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Research Article

Vertical electrical sounding method and Dar Zarrouk analysis to identify the distribution of seawater intrusion in Pelauw Village, Maluku

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Abstract

Groundwater is one of the essential resources that support human life. Excessive exploitation activities can cause groundwater problems such as seawater intrusion, especially in coastal areas. Groundwater salination must be a concern and measured to determine the condition and level of distribution. One of the non-invasive, inexpensive, and efficient methods to see seawater intrusion phenomena is the vertical electrical sounding (VES) technique of electrical resistivity method. This research aimed to analyze the distribution of seawater intrusion in Pelauw Village, Maluku, Indonesia, using the VES and Dar-Zarrouk parameters S and T. The S and T are longitudinal conductance and transversal resistance, respectively. This study collected 16 VES stations spread across residential areas near the coast of Pelauw Village. Groundwater affected by seawater intrusion in the study area has S>1.00 mho and T<1,000 Ωm^2. Three VES stations are suspected to have experienced seawater intrusion, namely V7, V8 and V12. These three stations are located near the shoreline and densely populated areas. Based on the 2D cross-section, the spread of seawater intrusion toward the land is about 200 meters. This seawater intrusion event is thought to have occurred due to groundwater exploitation by communities around the coast and active tectonic activity. The VES method and Dar Zarrouk Analysis proved compelling enough to delineate the spread of seawater intrusion, so based on these results, it can be a reference for mitigating groundwater pollution.

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Introduction

Pelauw Village is the center of Haruku Island, with a population of 9,835 people and an area of 35 km^2. Haruku Island mainly consists of hilly mountains, and settlements are primarily distributed in the coastal area. The coastal area of Haruku is characterized by coastal ecosystems consisting of mangroves, seagrasses, and coral reefs (Limmon and Manuputty, 2021). Most of the residents of Pelauw Village live in coastal areas and utilize fresh water from coastal aquifers to fulfill their needs. Groundwater is essential in fulfilling water needs, especially in dry areas with minimal rainfall, high evaporation, and minimal surface water (Benaafi et al., 2023). Overexploitation of groundwater to meet the domestic needs of the community, agricultural irrigation, and industrial activities causes environmental problems such as drought, groundwater quality degradation, and seawater intrusion (Werner et al., 2013; Moore and Joye, 2021). Groundwater salinization has become a significant concern for coastal areas around the world. Seawater intrusion can cause land degradation and lead to economic decline in coastal communities. The salinization of coastal aquifers can be prevented by making appropriate groundwater pumping management plans. Implementation of the management plan requires understanding groundwater aquifer conditions and saltwater distribution. Salinity distribution measurement and hydrological modeling are the most efficient methods to study seawater intrusion to sustain groundwater resources in coastal areas (Shinawi et al., 2022; Gaiolini et al., 2023).

The electrical Resistivity method has been widely used to identify and monitor groundwater conditions (Abdelrahman et al., 2023; Bahri et al., 2023). This electrical resistivity method is active in injecting a direct electric current into the earth's surface, and the potential difference response is measured through two electrodes (Oldenborger and Paradis, 2023). Electrical resistivity data acquisition techniques generally include vertical electrical sounding (VES) and electrical resistivity tomography (ERT). The VES method is suitable for seeing vertical lithological variations and deep subsurface penetration. At the same time, the ERT method is used to view subsurface conditions in two dimensions and is sensitive to spatial lithological variations (Everett, 2013). This method has been used to study seawater intrusion in desert areas of coastal Saudi Arabia (Alhumimidi, 2020), coastal areas of Nigeria (Folorunso, 2021; Ekwok et al., 2022; Obakhume, 2022), and coastal Ghana (Asare et al., 2022). In general, resistivity geoelectric methods are combined with hydrochemical data to study seawater intrusion phenomena more effectively (Wilopo et al., 2018; Ezekiel and Lasisi, 2020). Analyses based on VES data, such as the Dar-Zarrouk parameter analysis, are used to provide additional information on aquifer conditions and reduce ambiguity in interpretation (Ahamefula et al., 2012; Mohammed et al., 2023). This parameter can provide an overview of the zone of the aquifer area indicated by seawater intrusion and see the quality of the aquifer (Singh et al., 2004; Bahri et al., 2023).

This study used the VES method to investigate the suspected distribution of seawater intrusion in the Pelauw Village area. This seawater intrusion was based on findings by the local community regarding brackish well water around the coast. This event was thought to be caused by tectonic activity (Amukti et al., 2022), excessive groundwater extraction, and rising sea levels. Seawater intrusion will cause long-term health hazards if it continues to be consumed by the community, such as hypertension, heart disease, stroke, and (eclampsia), especially in pregnant women and others (Shammi et al., 2019). Some steps that can be taken to overcome seawater intrusion are constructing sea walls, using membranes to filter groundwater, and desalinating seawater to reduce groundwater pumping. Policy-making to address seawater intrusion should be based on how severe the level of intrusion is in the area (Hussain et al., 2019; Abd-Elaty et al., 2021). This research is the first step to estimating the extent and severity of seawater intrusion in Pelauw Village, Maluku. Based on the resistivity value of VES data and analysis using Dar-Zarrouk parameters, the seawater intrusion zone is characterized by a low resistivity value, high longitudinal conductance value, and low transverse resistance. This research is expected to provide information related to seawater intrusion, especially in the Pelauw Village area, and become a reference for sustainable development in the future.

Materials and Methods

Geology of the study area

Pelauw Village is located on Haruku Island, east of Ambon Island, and west of Saparua Island (Figure 1). Generally, the Maluku Islands' weather consists of summer and rainy seasons. The average annual rainfall is 134.45 mm, with the highest rainfall of 262.98 mm occurring in June and the lowest of 56.82 mm occurring in November. Morphologically, the study area consists of plains, gentle, undulating, and steep hills. During the Late Jurrasic to Early Cretaceous phases, faulting associated with the Callovian and carbonate rock separation occurred. The lowering of sea level during the Campanian period led to sandstone deposition and thick layers of carbonate rocks (Oliver and Barracouta Formations) (Pownall et al., 2013).

Haruku Island has a 14 km long active fault that runs east, but the western part of the fault bends to the northeast (Patria et al., 2021). The lithology of Haruku Island is dominated by Ambon volcanic rocks (Ambonites), limestone, and sedimentary deposits. Ambonites are products of two Hitu volcanoes consisting of tuffs, volcanic breccias, and agglomerates. Ambonites are correlated with cordierite granite in that both contain identical aluminous sillimanite-spinel and have pheno/xenocrysts of cordierite and garnet (Pownall et al., 2013). The limestone formation is Pleistocene in age and consists of coral, algae, and bryozoans. The youngest lithology is sedimentary deposits found on the north coast of Haruku Island, which consist of sandstones, siltstones, and claystone (Tjokrosaputro et al., 1993).

VES data collection

Vertical electrical sounding (VES) delineates groundwater zones classified as fresh, brackish, or saline. This method is very effective for studying groundwater conditions and is non-destructive. There are 16 VES stations distributed around the coastal area of Pelauw Village. The distribution of VES stations can be seen in Fig. Data was collected in January 2023 using a Naniura NRD 300 Plus resistivity meter. The Schlumberger configuration has a maximum half-spaced electrode length (AB/2) of 150 meters. The results of field measurements are in the form of electric current values and voltage responses.

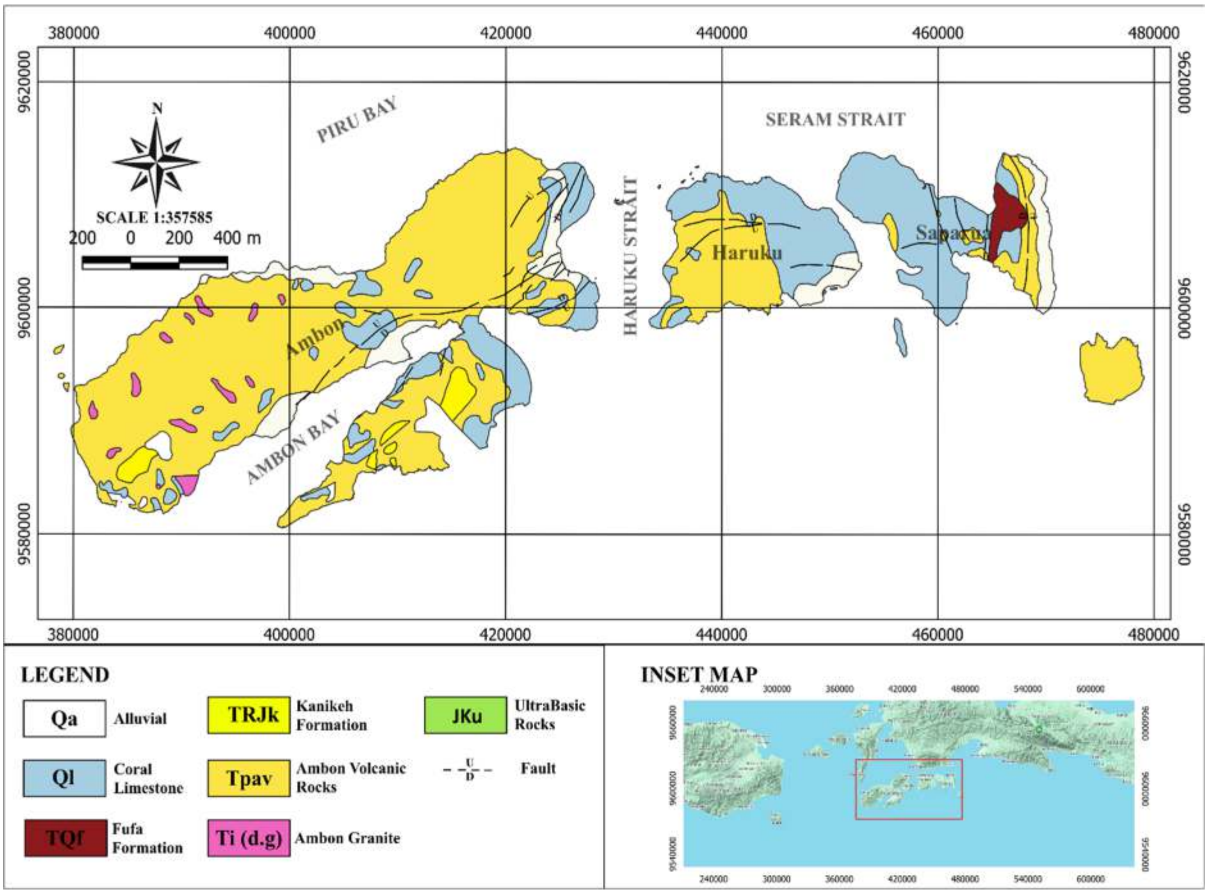

Figure 1. Geological maps of the study area.

Apparent resistivity is obtained by multiplying the geometry factor and voltage response and then dividing it by the electric current. The next step is the inversion modeling process using IP2WIN software to obtain the true resistivity and thickness of the subsurface layer. This resistivity value is a reference for interpreting subsurface lithology. The resistivity value in rocks is influenced by the constituent minerals, rock porosity, water content in the pore, permeability, and others.

Dar Zarrouk parameters to identify seawater intrusion

Dar-Zarrouk parameters refer to hydrogeological parameters that describe subsurface rock layers' lithological characteristics and hydraulic properties. These parameters are used to understand better an area's aquifer characteristics and groundwater distribution (Maillet, 1947). The Dar Zarrouk parameter consists of longitudinal conductance (S) in mho and transverse resistance (R) in Ωm^2. Their formula can be seen in equation (1) and (2).

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

$$T = \sum_{i=1}^{n} h_i . \rho_i \quad (2)$$

where: h and ρ are the thickness and true resistivity of each layer, and longitudinal conductance describes the flow of electric current in the direction of groundwater flow.

In contrast, transverse resistance describes the flow of electric current perpendicular to groundwater flow (Mohammed et al., 2023). Seawater intrusion is strongly associated with land degradation. Land degradation is a decrease in the value of land function and productivity, either temporary or permanent. Areas where seawater intrusion and land degradation are indicated are characterized by high longitudinal conductance values and low transverse resistance values (Singh et al., 2004).

Results and Discussion

VES results and correlation of lithological logs

Electrical resistivity is one of the methods commonly used for near-surface exploration. The apparent resistivity obtained directly from field measurements is processed through the inversion method to obtain subsurface parameters. These parameters are each layer's true resistivity and thickness, as shown in Table 1. From 16 VES measurement stations (Figure 2), this study obtained 3-layer and 4-layer earth models with each curve type. The next step is to interpret the lithology based on the resistivity values obtained.

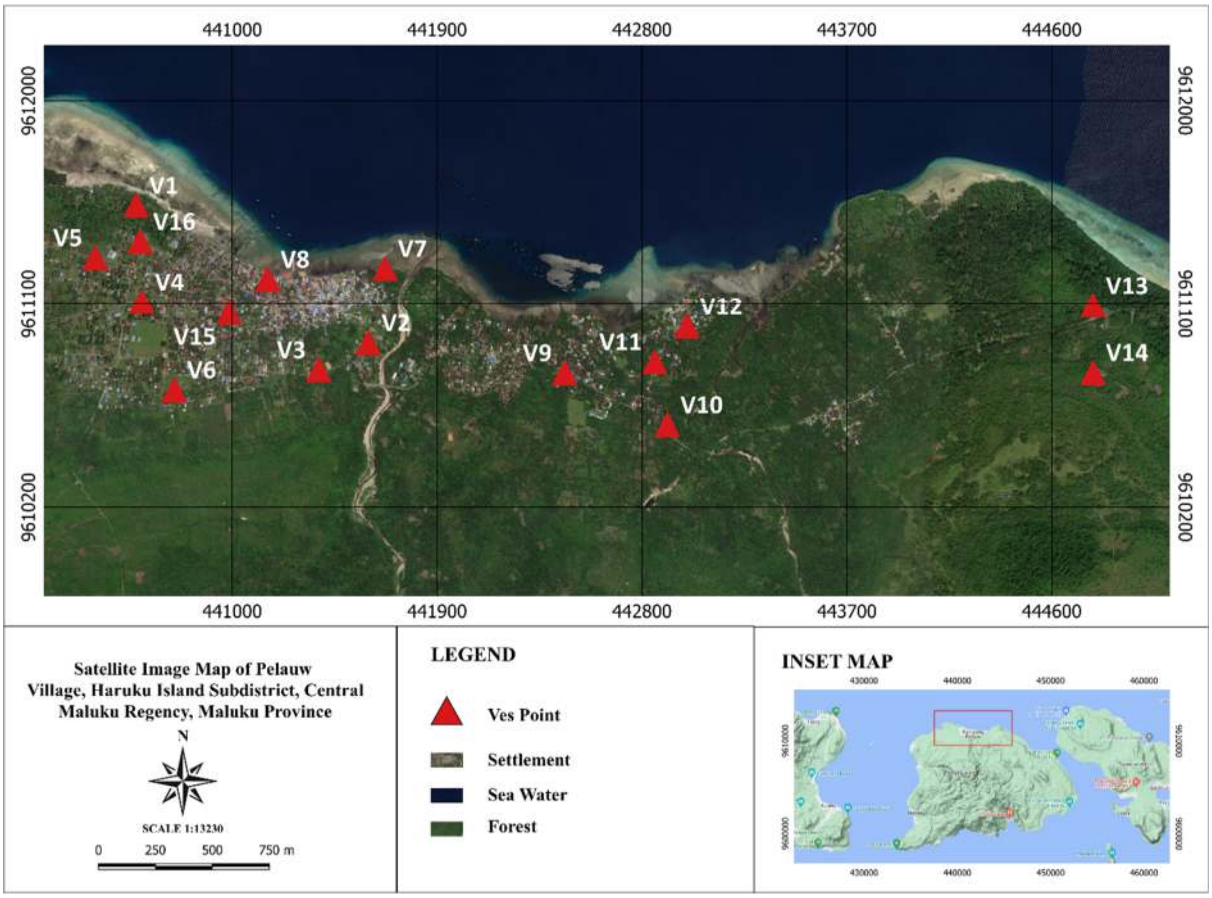

Figure 2. Map of VES stations

The research area is in limestone formations and alluvial deposits. Based on the resistivity value category, the research area consists of reef limestone lithology (>1,000 Ωm), passive limestone (100 Ωm-1,000 Ωm), sandstone (10 Ωm-100 Ωm), siltstone (7 Ωm-10 Ωm), and claystone (1 Ωm-7 Ωm). Layers with low resistivity values can also indicate seawater intrusion at that station. Minerals present in seawater infiltrate fresh groundwater and will lower its resistivity value.

The 1D VES results can be correlated to obtain a pseudo-2D cross-section. Three 2D pseudo-cross sections have been created, as shown in Figure 3. Cross section A (V8, V2, and V3) is in a densely populated residential area with elevations 0-22 meters above sea level. The trajectory is perpendicular to the coastline for 600 meters. In this cross-section, the aquifer layer is sandstone with a thickness of about 6 meters, and the bedrock layer is reef limestone. In this cross-section, there are indications of seawater intrusion events that spread as far as 200 meters from the shoreline. Then, cross-section B (V13, V12, and V11) is also in a densely populated residential area stretching 650 meters. In this cross-section, there is also an indication of seawater intrusion that spreads up to 200 meters from the shoreline. The aquifer layer in this layer is sandstone, with a thickness of about 6 meters, and the bedrock layer below is coral limestone. Furthermore, cross-section C (V1, V17, V4, and V6) stretches along 900 meters with elevations from 5-30 meters above sea level. In this cross-section, the aquifer is in the formation of sandstone, and there is no indication of seawater intrusion. Cross section C is located west of the study area, which is less densely populated. Population density has a significant effect on the rate of seawater intrusion in this area. This is also the case in almost all coastal areas, where areas with high population density are more at risk of water shortages due to seawater intrusion (Costall et al., 2018). Geological factors also influence the onset of seawater events.

Active fault activity exists between Ambon Island, Seram Island, and Haruku Island (Sahara et al., 2021; Sianipar et al., 2022). This activity can form subsurface fractures and create openings for seawater to enter groundwater. This activity is also the case in the coastal area of Nusalaut Island, Maluku, where tectonic activity can cause seawater intrusion and land subsidence (Amukti et al., 2022). The influence of tectonic activity on seawater intrusion events is a fairly rare phenomenon, which is mostly only influenced by human activity and development (Abdelfattah et al., 2023). One example of a seawater intrusion phenomenon caused by faulting is the Zhoushan Islands, Hangzhou Bay, China. This area is a small island and has similarities with the study area. Faults and fractured areas provide a pathway for seawater to enter the groundwater zone (Zhu et al., 2024).

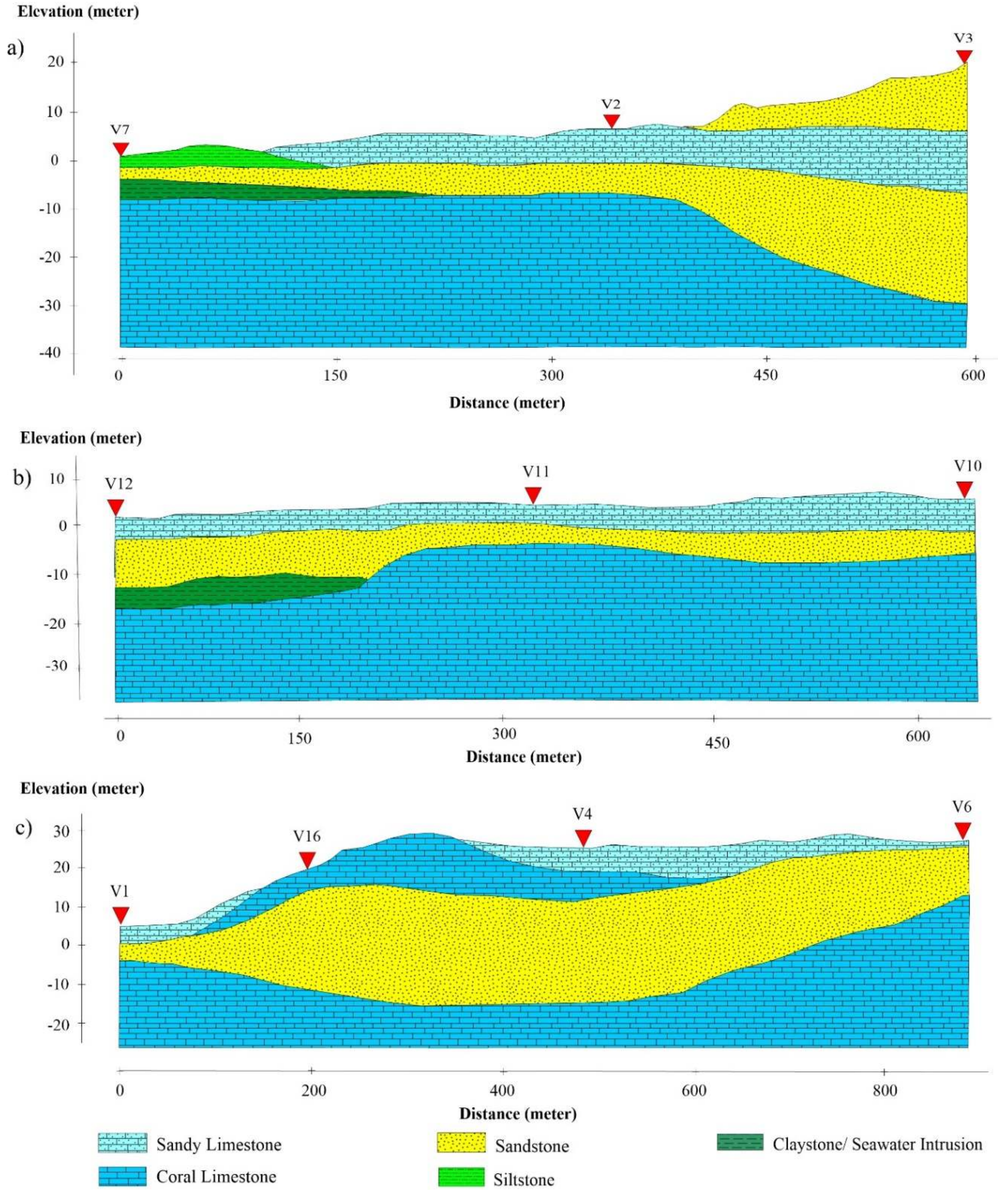

Figure 3. Pseudo-2D cross-section from lithological correlation results (a) V7 V2, and V3, (b) V1, V16, V4, and V6, and (c) V12, V11, and V10.

The analysis of Dar Zarrouk parameter

Dar Zarrouk parameters (Table 2) were used in this study to be more convincing regarding VES data interpretation. Dar Zarrouk parameter can classify an area into areas with fresh, brackish, or saline aquifers. Singh used longitudinal conductance and transverse resistance values to delineate areas with seawater-infiltrated aquifers and fresh aquifers in Orissa, India. Saline aquifers are characterized by high S values (>2 mho) and low T values (<2,000 Ωm^2) (Singh et al., 2004). Then, another study conducted by (Hasan et al., 2019) in Pakistan found the boundaries for saline aquifer (S>3.5 mho and T<700 Ωm^2), brackish aquifer (2.5<S<3.5 mho and 700<T< 1,700 Ωm^2), and fresh aquifer (S<2.5 mho and T>1,700 Ωm^2). These limit values can vary depending on the area's type of lithology and rock characteristics. Graphical analysis for the delineation of fresh water and saline water of aquifer in the study area can be seen in Figure 4.

Table 1. Distribution of resistivity and thickness of each layer from VES data.

VES Stations	Resistivity (Ωm)				Thickness			Curve Type
	ρ_1	ρ_2	ρ_3	ρ_4	h_1	h_2	h_3	
V1	262	16.7	26,105		4.21	4.13		H
V2	112	30.2	40,303		7.51	6.14		H
V3	39.9	234	7.14	824	14.6	12.9	23.4	KH
V4	211	2,833	42.1		4.56	9.04		K
V5	239	66.2	44,431	36.7	1.87	2.4	6.32	HK
V6	201	43.1	699		2.33	11.5		H
V7	8.27	58.6	2.14	3,583	2.08	2.28	4.69	KH
V8	18.9	3.65	7,944		2.31	4.33		H
V9	7.21	982	1.48		5.85	6.05		K
V10	35.1	13.8	12,129		8.73	4.32		H
V11	111	26.2	1,986		4.62	2.87		H
V12	48.6	23.6	1.66	3,633	2.23	12.1	4.65	H
V13	161	1,123	68.7	1,776	3.46	4.10	21.4	KH
V14	325	100	1,764		2.48	9.10		H
V15	37.7	1,432	89.3		8.02	4.43		K
V16	805	94	38,866		5.29	27.3		H

Table 2. Dar-Zarrouk parameters of the study area.

VES Stations	Latitude (°)	Longitude (°)	Longitudinal Unit Conductance S (mho)	Transverse Unit Resistance T (Ωm^2)
V1	-3.514339	128.464998	0.263374	1,171.99
V2	-3.519881	128.474178	0.270365	1,026.55
V3	-3.520967	128.472219	3.698354	3,768.22
V4	-3.518212	128.465221	0.024802	26,572.48
V5	-3.516437	128.463376	0.04422	281,409.70
V6	-3.521759	128.466497	0.278413	963.98
V7	-3.516878	128.474837	2.482008	160.85
V8	-3.517301	128.470191	1.308524	59.46
V9	-3.521089	128.481938	0.817534	5,983.28
V10	-3.523163	128.485997	0.561761	366.039
V11	-3.520661	128.485506	0.151164	588.014
V12	-3.518236	128.486787	3.359801	401.657
V13	-3.518377	128.502834	0.336641	6,631.54
V14	-3.521089	128.502834	0.098631	1,716.00
V15	-3.518662	128.468656	0.215826	6,646.114
V16	-3.515785	128.465149	0.296997	6,824.65

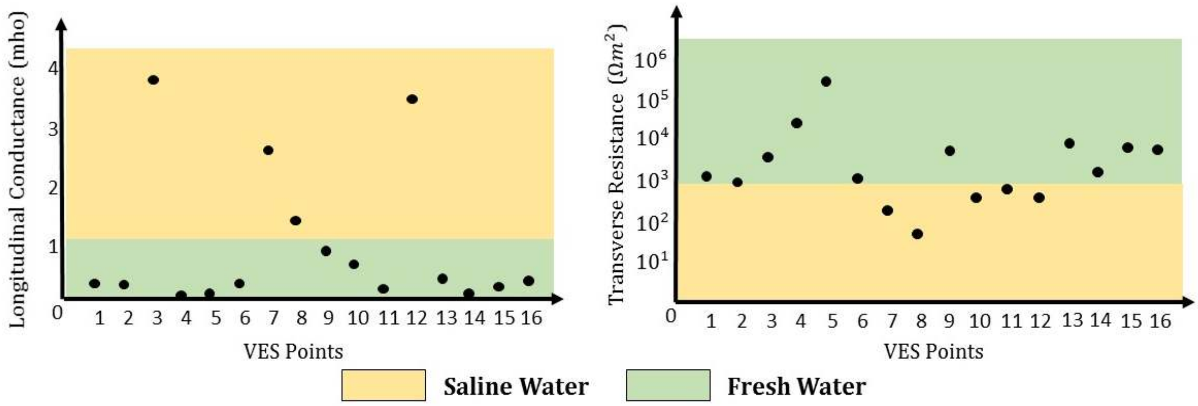

Figure 4. Graphical analysis for delineating fresh and saline aquifer water in Pelauw Village, Maluku.

Based on Dar Zarrouk parameter calculation and graphical analysis from Figure 4, the aquifer is categorized as saline water when S>1 mho and T<1,000 Ωm^2, and freshwater when S<1 mho and T>1,000 Ωm^2. At the S value, four stations have a value of more than one mho, while for the T value, there are five stations with a value of less than 1,000 Ωm^2. Station V3 has a high S value because a layer of water-saturated sandstone is quite thick and cannot be categorized as a saltwater aquifer because the resistivity value is still relatively high. The same happens at stations V10 and V11, which have low T values but aquifers with high resistivity values. The T value is also related to the transmissivity of an aquifer, which is the ability of the rock layer to drain water from the surface to the aquifer (Bahri et al., 2023). Based on the aquifer's S, T, and resistivity values, three stations, namely V7, V8, and V12, indicate a seawater intrusion event. The distribution of S and T values in the study area can be seen in Figures 5 and 6.

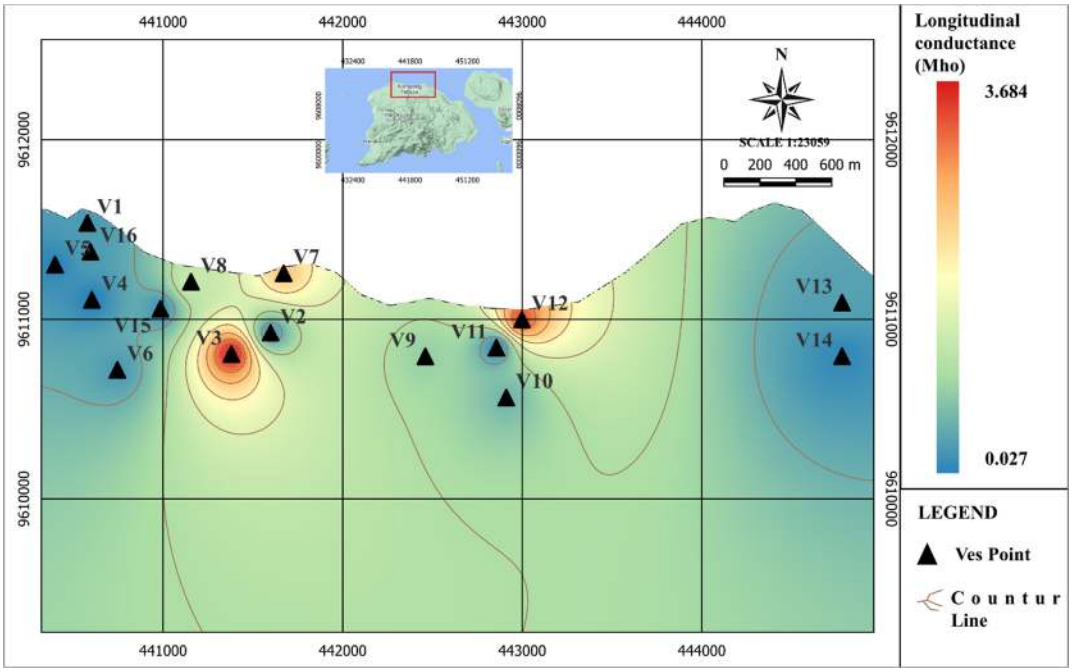

Figure 5. Map of longitudinal conductance in Pelauw Village, Maluku.

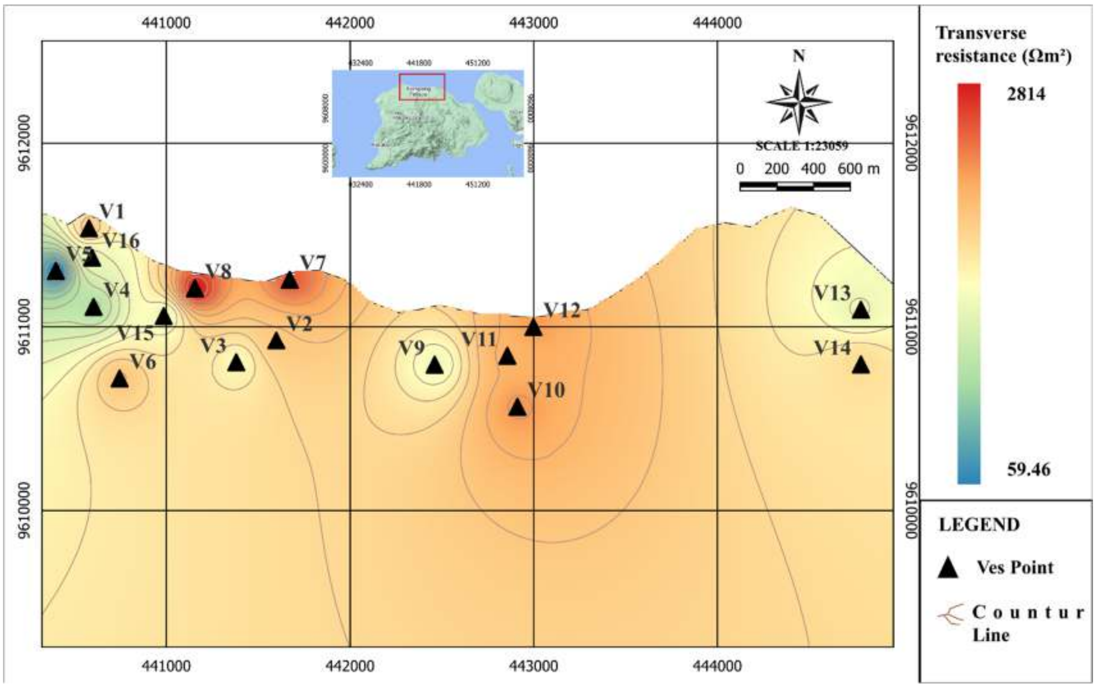

Figure 6. Map of transverse resistance in Pelauw Village, Maluku.

Handling land degradation due to seawater intrusion

Seawater intrusion is a major problem in coastal areas, resulting in land degradation and scarcity of potable water resources. Soil salinity at certain levels also causes agricultural land degradation and decreases agricultural productivity (Perera et al., 2018). Seawater intrusion events have decreased agricultural yields and changed agricultural land use, as happened in Nga Nam District, Vietnam (Nguyen et al., 2024). In addition to seawater intrusion, increasing sulfuric acid levels and flooding contribute to the degradation of agricultural land in this area. Whereas in the research area, seawater intrusion events still occur in residential areas and have not significantly affected agricultural areas. The community can fulfill the water needs for consumption by drilling in locations that are safe from seawater intrusion. Deep drilling can also be applied to avoid saltwater contamination because, based on the modeling results in Figure 3, seawater intrusion occurs in relatively shallow areas. The boundaries of areas safe from contamination can be based on the longitudinal conductance and transverse resistance values in Figures 5 and 6. Groundwater drilling can be carried out in areas with a minimum distance of 300 meters from the shoreline. Preventive measures should be implemented immediately to prevent the intrusion from spreading further. Measures such as improved management of groundwater extraction, mangrove planting around the coast, and others.

Conclusion

The vertical electrical resistivity (VES) method and Dar Zarrouk parameter analysis have successfully mapped the seawater intrusion in Pelauw Village, Haruku Island, Maluku. Seawater intruded areas are characterized by low layer resistivity values, high longitudinal conductance values, and low transverse resistance values. The seawater intrusion event in this area can be caused by excessive groundwater exploitation activities by the surrounding community. It can be seen that all three stations are located in areas with densely populated settlements. Geological factors such as active seismic activity can also affect the occurrence of fractures and make seawater enter the groundwater. Based on the results of this study, groundwater withdrawal activities should be reduced in quantity, especially in areas near the coast. Preventive efforts such as planting mangrove plants on the coast can also be made to prevent seawater from entering the groundwater (Hilmi et al., 2017).

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References

Abd-Elaty, I., Shahawy, A.E.L., Santoro, S., Curcio, E. and Straface, S. 2021. Effects of groundwater abstraction and desalination brine deep injection on a coastal aquifer. *Science of the Total Environment* 795:148928, doi:10.1016/j.scitotenv.2021.148928.

Abdelfattah, M., Abu-bakr, H.A., Aretouyap, Z., Sheta, M.H., Hassan, T.M., Geriesh, M.H., Shaheen, S.E., Alogayell, H.M., El-Bana, E.M.M. and Gaber, A. 2023. Mapping the impacts of the anthropogenic activities and seawater intrusion on the shallow coastal aquifer of Port Said, Egypt. *Frontiers in Earth Science* 11(June 2023), doi:10.3389/feart.2023.1204742.

Abdelrahman, K., Hazaea, S.A., Hazaea, B.Y., Abioui, M. and Al-awah, H. 2023. Science Groundwater potentiality in hard-rock terrain of southern Saudi Arabia using electrical resistivity tomography approach. *Journal of King Saud University - Science* 35(9):102928, doi:10.1016/j.jksus.2023.102928.

Ahamefula, U.U., Benard, I.O. and Anthony, U.O. 2012. Estimation of aquifer transmissivity using Dar Zarrouk parameters derived from surface resistivity measurements: A case history from parts of Enugu Town (Nigeria). *Journal of Water Resource and Protection* 4(December):993-1000, doi:10.4236/jwarp.2012.412115.

Alhumimidi, M.S. 2020. An integrated approach for identification of seawater intrusion in coastal region : A case study of northwestern Saudi Arabia. *Journal of King Saud University - Science* 32(7):3187-3194, doi:10.1016/j.jksus.2020.09.010.

Amukti, R., Alghifari, A.D., Elake, A.Y., Nendisa, F. and Souisa, C.J. 2022. Land subsidence investigation in Negeri Sila, Nusalaut Island, using resistivity method. *Indonesian Journal on Geoscience* 9(2):173-181, doi:10.17014/ijog.9.2.173-181.

Asare, A., Appiah-Adjei, E.K., Owusu-nimo, F. and Ali, B. 2022. Results in geophysical sciences lateral and vertical mapping of salinity along the coast of Ghana using electrical resistivity tomography : The case of Central Region. *Results in Geophysical Sciences* 12(November):100048, doi:10.1016/j.ringps.2022.100048.

Bahri, S., Ramadhan, A. and Zulfiah. 2023. Groundwater quality using vertical electrical sounding and Dar Zarrouk Parameter in Leihitu, Maluku, Indonesia. *Journal of Geosciences, Engineering, Environment, and Technology* 8(3):221-228, doi:10.25299/jgeet.2023.8.3.12976.

Benaafi, M., Abba, S., Tawabini, B., Abdulazeez, I., Salhi, B., Usman, J. and Aljundi, I.H. 2023. Integrated clustering analysis for delineating seawater intrusion and heavy metals in Arabian Gulf coastal groundwater of Saudi Arabia. *Heliyon* 9(e19784):1-18, doi:10.1016/j.heliyon.2023.e19784.

Costall, A., Harris, B. and Pigois, J.P. 2018. Electrical resistivity imaging and the saline water interface in high-quality coastal aquifers. *Surveys in Geophysics* 39:753-816, doi:10.1007/s10712-018-9468-0.

Ekwok, S.E., Ben, U.C., Eldosouky, A.M., Qaysi, S., Akpan, A.E. and Andráš, P. 2022. Towards understanding the extent of saltwater incursion into the coastal aquifers of Akwa Ibom State, Southern Nigeria using 2D ERT.

Journal of King Saud University - Science 34(8):102371, doi:10.1016/j.jksus.2022.102371.

Everett, M.E. 2013. *Near Surface Applied Geophysics*. Cambridge University Press.

Ezekiel, T. and Lasisi, K.H. 2020. Seawater intrusion in the coastal aquifers of East and Horn of Africa : A review from a regional perspective. *Scientific African* 8:e00402, doi:10.1016/j.sciaf.2020.e00402.

Folorunso, A.F. 2021. Mapping a spatial salinity flow from seawater to groundwater using electrical resistivity topography techniques. *Scientific African* 13:e00957, doi:10.1016/j.sciaf.2021.e00957.

Gaiolini, M., Colombani, N., Mastrocicco, M. and Postacchini, M. 2023. Seawater intrusion assessment along the Volturno River (Italy) via numerical modeling and spectral analysis. *Journal of Hydrology* 626(130289):1-12, doi:10.1016/j.jhydrol.2023.130289.

Hasan, M., Shang, Y., Akhter, G. and Jin, W. 2019. Application of VES and ERT for delineation of fresh-saline interface in alluvial aquifers of Lower Bari Doab, Pakistan. *Journal of Applied Geophysics* 164:200-213, doi:10.1016/j.jappgeo.2019.03.013.

Hilmi, E., Kusmana, C., Suhendang, E. and Iskandar. 2017. Correlation analysis between seawater intrusion and mangrove greenbelt. *Indonesian Journal of Forestry Research*,4(2):151-168, doi:10.20886/ijfr.2017.4.2.151-168.

Hussain, M.S., Abd-Elhamid, H.F., Javadi, A.A. and Sherif, M.M. 2019. Management of seawater intrusion in coastal aquifers: A review. *Water* 11(12):2467, doi:10.3390/w11122467.

Limmon, G.V. and Manuputty, G.D. 2021. Coral reef condition at north coastal of Haruku Island Maluku Tengah. *IOP Conference Series: Earth and Environmental Science* 777(1), doi:10.1088/1755-1315/777/1/012042.

Maillet, R. 1947. The fundamental equation of electrical prospecting. *Geophysics* 12(4):529-556.

Mohammed, M.A.A., Szabó, N.P. and Szűcs, P. 2023. Exploring hydrogeological parameters by integration of geophysical and hydrogeological methods in northern Khartoum state, Sudan. *Groundwater for Sustainable Development* 20(December 2022), doi:10.1016/j.gsd.2022.100891.

Moore, W.S., and Joye, S.B. 2021. Saltwater intrusion and submarine groundwater discharge: Acceleration of biogeochemical reactions in changing coastal aquifers. *Frontiers in Earth Science* 9(April):1-14, doi:10.3389/feart.2021.600710.

Nguyen, P.C., Vu, P.T., Khuong, N.Q., Minh, H.V.T. and Vo, H.A. 2024. Saltwater intrusion and agricultural land use change in Nga Nam, Soc Trang, Vietnam. *Resources* 13(18):1-19, doi:10.3390/resources13020018.

Obakhume, K.A. 2022. Integrated geophysical characterization of saltwater intrusion in Lagos State, Eastern Dahomey Basin, Southwestern Nigeria. *Scientific African* 16:e01251, doi:10.1016/j.sciaf.2022.e01251.

Oldenborger, G.A. and Paradis, D. 2023. Hydraulic conductivity estimation and lithological classification of an esker aquifer system using surface electrical resistivity surveys and a neural network. *Journal of Applied Geophysics* 215:105106, doi:10.1016/j.jappgeo.2023.105106.

Patria, A., Tsutsumi, H. and Hilman, D. 2021. Active fault mapping in the onshore northern Banda Arc, Indonesia : Implications for active tectonics and seismic potential. *Journal of Asian Earth Sciences* 218(October 2020):104881, doi:10.1016/j.jseaes.2021.10488.1

Perera, M.D.N.D., Ranasinghe, T.K.G.P., Piyadasa, R.U.K. and Jayasinghe, G.Y. 2018. Risk of seawater intrusion on coastal community of Bentota river basin Sri Lanka. *Procedia Engineering* 212 (2018):699-706, doi:10.1016/j.proeng.2018.01.090.

Pownall, J.M., Hall, R. and Watkinson, I.M. 2013. Extreme extension across Seram and Ambon, eastern Indonesia : evidence for Banda slab rollback. *Solid Earth* 4:277-314, doi:10.5194/se-4-277-2013.

Sahara, D.P., Nugraha, A.D., Muhari, A., Rusdin, A.A., Rosalia, S., Priyono, A., Zulfakriza, Z., Widiyantoro, S., Puspito, N.T., Lesmana, A., Kusumawati, D., Ardianto, A., Baskara, A.W., Halauwet, Y. and Shiddiqi, H.A. 2021. 2019 Ambon aftershocks catalog data compiled using local and regional seismic networks. *Data in Brief* 34:106728, doi:10.1016/j.dib.2021.106728.

Shammi, M., Rahman, M., Bondad, S.E. and Doza, B. 2019. Impacts of salinity intrusion in community health: A review of experiences on drinking water sodium from coastal areas of Bangladesh. *Healtcare* 7(50), doi:10.3390/healthcare7010050.

Shinawi, A. El, Kuriqi, A., Zelenakova, M., Vranayova, Z., and Abd-Elaty, I. 2022. Land subsidence and environmental threats in coastal aquifers under sea level rise and over-pumping stress. *Journal of Hydrology* 608: 127607, doi:10.1016/j.jhydrol.2022.127607.

Sianipar, D., Daryono, D., Halauwet, Y., Ulfiana, E., Sipayung, R., Daniarsyad, G., Heryandoko, N., Prasetyo, R.A., Serhalawan, Y. and Karnawati, D. 2022. Intense foreshock swarm preceding the 2019 MW 6.5 Ambon (Seram, Indonesia) earthquake and its implication for the earthquake nucleation process. *Physics of the Earth and Planetary Interiors* 322(1):106828, doi:10.1016/j.pepi.2021.106828.

Singh, U.K., Das, R. and Hodlur, G. 2004. Significance of Dar-Zarrouk parameters in the exploration of quality-affected coastal aquifer systems. *Environmental Geology* 45:696-702, doi:10.1007/s00254-003-0925-8.

Tjokrosaputro, S., Rusmana, E. and Achdan, A. 1993. Geological map of Ambon sheet, Maluku. Center for Geological Research and Development (*in Indonesian*).

Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T. and Barry, D.A. 2013. Seawater intrusion processes, investigation, and management: Recent advances and future challenges. *Advances in Water Resources* 51:3-26, doi:10.1016/j.advwatres.2012.03.004.

Wilopo, W., Risanti, Susanto, R. and Putra, D.P.E. 2018. Seawater intrusion assessment and prediction of sea-freshwater interface in Parangtritis coastal aquifer, South of Yogyakarta Special Province. *Journal of Degraded and Mining Lands Management* 8(3):2709-2718, doi:10.15243/jdmlm.2021.083.2709.

Zhu, Z., Shan, Z., Pang, Y., Wang, W., Chen, M., Li, G., Sun, H. and Revil, A. 2024. The transient electromagnetic (TEM) method reveals the role of tectonic faults in seawater intrusion at Zhoushan islands (Hangzhou Bay, China). *Engineering Geology* 330(2024):107425, doi:10.1016/j.enggeo.2024.107425.