rock formations, where alluvial deposits tend to have thick clay layers. Generally, this research area is classified as a moderate to good-capacity aquifer. This area also has a high enough transverse resistance value. Then if related to aquifer transmissivity, this area is classified as a good transmissivity aquifer, especially at VES 2, VES 5, VES 6, VES 7, and VES 8. If correlated to rock formations, areas with limestone and volcanic rocks have better transmissivity than areas with alluvial deposits. In the future, for a more detailed and comprehensive exploration of groundwater, it is necessary to carry out electrical resistivity tomography (ERT) and geochemical methods to determine the quality of groundwater.

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