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2D Geoelectrical Resistivity Method For Groundwater Potential Mapping In Coastal Aquifers

I Nengah Simpen
Earth Physics Laboratory, Department Of Physics, Faculty Of Mathematics And Science, Udayana University, Jl. Raya, UNUD Campus, Bukit Jimbaran, South Kuta, Badung, Bali, Indonesia, 80361

Ni Made Widya Pratiwi
Department Of Civil Engineering, Faculty Of Engineering, Warmadewa University, Bali, Indonesia

Abstract
*Groundwater is the primary source of freshwater in many coastal regions; however, intensive groundwater abstraction has increased the risk of seawater intrusion, resulting in groundwater quality degradation. This study aimed to evaluate the capability of the two-dimensional (2D) electrical resistivity method for mapping groundwater potential and identifying seawater intrusion in a coastal aquifer. The survey was conducted using a multichannel resistivity imaging system with the Wenner–Schlumberger electrode configuration, followed by numerical inversion to obtain subsurface resistivity models. Interpretation of resistivity data was verified through borehole drilling and electrical conductivity (EC) measurements of groundwater from both dug and drilled wells. The resistivity model revealed two distinct aquifer systems: an unconfined aquifer with resistivity values ranging from **1.77 to 55.4 Ω·m**, interpreted as being affected by seawater intrusion, and a confined aquifer with resistivity values of approximately **70 Ω·m**, indicating freshwater-bearing formations protected from saline intrusion. Borehole drilling confirmed that fresh groundwater was first encountered at a depth of **12 m** within fractured rock filled with alluvial sand. Electrical conductivity measurements further supported the interpretation, with dug wells exhibiting EC values of **850–1,341.55 µS/cm**, indicating seawater intrusion, whereas the drilled well showed an EC value of **200 µS/cm**, representing good-quality freshwater. These findings demonstrate that the 2D electrical resistivity method is an effective, non-destructive tool for delineating coastal aquifers, identifying seawater intrusion, and determining optimal drilling locations for sustainable groundwater development in coastal areas.*

Keywords: *2D electrical resistivity method, coastal aquifer, groundwater exploration, seawater intrusion, groundwater potential.*

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I. Introduction

Coastal areas are regions with complex hydrological dynamics and a high dependence on groundwater as the primary source for domestic, industrial, and tourism needs[1]–[4]. Population growth, increased economic activity, and limited surface water resources have led to a significant and ongoing increase in groundwater exploitation in coastal areas[5]. These conditions trigger a decline in the groundwater table and cause serious environmental problems, one of which is seawater intrusion into aquifers [6]. Seawater intrusion leads to the degradation of groundwater quality and potentially threatens the sustainability of clean water sources for coastal communities. Therefore, understanding the distribution and potential of coastal aquifers is crucial for maintaining water security in these areas.

From a hydrogeological perspective, coastal aquifers have a unique characteristic: the interaction between freshwater and seawater systems. Under hydrostatic conditions, the presence of a freshwater lens above seawater follows the Ghyben–Herzberg equilibrium principle, whereby a one-meter drop in the freshwater table can cause seawater intrusion up to forty meters inland. This phenomenon highlights the vulnerability of coastal aquifer systems to overexploitation and climate change, including sea-level rise [7]. Therefore, an approach is needed that can provide an accurate spatial representation of the distribution of freshwater and the boundaries of the saline intrusion zone.

Geophysical methods, particularly the 2D Electrical Resistivity Method, are one of the leading approaches for mapping groundwater potential in coastal areas. This technique provides information on the lateral and vertical distribution of subsurface resistivity, enabling a more comprehensive identification of aquifer layers, freshwater saturation zones, brackish water zones, and seawater intrusion compared to traditional

1D electrical resistivity methods. Furthermore, the two-dimensional inversion approach allows for more realistic modeling of subsurface contours in heterogeneous coastal geological conditions [8]–[12].

Although this method has been widely applied in various coastal regions around the world, local geological characteristics, environmental conditions, and differences in survey parameters necessitate more specific applied research in Indonesia's coastal areas. Thus, this study was conducted to analyze the capability of the 2D resistivity method in mapping coastal groundwater potential and delineating indications of subsurface seawater intrusion in detail. The results of this study are expected to contribute scientifically to the development of hydrogeophysics and serve as a basis for technical considerations in the sustainable management of groundwater resources in coastal areas.

II. Material And Methods

Hydrogeology of Coastal Aquifers

Coastal aquifers are hydrogeological systems characterized by the dynamic interaction between freshwater and seawater. The difference in density between the two fluids results in distinctive hydrostatic conditions, in which freshwater naturally floats above seawater. Under steady-state conditions, the depth of the freshwater–seawater interface can be approximated using the Ghyben–Herzberg equation [7], [13], [14], namely:

$z = 40 \cdot h$

where z is the depth of the interface below sea level (m) and h is the height of the freshwater table above sea level (m).

This phenomenon indicates that a 1-meter drop in the groundwater table can cause seawater intrusion of up to approximately 40 meters inland, making coastal areas highly vulnerable to groundwater overexploitation. Furthermore, the variability in the lithology of coastal sediments—generally consisting of sand, silt, and clay—affects the storage capacity and movement of fluids (groundwater) within the aquifer, thus requiring accurate and non-destructive subsurface characterization methods.

Principles of the 2D Electrical Resistivity Method

The electrical resistivity method works by injecting an electric current (I) into the ground through current electrodes, then measuring the potential difference (ΔV) across the potential electrodes. Apparent resistivity (ρ_a) is calculated using [15]

$\rho_a = K \cdot \Delta V / I$

where K is a geometric factor that depends on the electrode configuration. Variations in the measured resistivity values reflect subsurface heterogeneity, including rocks, soil, and the pore fluids that fill them.

2D Electrical Resistivity Method

The 2D electrical resistivity method is a technique for mapping subsurface resistivity using a multi-channel electrode configuration that allows for the creation of lateral and vertical resistivity cross-sections.

Advantages of 2D over 1D include:
- o The ability to model lateral heterogeneity
- o High resolution for complex aquifer systems
- o Effectiveness in detecting seawater intrusion boundaries
- o Generation of subsurface models based on numerical inversion

Resistivity models are obtained through an inversion process designed to minimize the difference between observed data and a theoretical model.

Resistivity Interpretation for Coastal Aquifers Resistivity interpretation

Resistivity interpretations in coastal environments generally refer to characteristic value ranges [15]: Table 1. Reference resistivity values in coastal environments

Geological Environment Resistivity Range (Ωm) Freshwater-saturated sand aquifer hight (≈ 20–100 Ωm) Saturated clay layer Very low (≈ 1–10 Ωm)
Brackish water zone low (≈ 5–20 Ωm)
Seawater intrusion Very very low (≈ < 5 Ωm)

In general, the resistivity range for coastal areas is as follows:[16][17]

Table 2. Typical resistivity values of rocks, soils, and groundwater

No.	Material / Geological	Environment	
1	Mud / Clay	Water-saturated	1–5
2	Sandy Clay	Water-saturated	5–15
3	Silt	Water-saturated	5–20
4	Fine Sand	Water-saturated	10–30
5	Medium to Coarse Sand	Water-saturated	30–100
6	Gravel	Water-saturated	60–300
7	Sandstone	Water-saturated	10–100
8	Sandstone	Dry	500–2,000
9	Limestone	Water-saturated	50–500
10	Limestone	Dry	1,000–10,000
11	Tuff / Volcanic Lapilli	Water-saturated	20–200
12	Massive Volcanic Rock	Dry	>1,000
13	Freshwater Aquifer	—	20–200
14	Brackish Water Aquifer	—	5–20
15	Seawater-Intruded Groundwater System	—	<5
16	Seawater	—	0.2–2
17	Freshwater	—	10–100
18	Brackish Water	—	2–10
19	Shallow Coastal	—	10–50

Freshwater Lens
Saturation Condition / Characteristics
Resistivity Range (Ω·m)
Geological / Hydrogeological Interpretation
Highly conductive, low permeability, commonly acts as an aquitard or confining layer
Transitional layer with low groundwater potential
Semi-permeable material, commonly found in coastal alluvial plains
Shallow aquifer, frequently interbedded with clay
Productive aquifer with good porosity and permeability
Highly productive aquifer with excellent hydraulic connectivity
Resistivity depends on cementation, porosity, and mineral composition
Very high resistivity under unsaturated conditions
Common in coastal karst environments; strongly influenced by fractures and dissolution features
High resistivity; affected by the degree of karstification

Good groundwater potential in coastal volcanic environments
High resistivity due to low porosity and limited water content
Typical resistivity range of freshwater-bearing sedimentary aquifers
Transitional zone, commonly associated with the early stage of seawater intrusion
Highly conductive due to elevated salinity
Highly conductive fluid because of dissolved salts
Resistivity varies with dissolved mineral content
Mixture of freshwater and seawater Frequently degraded by seawater intrusion
20 Capillary Fringe Zone — 5–20
Transitional zone between groundwater and the unsaturated (vadose) zone

III. Data Collection Methods

Survey Design and Route Selection

The survey was conducted in coastal zones showing indications of intensive groundwater use and the potential for seawater intrusion in Candidasa Karangasem Bali. The determination of the geoelectric survey lines took into account the direction of the coastline, geomorphology, accessibility, and the distribution of suspected freshwater aquifer lenses. The measurement lines were arranged parallel to the coastline to capture lateral variations in the freshwater–brackish–saline aquifer system according to field conditions. In this study, a single measurement track with a length of 235 m was constructed

Equipment and Measurement System

Data acquisition utilized a multichannel resistivity imaging system SKILL PRO. This equipment enables simultaneous measurements with internal quality control, noise handling, and an auto-stacking system. The Wenner–Schlumberger electrode configuration was selected for its balanced sensitivity to both vertical and lateral resistivity variations, as well as its reliability in heterogeneous coastal environments.

IV. Research Results

Data analysis was performed using the Res2Dinv program; the results are resistivity contour maps, as shown in the figure, with a margin of error of 7%.

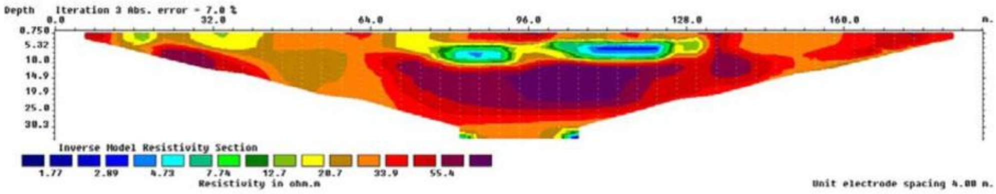

Figure 1. Resistivity cross-section of the survey line

In the study area, there are also dug wells with water table depths ranging from 4 to 6 m. The locations of the survey line, dug wells, and drilled wells are shown in Figure 2.

https://www.google.co.id/maps/@-8.5140498,115.5793704,398m/data=!3m1!1e3?hl=id

1, 2, 3: dug wells

Figure 2. Location of the survey transects, dug wells, and drilled wells

Interpretation of Aquifer Locations

Based on the results of the geoelectric survey, it was found that there are two types of aquifers in the study area: confined aquifers and unconfined aquifers. Unconfined aquifers have low resistivity ranging from 1.77 ohm·m to 55.4 ohm·m. Confined aquifers have resistivity in the range of 70 ohm·m. According to Adepelumi (2009), areas with low resistivity indicate the presence of an aquifer that has been intruded by seawater; the water quality ranges from brackish to low-quality groundwater due to this seawater intrusion. Dug wells were constructed by local residents to extract water from the unconfined aquifer. Based on the results of the geoelectric survey, the area around the dug wells has a resistivity value of approximately 33.9 ohm·m, which means this area has low-quality water. Areas with resistivity values higher than 70 ohm·m are confined aquifers. It appears that the confined aquifer is surrounded by a protective layer. Based on resistivity data [16], [17], this area is part of an aquifer that has not yet been intruded by seawater; therefore, when drilling a well, the water from this aquifer is the best source to tap. In this study, the optimal drilling depth to achieve the best results is between 94 and 98 m, as shown in Figure 3

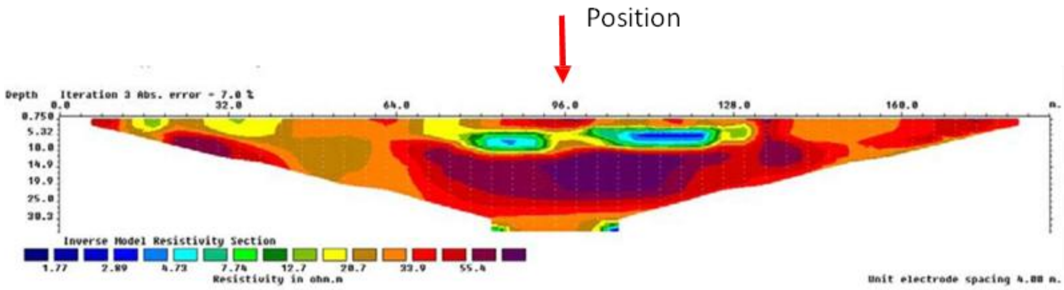

Figure 3. Drilling position

Drilling

In the confined aquifer, a borehole was drilled at the 96 m mark to a depth of 18 m. After drilling, the following rock layers were identified:

Table 3. Lithological log and groundwater conditions from borehole drilling

No.	Depth (m)	Lithology	Description
1	0.00-1.50	Sandy Clay	—
2	1.50-4.00	White Sand	—
3	4.00-5.00	White Sand with Minor Coral Fragments	—
4	5.00	Groundwater Encountered	Groundwater was encountered; the water was saline based on field observation (taste).
5	5.00-8.00	Sand with Coral Fragments	Groundwater remained present.
6	9.00-11.00	Sand with Coral Fragments (larger coral fragments than the overlying layer)	Groundwater was encountered; however, the water had an unpleasant odor.
7	11.00-12.00	Sandy Claystone with Moderately Hard Texture	Groundwater remained present.
8	12.00	Fresh Groundwater Encountered	Good-quality groundwater was encountered and remained present.
9	12.00-17.50	Fractured Rock with Alluvial Sand Filling the Fractures	Groundwater remained present.
No.	Depth (m)	Lithology	Description
10	17.50-18.00	Sandy Claystone with Moderately Hard Texture	Drilling was terminated at this depth.

Good-quality water was first encountered at a depth of 12 m after penetrating relatively hard rock. This aquifer consists of rock fractures filled with alluvial sand. Samples of the rock and alluvial sand collected during drilling are shown in Figure 4. Since the soil layers had become soft, or the fractured rock had run out, drilling was stopped at a depth of 18 m. The well was then lined with casing and a screen from a depth of 14 m downward.

Figure 4. Examples of rock and alluvial sand from the drilling site

Water Analysis

The electrical conductivity (EC) of the well water was then measured for both drilled and dug wells. The EC values are shown in Table 3. Based on Table 3, the drilled well did not experience intrusion, whereas the dug well did.

Table 4. Electrical Conductivity Values of Water from Dug Wells

No.	Well	Depth (m)	Formation Resistivity (Ω·m)*	Well-Water Electrical Conductivity (μmho/cm)	Interpretation [16], [17]
1	Dug Well 1	4	39.9	1,341.55	Seawater intrusion has occurred
2	Dug Well 2	6	39.9	850.00	Seawater intrusion has occurred
3	Dug Well 3	5	39.9	1,288.81	Seawater intrusion has occurred
4	Drilled Well	12	70	200.00	No seawater intrusion was detected

Note: *Based on geoelectrical resistivity data.

V. Conclusion

Based on the results of research conducted using geelectric methods, it can be concluded that this method can map rock resistivity; thus, when planning to drill a well—particularly one near the coast—it is possible to determine which aquifers have been intruded by seawater. Consequently, the well water obtained will not be salty or brackish. This study demonstrates that the geoelectric method plays a crucial role in the construction of boreholes near the coast. Without the aid of the geoelectric method or other geophysical methods, there is no guarantee that the well water obtained will be of good quality.

VI. Recommendations

The results of this study indicate that geoelectric methods play a crucial role in the construction of boreholes near the coast. Without the aid of geoelectric or other geophysical methods, there is no guarantee of finding a good water source. Therefore, when planning to construct a borehole—especially near the coast—it is advisable to conduct a survey first to determine the location of a suitable aquifer.

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