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Research article

An Effective Method for Quantitative Interpretation of Seawater Intrusion in Shallow Aquifers from Electrical Resistivity Data

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Abstract

Groundwater in coastal areas is vulnerable to saltwater intrusion. Electrical resistivity is commonly used in order to detect saltwater intrusion due to its ability to distinguish the occurrence of saltwater in the pore water. In this research, a correlational approach was used to estimate percentage seawater content that was mixed with fresh water in a shallow aquifer. The study area was located in Dumai City, which was covered mainly by peat soil, but some areas were covered by sand and silt. A ground surface resistivity survey and direct soil resistivity measurements were used in the study. For both experiments, the Wenner configuration of electrical resistivity was employed. In order to determine the direct soil resistivity values, measurements of the soil's fluid content and character were made. The findings indicate that the resistivity value in the aquifer increased to 5–10 Ω m at a 25% seawater content, from roughly 2–5 Ω m at a 50% seawater content. The pore soil's rising salt content was the primary source of the sharp decline in resistivity values. By measuring the electrical resistivity on the surface, it is possible to accurately forecast the percentage of seawater mixture in the pore soil fluid.

Keywords: seawater intrusion; electrical resistivity; Dumai; groundwater

1. Introduction

A crucial issue with groundwater in coastal regions is the infiltration of seawater into aquifers beneath the surface. The severity of this issue has escalated to the point where finding fresh groundwater for drinking and everyday necessities is challenging (Basack et al., 2022; Panthi et al., 2022). Overexploitation of groundwater (Alfarrah & Walraevens, 2018; Wu et al., 2020; Armanuos et al., 2022) results in a significant fall in the hydrostatic pressure of the aquifer, and this pressure fall is one factor that allows seawater seepage into the aquifer (Prusty & Farooq, 2020; Baharuddin et al., 2023). In addition, seawater trapped from sedimentation processes in previous geological periods can contribute to seawater

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found in the aquifer (Pramada et al., 2021). According to Larsen et al. (2017), Holocene seawater trapped in the aquifer remains one of the causes affecting the salinity of groundwater.

Several techniques for monitoring seawater incursion have been reported. Using both chemical and physical water analysis, Martínez-Pérez et al. (2022) used an integrated approach to monitor aquifer saltwater intrusion. Furthermore, the tidal effect in an aquifer can be verified using hydraulics studies (Crestani et al., 2022). The identification of alternating silt layers and their continuity can be assisted with the help of the geophysical methods (Kumar et al., 2022). In order to investigate seawater intrusion, electrical resistivity surveys are frequently used (Islami & Irianti, 2021). Moreover, shallow aquifers along coastal regions have been effectively mapped using the electrical resistivity method (Khaki et al., 2014, 2016; Azizah et al., 2019). According to Abdulameer et al. (2018), the electrical resistivity approach was successfully used to map potential seawater intrusion areas in southern Iraq. According to study findings that have been made public to this day, brackish and saltwater intrusions in aquifers can be detected using electrical resistivity.

Nevertheless, there have been no studies to date that use electrical resistivity to directly forecast the percentage of seawater in freshwater in aquifers into which seawater has infiltrated. To ascertain the potential proportion of seawater mixed with fresh water in an aquifer, a correlation approach was employed in this study. Therefore, it was feasible to use an electrical resistivity method to directly forecast the percentage of seawater combined with fresh water.

This investigation was carried out in the Indonesian coastal region near Dumai City. The sites chosen for gathering field data were selected at random among the peat and non-peat regions surrounding the city of Dumai. The coastal region of Dumai is situated right next to the Rupat Strait, which is a portion of the Malacca Strait. Dumai is located in the Central Sumatra Basin, where peat soil covers over thirty percent of the land area. In the Sumatran basin, the peat soil's thickness ranges from roughly 0.5-7 m. In the Dumai region, the aquifer system consists of alternating sand layers that extend from the near surface to a depth of roughly 200 m (Anda et al., 2021). Peat soils predominate in the coastal regions surrounding the Dumai, particularly in the eastern portion of the Dumai up to a few kilometers south of the Dumai city. However, clastic deposits predominate on the soil surface in some areas of the Southwest. A map of the research area is shown in Figure 1. The elevation contours are shown on this map as colored lines. The resistivity survey line is shown in white, the soil sampling positions are indicated by yellow markers, and the water sampling locations are indicated by turquoise circles.



Figure 1. Map of the research area showing the locations of the resistivity surveys, and soil and water sampling points

2. Materials and Methods

Several steps were taken in this investigation. The study started with soil characterization, then moved on to chemical analysis of sea-fresh water mixtures, resistivity measurements of seawater mixed with freshwater variations, resistivity measurements of soils saturated with different combinations of sea-fresh water mixture, and lastly, field measurements of electrical resistivity and the percentage of seawater in the intruded aquifer.

2.1 Soil characterization

Soil samples were collected from several places as seen in Figure 1. Two packets of soil samples, weighing roughly 1 kg each were collected at each site. All soil samples were measured for their grain size using a standard procedure (Teixeira & Martins, 2003) which the soil samples were dried at 50°C for 24 h, and the dried soil was sieved to get their grain size. For the first packet, the soil's grain size was determined using the method mentioned in Hamlin (1991), in which the soil's grain size is divided into gravel, clay, fine, medium, and coarse sands. The second packet was utilized to measure the soil resistivity with different saturated water.

2.2 Water sample analysis

Three bottles of 500 mL water samples were taken at each site. Standard techniques (Clesceri et al., 1999) were then used to analyze the physical and chemical characteristics of the samples. Water in the first packet was used for *in situ* physical character analysis, which included temperature, conductivity, total dissolved solids, and pH. Water in the second and third packets were used for analysis of primary anion and cation content including Cl, SO₄, K, Ca, Mg, and Na, which were determined using Inductively Coupled Plasma Optical Emission Spectrometer (Optima 5300 DV, Perkin Elmer), and Ion Chromatography (861 Advanced Compact IC, Metrohm). The electrical resistivity survey was thereafter calibrated against these water sample chemical data.

2.3 Chemical analysis of sea-fresh water mixture

The primary chemical composition of the seawater and sea-fresh water mixture was determined by measurement. The available well, which was roughly 15 km from the coastline, provided the freshwater samples. The well depth was 12 m below the ground surface. The well altitude was about 16 m above mean sea level. The reason this well was selected was because seawater should have not been able to get inside of it. The primary chemical compositions of a series of mixtures of saltwater and freshwater with 0%, 5%, 10%, 25%, 50%, 75%, and 100% seawater content was measured in the laboratory. The sea-fresh water mixtures were used for analysis of their compositional variation against resistivity variation.

2.4 Direct resistivity measurement of soil saturated with sea-fresh water mixture

Various mixtures of seawater and freshwater were used to saturate the soil samples. The soil samples were for 4 h to make sure that they were fully saturated. All of the saturated soil samples were subjected to direct resistivity measurements in the lab using the Wenner

configuration and 0.05 m electrode spacing. In order to anticipate the percentage of seawater content mixed with freshwater in the aquifer through the analysis of electrical resistivity survey data, these resistivity values from the measurements were later used as a reference.

2.5 Geological and resistivity calibration

To get the actual geological data in the research region, a new well was drilled. The geology and resistivity data were calibrated using this well data. A community area was selected as the well location. Soil samples were taken at the aquifer zone. The resistivity values of soil saturated with a range of sea and freshwater mixtures was also determined using soil samples taken from this well.

2.6 Electrical resistivity survey

The Wenner configuration was used in the field for 1D and 2D electrical resistivity surveys because it provides greater signal strength (Telford et al., 1990) and requires less time for data collection (Loke, 2013). The maximum output voltage and current for the Naniura NRD-300 resistivity meter apparatus used were 1 ampere and 1000 volts DC, respectively. Electrodes were spaced 3 m apart for the 2D electrical resistivity survey, and the total length of the line survey was 120 m. While for the 1D survey, the electrode spacing was also 3 m as the 1D electrical survey (Niculescu & Andrei, 2019). Numerous sites underwent electrical resistivity surveying. The survey started at a distance of roughly 300 m from the coast and extended to 10 km inland. Following observations, the result would clearly show changes in the subsurface resistivity nature. Res1D and Res2DInv softwares by Loke & Barker (1996) and Loke (2001) were used to process the 1D and 2D electrical resistivity data, respectively. On the basis of direct soil measurements and analysis of the saturated sea-fresh water mixtures, the electrical resistivity data were then evaluated. In this way, resistivity measurements at the surface were used to determine the proportion of seawater present in the aquifer.

3. Results and Discussion

3.1 Soil grain size distribution

Table 1 displays the grain size distributions of the soil samples collected from the study region. The Table only includes grain size information from the clastic sediment soil samples. Particle size measurements were not done for peat soils. From Table1, it is evident that no gravel was discovered in the soil samples. Silt and clay predominated in soil samples S01 through S04, which were collected at a depth of 1 m. However, sand predominated in samples S05 and S06, which were drawn from the well newly drilled for this investigation, and the sand was of fine and medium-size.

No Sample	Sampling Depth (m)	Silt and Clay (%)	Fine Sand (%)	Medium Sand (%)	Coarse Sand	Gravel (%)
S01	1	94.7	2.3	3	0	0
S02	1	94.7	2.3	2.9	0	0
S03	1	96	1	2.9	0.1	0
S04	1	91.5	1	7.1	0.4	0
S05	16	0.4	52	40.2	7.4	0
S06	20	0.3	16.5	59.7	23.3	0

Table 1. Soil grain size in selected locations of the study area

3.2 Chemical content of seawater freshwater mixtures

The primary chemical composition of seawater mixtures compared to the standard chemical content of seawater is displayed in Table 2. The source of these numbers was Hounslow (1995). In all of the water samples, CI had the highest content, followed by SO4 and Na. The AL05 water sample, a 5% seawater mixture, exhibited a CI content of 498 mg/L, whereas seawater (AL100) contained CI at a concentration of 16712 mg/L. The scatter plot of data from Table 2 in Figure 2 illustrates the relationship between the percentages of seawater and chemical content. It is evident that when the percentage of saltwater increased (AL00-AL100), the CI concentration rose linearly. Moreover, the other major chemical components of saltwater (SO₄, K, Ca, Mg, and Na) displayed the same linear tendency with the CI. The correlation coefficient (R2) between all chemical concentrations is high, hovering around 1. This implies that the chemical and trend analysis of the seawater were exact and reliable.

Sample ID	Seawater	CI SO₄		К	Ca	Mg	Na
	(%)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
AL00	0.00	11.42	5.00	2.33	11.30	0.7	2.3
AL05	5.00	498.10	79.00	29.12	25.22	50.2	Sat
AL10	10.00	1185.18	162.00	57.42	37.62	87.6	Sat
AL25	25.00	4057.08	227.00	115.44	88.44	264.3	2487.1
AL50	50.00	7444.28	868.00	192.20	186.50	654.4	4882.3
AL75	75.00	10616.22	1184.00	298.40	284.34	995.9	7944.0
AL100	100.00	16712.36	1938.00	378.30	398.80	1272.0	10687.5
Hounslow	Seawater	19000.00	2700.00	390.00	410.00	1350.0	10500

Table 2. Chemical analysis of water samples

Note: The amount of seawater in the water sample varies. The seawater chemical content standard value, which was obtained from Hounslow (1995), is presented in the bottom row of the Table.



Figure 2. Water chemical content varies with the percentage of seawater, (a) Cl and SO₄, (b) Ca and Mg (c) K and Na

3.3 Resistivity and soil property correlation

Figure 3 shows a bar chart plotting the results of direct resistivity measurements on soils saturated with seawater and with a combination of seawater and freshwater. The soil samples that were solely saturated with freshwater exhibited high resistivity in comparison to the other soil samples, as shown in Figure 3. In comparison to soils that were predominantly silt and clay, sand-dominated soils had comparatively high resistivity values. In the silt- and clay-dominated soils, the resistivity value did not appear to vary significantly. This was because, with the exception of peat soil which had a resistivity value of 136 Ω m, which was higher than other soils, all soils had essentially the same granular character. The resistivity values of the soil samples that had been saturated with 25% seawater-fresh water showed a significant decrease to between 10 and 22 Ω m. Additionally, it can be observed that the peat sample, which was similar to the soil soaked with fresh water, had a high resistance value (22 Ω m). This was probably because the soil contained organic matter from fallen trees, which raised the resistivity value (Islami et al., 2023).



Figure 3. Percentage of seawater in the soil samples and resistivity values

Similar resistivity measurement trends for soils with a 25% and 10% seawater content were seen for the samples with a 50% sea-fresh water mixture. Simply put, the resistivity values in the sample with 50% seawater content were generally a little bit lower than resistivity values in the samples with 25% seawater content. Similarly, this trend was also noted in the resistivity values of the samples at 75% and 100% seawater contents. It was evident that a 5% seawater addition to freshwater resulted in a sharp decline in resistivity. This was due to the fact that anion-rich water will significantly raises a material's conductivity rating. As a result, the resistivity values sharply decline. Nevertheless, until the saltwater concentration reaches 100%, the resistivity value decreases exponentially rather than linearly (Figure 3).

3.4 Electrical resistivity survey

A new well (marked as WS2 in the Figure 1) was drilled next to one of the inhabitants' homes in order to calibrate the interpretation of 1D and 2D electrical resistivity data against geological data. The well was utilized by the community for everyday purposes from this time on. The drilling procedure and the lithology log-which was derived from the gathering of soil samples during the drilling process—are shown in Figure 4. Every meter or so during drilling, a soil sample was taken and examined. In this well, embankment soil was present from the top to a depth of 90 cm, followed by dark brown peat soil down to a depth of 5 m. Subsequently, 13 m of dark gray clay soil were discovered. Fine gray sand dominated from 13 to 18 m below the surface, followed by coarse sand down to 24 m. The first aquifer zone, which was frequently utilized by the population for groundwater extraction, was located between 13 and 24 m below the surface. This coarse-grained sand was collected during the soil collection process at a depth of roughly 18 to 24 m. When the sand was exposed to the surface after a few hours, it developed a slight reddish tint. There was a little region of slight color variation below the layer of coarse sand and then a layer of gray clay extended from 24 and 50 m in depth. Fine gray sand, which extended from 50 m to the well's maximum depth of 60 m, makes up the final layer.

The electrical resistivity model shown in Figure 5 was created at a distance of roughly 100 m adjacent to the recently dug well. It was carried out on the resistivity survey (RS02) precisely at the 84-m mark. On the model, electrode positions are plotted on the Xaxis, and depth of data inversion is plotted on the Y-axis. Using the Res2DInv program, the model was created during the inversion phase. It demonstrates that the upper surface had a resistance value of about 180 Ω m and was represented with vellow color in the true resistivity electrical model. Peat in the vadose zone was related to this value. At a depth of around 5 to 12 m, the true resistivity was about 70 Ω m and it likely corresponded to the dark gray clay zone. Next, the resistivity value (turguoise color) was about 40 Ω m corresponded to the aquifer zone at a depth of between 12 and 25 m. The aquifer was made up of sand that had been marginally of less than 5% salt water mixed with the freshwater. This interpretation was based on data in Table 3, which showed that the resistivity value for sandy soils saturated with 5% seawater was around 20 Ω m. Furthermore, the water chemistry data from WS2 (Table 4), which was approximately 100 m away from the electrical resistivity survey line, also provided credence to this conclusion. The groundwater for WS2 had a salinity of 0.2% and a CI level of 276 mg/L, as seen in Table 3. This figure shows that the aquifer had less than 5% of seawater mixed with freshwater.

Figure 5 shows the RS01 and RS02 true resistivity electrical models. In the resistivity model RS01 in Figure 5(b), the resistivity value on the surface was roughly 15 Ω m. The resistivity value of roughly 70 Ω m in the following layer corresponded to the clay layer. The shallow aquifer emerged at a depth of 7 m below the surface. This layer had a resistivity value of less than 5 Ω m. The lowest resistivity value in this zone was 3 Ω m. The percentage of seawater combined with freshwater in this case ranged from around 25% to 50%, based on the resistivity value and the data in Table 3. The groundwater's CI content of 1798.5 mg/L in well WS1, which was located 50 m from the survey line, lends further credence to this quantitative interpretation (Table 4). The resistivity value of seawater (2021) to be approximately 5-10 Ω m.



Figure 4. Drilling process of the new well WS2 (left) and lithology log of the well WS2 (right)



Figure 5. Two dimensional electrical resistivity models for survey lines (a) RS01 and (b) RS02

Seawater	S01	S02	S03	S04	S05	S06	Peat
(%)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)	(Ωm)
0	49.2	47.1	44.4	45.7	108.6	113.4	136.1
5	11.8	11.5	10.9	11.1	19.9	20.0	22.4
10	6.9	7.0	6.7	6.8	11.5	12.1	12.9
25	5.4	5.1	4.9	4.9	9.1	9.4	9.9
50	2.9	2.5	2.4	2.4	4.8	4.9	5.1
75	1.3	1.2	1.2	1.2	2.3	2.4	2.6
100	0.9	0.8	0.8	0.6	1.7	1.8	1.9

Table 3. Direct resistivity measurements of saturated soil containing variations in sea water content

Well ID	Depth	рН	Salinity	TDS	СІ	SO4	к	Ca	Mg	Na	Fe
	(m)		‰	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
WS1	15	7.4	1.1	3260	1798.5	470.2	2.3	73.6	48.8	67.4	0.3
WS2	18	6.9	0.2	792	276.9	69.6	1.5	44.5	21.4	10.2	3.8
WS3	12	6.7	0	163	63.9	12.6	1.3	15.2	3.2	22.2	0.7

Table 4. Physical and chemical data of water samples

Figure 6 displays the outcomes of the 1D modeling of the electrical resistivity survey data used in this investigation. The resistivity model with depth prediction, and the computed and observed data are all visible in this 1D model (Figure 6 (a), (b), (c) and (d)). In order to view and calibrate 1D data with 2D data controlled by well lithology log data, the 2D electrical survey at RS06 was conducted at the same location as RS02 (2D electrical resistivity data). Four layers with different true resistivities were visible in the RS06 electrical model. The resistivity value was about 180 Ω m from the surface to a depth of about 5 m. It is believed that this area is a vadose zone. The zone with a resistivity value of roughly 110 Ω m, which corresponded to the clay zone, is the next resistivity layer. Then another layer with a resistivity value of roughly 23 Ω m is seen at a depth of roughly 11 to 25 m. This area is part of a shallow aguifer. The lithology log data of the wells conducted in this study (Figure 4) confirmed the existence of this aguifer zone, which was similar to RS02. It demonstrates that fine and coarse sand predominated in this depth range. It is evident from the findings of the 1D and 2D electrical resistivity measurements (RS06 and RS02), which were taken at the same location, that at a particular depth, both of them exhibited nearly the same resistivity pattern.

Figure 6 shows the 1D electrical resistivity models for RS03, RS04, RS05 and RS06. No zone has a low resistivity value in RS03. This model shows a shallow aquifer with a resistivity of roughly 80 Ω m at a depth of roughly 11 m to approximately 22 m. This indicates that there is no evidence of seawater present in the shallow aquifer at this site. The groundwater samples from this site (WS3), which had 0% salinity and comparatively low CI (63.9 mg/L), further support this. Additionally, there is no discernible seawater in the aguifer zone at RS04. This interpretation is supported by the fact that the resistivity value in the aquifer zone is approximately 60 Ω m, which indicates that, in accordance with Table 3, the aquifer is entirely composed of freshwater and is not mixed with seawater. While seawater is present in RS05 at 25%, and it is easily noticeable. The resistivity value in the aguifer zone is observed to be approximately 8 Ω m. A quantitative interpretation of the percentage of mixed seawater content in the aguifer can be predicted from 1D and 2D electrical resistivity data by understanding the characteristics of the soil as well as the resistivity of the soil that is saturated with different types of seawater mixtures under freshwater conditions. Finally, depth slices of true resistivity distribution in the research area were produced using interpolation (Figure 7).



Figure 6. One dimensional electrical resistivity models for (a) RS03, (b) RS04, (c) RS05 and (d) RS06





4. Conclusions

A quantitative analysis of electrical resistivity data is clearly demonstrated in this study, particularly in coastal areas where seawater intrusion into freshwater aquifers can occur. In the Dumai area, thorough studies of the properties of the soil, chemical analyses, and direct resistivity measurement were conducted. The resistivity of the soil was partly influenced by the size of the soil grains and it positively correlated with increase in the amount of sand in the soil. There was a strong association between the pore soil content in the aguifer and the electrical resistivity of the soil saturated with a distinct salt-fresh water mixture. When the amount of saltwater was increased, the resistivity value fell off significantly. The primary factor influencing the reduction of the soil's resistivity was the ion content of the water in the pore soil. As the amount of saltwater in the porous soil increased. the resistivity of the soil saturated with the salt-fresh water mixtures decreased. Resistivity data can be used to quantitatively analyze seawater intrusion into an aquifer. The percentage of seawater in the fresh groundwater in the research area's shallow aguifer varied. About 500 m from the coast, it was discovered that 50% of the water in the aquifer was saltwater. In contrast, the aquifer contained roughly 25% saltwater in the area about 5 km from the coast.

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6. Conflicts of Interest

The authors declare that they have no conflicts of interest.

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