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Characterization of Seawater Intrusion into Groundwater Aquifers Using the Electrical Resistivity Method in the Coastal Area of Tateli, North Sulawesi

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Abstract: This study aims to characterize the potential seawater intrusion in the aquifers of the coastal area of Tateli Beach, Manado. A geoelectrical resistivity survey was conducted using a dipole–dipole configuration with 48 potential electrodes spaced 10 m apart. The data were processed using RES2DINV software to generate two-dimensional resistivity sections. The resistivity values were correlated with groundwater quality data from nearby wells, particularly salinity and electrical conductivity. The modeling results revealed a low-resistivity zone (≤10 ohm·m), interpreted as a water-saturated aquifer down to a depth of approximately 20 m, overlain by a high-resistivity layer (≥5,000 ohm·m) acting as an aquifuge. Groundwater samples indicated salinity values of 0.01–0.02% and electrical conductivity ranging from 208 to 483 µS/cm, which are still classified as freshwater. In addition, a deeper aquifer was identified at around 50 m depth. These findings suggest that no significant seawater intrusion is currently present. The integration of resistivity imaging and groundwater quality analysis supports the conclusion that the aquifers remain preserved, although continuous monitoring is required to detect potential changes due to human activities and climate impacts.

Keywords: Coastal aquifer; Electrical resistivity; Groundwater quality; Seawater intrusion; Tateli Beach

Introduction

Coastal aquifers serve as crucial freshwater sources in low-lying coastal regions, supplying water for industry, agriculture, and domestic needs (Mujib et al., 2024). In many tropical coastal areas, including Indonesia, shallow aquifers are the only locally available and economically feasible sources of clean water. However, increasing freshwater demand driven by population growth, urban expansion, and economic development has led to the overexploitation of groundwater. This is further exacerbated by reduced rainwater infiltration due to land-use changes, ultimately heightening the risk of seawater intrusion—defined as the encroachment of saline water into freshwater aquifer systems (Nugroho et al., 2025; Sahana & Waspodo, 2020).

Seawater intrusion is a critical issue in coastal zones, which are often densely populated and function as economic centers. If unmanaged, this phenomenon can lead to long-term degradation of freshwater resources and is often irreversible in the short term. In addition to overpumping, climate change and sea level rise further increase the vulnerability of shallow aquifers to saltwater intrusion.

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In Indonesia, North Sulawesi Province—especially the coastal area of Tateli Beach in Minahasa Regency—faces considerable pressure on its groundwater systems due to its proximity to Manado City, the provincial capital. The city's urban development has spurred residential expansion and infrastructure construction along the coast, directly increasing water demand in surrounding areas like Tateli. This pressure includes the need for clean water supply to meet Manado's growing population and service sectors, making Tateli a critical zone for resource monitoring.

Geologically, the Tateli coastal region is characterized by a complex hydrogeological system, with aquifers embedded within volcanic rocks and unconsolidated coastal sediments that exhibit varying permeability. These aquifers are often confined by impermeable layers, making direct identification difficult. As such, non-invasive geophysical techniques—particularly the geoelectrical method using dipole-dipole configurations—are effective tools for mapping subsurface resistivity structures and detecting the presence of aquifers and potential seawater intrusion (Muslim et al., 2021; Wardhana et al., 2017). This method allows differentiation between freshwater-saturated zones, transitional zones, and saline zones based on variations in resistivity values.

To validate the interpretation of geoelectrical data, water quality testing was also conducted on wells near the survey lines, focusing on salinity and electrical conductivity parameters. Electrical conductivity and salinity values that remain below the thresholds established by the World Health Organization (WHO, 2017) indicate that the groundwater is still classified as freshwater and has not been affected by seawater. This approach supports integrated early detection of seawater intrusion, and strengthens the interpretation of resistivity data (WHO, 2017).

Therefore, this study aims to characterize the subsurface resistivity structure and assess the potential for seawater intrusion into coastal aquifers in the Tateli Beach area. The findings are expected to contribute to sustainable groundwater management and inform conservation strategies in coastal North Sulawesi, particularly in the face of climate change and increasing developmental pressures.

Method

Geoelectrical data acquisition was conducted in the coastal area of Tateli Beach in August 2023. Measurements were carried out using the Multi-Channel, Multi-Electrode Resistivity and IP Meter MAEX612-EM across four survey lines arranged perpendicular to the shoreline (Figure 1 and 2). Each survey line consisted of 48 electrodes with a spacing of 10 meters, configured in a dipole–dipole array (Mangensiga et al., 2020; Wahyudi et al., 2021). The electrode spacing was determined as the maximum distance accommodated by the instrument.

The Geoelectrical Resistivity Method is a geophysical technique designed to determine subsurface resistivity variations by injecting direct current (DC) into the ground through two current

electrodes, while the resulting potential difference is measured by two potential electrodes. In this study, a dipole–dipole configuration was employed, as it provides high sensitivity to both vertical and horizontal subsurface variations (Karimah et al., 2022). Based on this principle, the apparent resistivity is calculated using the Formula 1.

$$\rho\_a = \pi \, n \, a \, (n+1)(n+2) \, (\Delta V/I) \qquad (1)$$

where ρ_a is the apparent resistivity (Ωm), n is an integer, ΔV/I represents the resistance (R, ohm), and I is the current (Ampere) (Karimah et al., 2022). In this configuration, r is the distance between electrodes C1–C2 and P1–P2, while nr represents the distance as the potential electrodes (P1–P2) are shifted progressively to the right until reaching the maximum survey line. During measurements, the potential electrodes were shifted by n steps while the current electrodes remained in position; the current electrodes were then shifted, followed by the potential electrodes, and this sequence was repeated until the maximum survey line was reached.

The apparent resistivity values obtained were recorded directly by the instrument. To ensure spatial accuracy, these data were integrated with coordinate and elevation information acquired using a Garmin GPS. The dataset was subsequently processed with RES2DINV software to generate two-dimensional subsurface resistivity cross-sections (Costall et al., 2018).

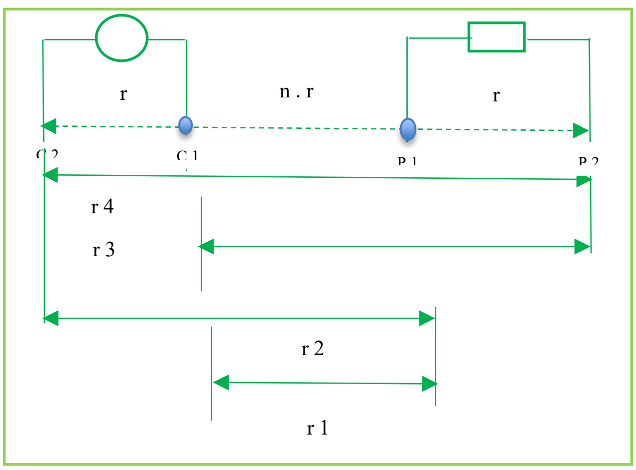

Figure 1. Dipole-Dipole Configuration

For the integrative analysis, the resistivity modeling results were correlated with salinity and electrical conductivity parameters from groundwater samples collected at two hand-dug wells located 39.6 m and 30.4 m from the survey line, respectively. Groundwater sampling was performed one day after geoelectrical acquisition under clear weather conditions, without prior rainfall, and during normal tidal conditions. These conditions were chosen to minimize external influences on groundwater quality between the two measurement phases.

Salinity and electrical conductivity were measured in situ using a portable meter immediately after sample collection. The probe was immersed directly into the water samples, and the readings were recorded in the field. This approach minimized the potential for water quality changes during storage and ensured that the measurements accurately represented actual field conditions. The groundwater quality results were then matched with their corresponding positions on the resistivity cross-sections to identify the relationships between resistivity zones and water quality parameters, thus enabling a more reliable interpretation of potential seawater intrusion.

Finally, to clarify the overall workflow, the research design is presented in the form of a flowchart (Figure 2).

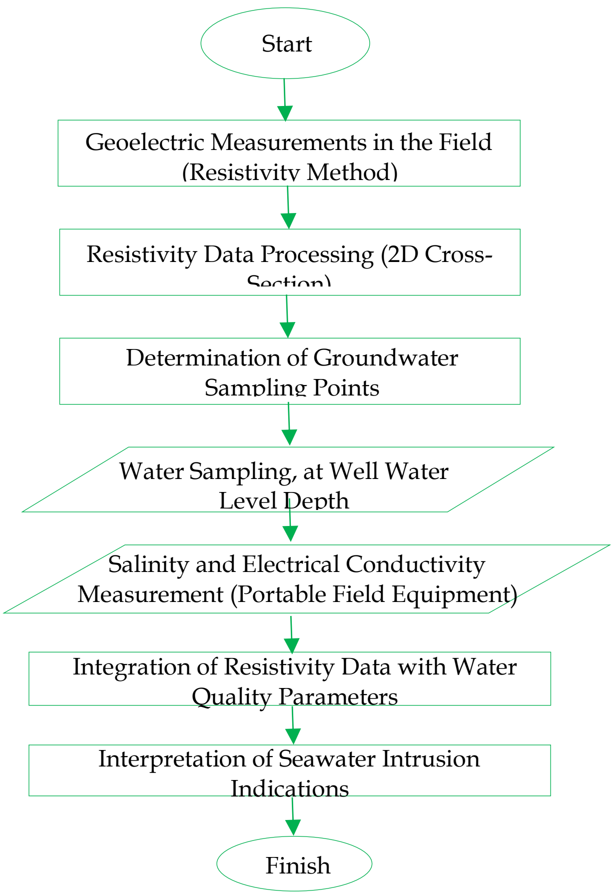

Figure 2. Research Flowchart

Result and Discussion

The subsurface resistivity modeling results along Line 1 in the coastal area of Tateli Beach, Manado, North Sulawesi (01°27'11.66" – 01°27'22.41" N to 124°45'48.31" – 124°45'38.89" E) reveal variations in resistivity distribution down to a depth of approximately ±70 meters. The inversion section generated using RES2DINV software displays a low-resistivity anomaly (≤10 Ωm) at depths of 5–20 meters, visualized as a dark-blue zone. This anomaly extends from around the 250-meter mark to nearly 410 meters from the survey line endpoint, trending toward the shoreline (Figure 5).

Interpretation of the resistivity section indicates three primary zones representing subsurface lithological conditions. First, the dark-blue zone (≤10 Ωm) is interpreted as a water-saturated aquifer. In coastal contexts, such low values may reflect seawater intrusion or freshwater aquifers within fine-grained sediments such as silt or clay (Muslim et al., 2021; Wardhana et al., 2017). This pattern is consistent with the findings of Juniar et al. (2025), who confirmed the capability of resistivity distribution to detect shallow coastal aquifers, thereby strengthening the assumption that this anomaly corresponds to a shallow freshwater aquifer. Second, the light-green zone (50–250 Ωm) surrounding the blue zone is likely composed of water-saturated sand or medium–coarse-grained materials with higher permeability, functioning as a more potential aquifer unit for groundwater storage and flow. Third, beneath these layers, a yellow to orange zone (5,000–25,000 Ωm) is interpreted as compact rock formations such as volcanic tuff, consolidated sandstone, or bedrock, which are impermeable or dry. This high-resistivity layer acts as the aquifer's lower boundary and a vertical barrier to groundwater flow, functioning as an aquitard or confining layer that is semi-permeable and capable of restraining seawater intrusion (Darsono et al., 2023).

To validate the geoelectrical interpretation, groundwater quality testing was conducted on wells near the survey line. Parameters examined included salinity and electrical conductivity. Measurements at the well located along Line 1 at the 250-meter mark (01°27'16.96'' N, 124°45'41.96'' E) showed salinity of 0.02% and an EC value of 483 µS/cm (Tables 1). Based on freshwater classification thresholds, groundwater at this site is still categorized as freshwater (Table 2). These values also fall below the standards set by WHO (2017), indicating that groundwater within the low-resistivity zone has not yet been affected by seawater intrusion. This finding is consistent with Rustadi et al. (2022), who emphasized that groundwater quality testing serves as an important supporting indicator for the early detection of seawater intrusion and reinforces resistivity-based interpretations.

Table 1. Characterization values of Well Water Samples

No	Well location	Salinity (%)	Electrical conductivity (EC)(µs/cm)
1	01^{0} 27′16.96′′N-124^{0} 45′41.96′′E	0.02	483
2	01^{0} 27′12.25″N-124^{0} 45′29.47′′E	0.01	208

Thus, the subsurface conditions along Line 1 suggest the presence of a freshwater aquifer at depths of 5–20 meters, which has not been intruded by seawater. This aquifer has potential as a clean water source for coastal communities, although periodic monitoring and integration with further geochemical analyses remain necessary to anticipate future intrusion risks.

The subsurface resistivity modeling results along Line 2 in the coastal area of Tateli, Manado (01°27′11.81″–01°26′58.97″ N and 124°45′49.69″–124°45′55.41″ E)(Figure 6), revealed a low-resistivity zone (≤10 Ωm) at a depth of approximately 5–20 meters. This zone, visualized in dark blue on the inversion section, is located between potential electrodes 27 and 36. The survey line was placed in a coastal zone directly adjacent to the shoreline, meaning that the modeling results not only represent shallow hydrogeological conditions but also reflect aquifer–seawater interactions that are susceptible to seawater intrusion.

Table 2. Classification of Groundwater Based on Electrical Conductivity Values (Nisa & Yulianto, 2012)

EC (µs/cm)	Classification
< 1,500	Freshwater
1,500-5,000	Fresh–Brackish
5,000-15,000	Brackish
15,000-50,000	Salty water

The resistivity section interpretation indicates several main zones representing subsurface lithology. The dark-blue zone (≤10 Ωm) is interpreted as a water-saturated aquifer, which in coastal settings may indicate seawater intrusion or freshwater aquifers within fine sediments such as saturated clay, silt, or water-bearing sand (Niculescu & Andrei, 2021; Rahmaniah et al., 2021). Additionally, the resistivity imagery highlights several lithological variations, including green zones (10–100 Ωm) indicating clayey sand or coarse silt as transitional layers, yellow to orange zones (100–1000 Ωm) interpreted as dry sand or compacted gravel with low permeability, and red to dark-purple zones (≥5000 Ωm) representing hard rock, highly compacted gravel, or resistant igneous/metamorphic rocks that are impermeable (Cahyadi et al., 2017; Fatimah et al., 2021; Rustadi et al., 2022). These impermeable units act as aquitards or barriers to seawater intrusion. This condition supports the interpretation that the detected aquifer represents a confined aquifer, in which groundwater is trapped between two impermeable layers, thereby offering greater protection against contamination (Rahmaniah et al., 2021; Syamsuddin et al., 2023).

Table 3. Classification of Groundwater Based on Salinity Values (Nisa & Yulianto, 2012)

Salinity (%)	Classification
< 0.5	Freshwater
0.5 - 30	Moderately Saline
30 - 50	Saline
>50	Brine

Table 4. Resistivity Values of Material/Rock Types (Telford et al., 1990)

Material/Rock	Resistivity Value (Ohm m)
Sea water	0.2 - 1
Watern – saturated clay	1 - 10
Sand/Water-saturated sand	5 - 50
Gravel / Water-saturated sand	10 - 100
Dry sand / Semi-saturated	100 – 1,000
Igneous rock	1,000 – 100,000
Water – saturated volcanic tuff	10 - 100
Vesicular lava	10 – 1,000
Volcanic breccia	100 – 5,000
Fresh groundwater (pure aquifer – without carrier material)	10 - 100

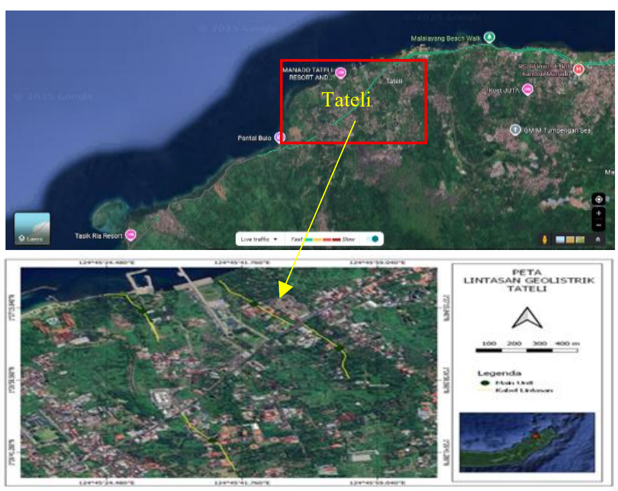

Figure 3. Field Measurement Location

Figure 4. Field photo of resistivity survey at Tateli beach, Manado

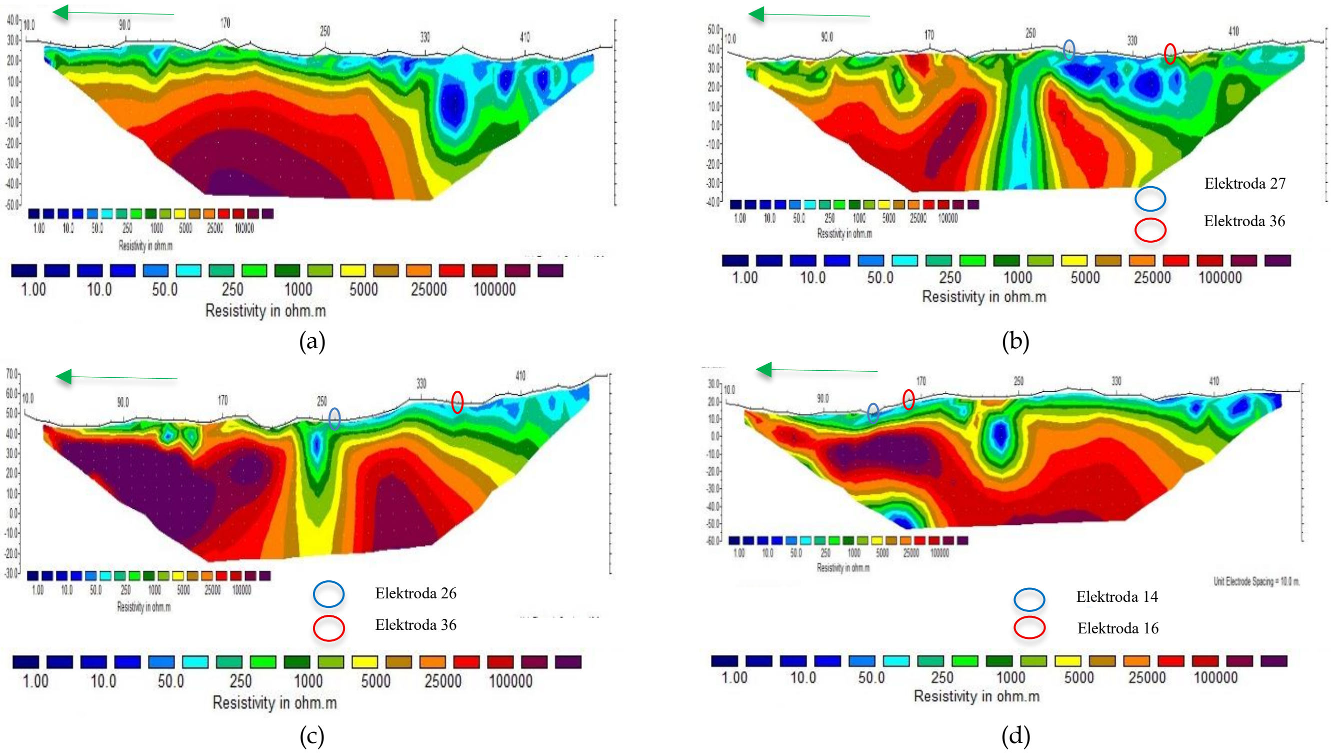

Figure 5. Data analysis reslt: (a) Resistivity Cross-Section of Line 1; (b) Resistivity Cross-Section of Line 2; (c) Resistivity Cross-Section of Line 3; and (d) Resistivity Cross-Section of Line 4

To validate the geoelectrical interpretation, groundwater quality tests from nearby wells were also analyzed. Measurements from a well located along Line 1 (as a continuation of Line 2) showed a salinity of 0.02% and an electrical conductivity value of 483 µS/cm. These values fall within the freshwater category (Tables 1) and remain below the freshwater quality standards established by the WHO (2017). This supports the interpretation that the low-resistivity zone in Line 2 corresponds to a freshwater aquifer that has not yet been intruded by seawater (Rahmaniah et al., 2021).

Thus, the subsurface conditions along Line 2 indicate the presence of a confined freshwater aquifer that is relatively well protected by surrounding impermeable layers. This zone has strong potential to serve as a sustainable source of clean water in coastal areas vulnerable to seawater intrusion. However, the dynamics of seawater intrusion are strongly influenced by hydraulic pressure, sea-level rise, and excessive groundwater extraction (Niculescu & Andrei, 2021). Therefore, continuous monitoring is necessary to enable early detection of potential future intrusion.

The subsurface resistivity modeling results along Line 3 in the coastal area of Tateli, Manado (01°26′50.44″–01°26′37.09″ N and 124°45′33.00″–124°45′40.82″ E) (Figure 7), revealed variations in resistivity distribution down to a depth of approximately ±70 meters. Based on the inversion section generated using RES2DINV software, a dark-blue zone with resistivity values of ≤10 Ωm was identified at depths of around 10–20 meters, interpreted as a groundwater aquifer (Figure 4) (Cong-Thi et al., 2021).

This zone extends between potential electrodes 26 and 36 along Line 3, with the line's endpoint located relatively far inland, about ±900 meters from the shoreline. Its elevation above sea level indicates that the zone can be classified as a shallow freshwater aquifer. According to resistivity interpretation, such low anomalies are generally associated with water-saturated zones within sedimentary materials such as sand, gravel, and clay, which exhibit high porosity and water storage capacity (Purwaditya Nugraha, 2023; Sulu et al., 2015). The typical resistivity range of these aquifer-forming materials lies between 1–100 Ωm (Azffri et al., 2021).

Above and around the dark-blue zone, green to yellow areas with resistivity ranges of approximately 100–1000 Ωm were identified. The green zone can be interpreted as a transitional layer between saturated and semi-saturated materials, possibly clayey sand or partially dry sand. Meanwhile, the yellow zone indicates more compact materials with low water content, such as tuff, compact sand with limited moisture, or drier clay layers (Ahmad et al., 2020). In addition, several parts of the line, particularly in the central and deeper sections, exhibit brown to orange colors representing higher resistivity values (5,000–25,000 Ωm). These zones are associated with solid rock formations or lithified sedimentary layers such as hard sandstone, volcanic breccia, or pyroclastic deposits. The high resistivity values indicate low permeability, reinforcing their role as confining layers (aquitards or aquicludes) within the aquifer system **(Santosa, 2021;** (Mende et al., 2017).

The subsequent layers exhibit even higher resistivity values (25,000–100,000 Ωm), visualized as red to dark-purple colors. According to the Manado geological map, this area is dominated by hard volcanic rocks such as andesite and basalt, which are characterized by very low porosity and low hydraulic conductivity (Weydt et al., 2022).

This geological setting supports the presence of a confined aquifer system, in which freshwater-bearing layers are trapped between two impermeable strata. The presence of such a system is crucial for groundwater conservation, as it offers greater resistance to surface contamination and seawater intrusion. Furthermore, it provides a vital alternative source of clean water, particularly in coastal areas under significant anthropogenic pressure (Pasamba et al., 2017).

The existence of this freshwater aquifer is corroborated by hydrogeochemical data from Line 4, which is adjacent and continuous with Line 3. A salinity value of 0.01% and an electrical conductivity of 208 μS/cm (Tables 1) indicate that groundwater still meets freshwater criteria based on WHO and SNI classifications (Sulu et al., 2015). These values confirm that no signs of seawater intrusion have yet affected the aquifer system in this area.

Overall, the geoelectrical interpretation along Line 3 suggests that the identified low-resistivity zone most likely represents a freshwater aquifer naturally protected by surrounding impermeable layers. This indicates that the aquifer remains safe from seawater intrusion and holds strong potential as a clean water source for coastal communities.

Nevertheless, it is important to note that the hydraulic balance between groundwater and seawater can change dynamically due to groundwater overexploitation, sea-level rise, and the impacts of climate change. Therefore, regular monitoring of groundwater quality and subsurface resistivity is strongly recommended for the early detection of potential seawater intrusion in the future (Agossou et al., 2022; Rustadi et al., 2022).

The subsurface resistivity modeling along Line 4 (01°27′18.95″–01°27′07.81″ N and 124°45′24.18″–124°45′31.05″ E) (Figure 8), located approximately 5 meters from the shoreline, reveals significant resistivity variations down to a depth of about ±70 meters (Figure 5). The inversion section shows a dominant dark-blue zone with resistivity values ≤10 ohm·m at shallow depths, interpreted as a water-saturated aquifer. These values correspond to the general range of freshwater aquifers, which is 1–100 ohm·m (Muhardi et al., 2020).

This dark-blue zone is inferred to represent an unconfined aquifer that developed within porous sediments such as sand, gravel, silt, and clay. It is overlain by green to yellow zones with resistivity values ranging from about 50–1,000 ohm·m, representing semi-saturated materials such as moist sand, wet clay, or partially consolidated tuff (Ahmad et al., 2020; Putri et al., 2021). At greater depths, brown, orange, red, and dark-purple zones with resistivity values ≥5,000 ohm·m emerge, interpreted as hard rock layers such as volcanic breccia, andesite, basalt, or solidified lava. These impermeable layers act as aquitards, functioning as natural barriers to groundwater flow (Alaydrus, 2022), and form the main geological foundation of the Tateli coastal area (Comte et al., 2017; Siregar, 2017).

Furthermore, at a depth of about 50 meters, specifically between potential electrodes 14 and 16, another dark-blue zone with resistivity ≤10 ohm·m is observed. This zone is presumed to represent a confined aquifer trapped between two impermeable layers. Such aquifer systems are commonly found in coastal areas with Quaternary volcanic rocks and marine sediments, which tend to be more stable and protected from surface water quality fluctuations (Moulds et al., 2023; Sendrós et al., 2021).

The hydrogeological context indicates the presence of two aquifer systems: a shallow unconfined aquifer and a deeper confined aquifer. The shallow aquifer is formed within highly permeable porous sediments and serves as the primary groundwater source in the coastal area. Meanwhile, the deeper aquifer is well-protected by impermeable layers, functioning as a groundwater reserve with relatively stable quality.

The presence of freshwater is further supported by groundwater quality tests from a well located approximately 250 meters from the end of Line 4 toward the shoreline (01°27′12.25″ N – 124°45′29.47″ E). The well shows a salinity of 0.01% and electrical conductivity of 208 µS/cm (Tables 1), indicating that the water still falls under the freshwater category according to WHO and SNI classifications (Permana et al., 2021). This confirms that no seawater intrusion has been detected along Line 4 to date.

Overall, the results of resistivity modeling combined with groundwater quality analysis demonstrate that the study area hosts two active aquifer systems that are still naturally protected by impermeable layers. However, the utilization of groundwater, especially from the deeper aquifer, must be carefully managed to avoid hydraulic pressure decline, which could trigger seawater intrusion (Jeuken et al., 2017). Therefore, management strategies based on resistivity zonation, conservation of recharge areas, and periodic water quality monitoring are strongly recommended to ensure the sustainability and resilience of the Tateli coastal aquifer system against climate change impacts and anthropogenic pressures.

Conclusion

The subsurface resistivity modeling in the coastal area of Tateli Beach revealed the presence of freshwater aquifers, indicated by higher resistivity values compared to low-resistivity zones associated with seawater-saturated layers. This interpretation is supported by salinity and electrical conductivity measurements from groundwater samples, which remain within the freshwater category. In addition, the identification of a deeper aquifer at around 50 meters depth indicates the existence of groundwater reserves that are naturally protected. Therefore, this study concludes that seawater intrusion in the study area is still within a safe threshold, although continuous monitoring is essential to anticipate potential changes in coastal hydrogeological conditions in the future. These findings provide important insights for sustainable groundwater management in coastal areas, particularly in regions vulnerable to seawater intrusion.

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Author Contributions

Conceptualization, data curation, writing-original draft preparation, methodology, formal analysis, investigation,F., and D.P.P.;supervision, writing-review and editing,validation, visualization, M.D.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

All authors declare that there is no conflict of interest.

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