Integrated electrical resistivity imaging and groundwater quality assessment for environmental monitoring of shallow aquifers at the Cadika landfill, south Sulawesi, Indonesia

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ABSTRACT

Landfills that are not equipped with protective liners risk producing leachate that seeps into shallow aquifers, thereby reducing groundwater quality. This issue is particularly relevant in tropical regions, where communities still rely on groundwater as their main source of clean water. This study combines two-dimensional electrical resistivity imaging (ERI) with laboratory-based groundwater quality analysis to map leachate migration pathways and evaluate their impact on shallow aquifers around the Cadika landfill in south Sulawesi, Indonesia. Geophysical data acquisition was conducted on seven profiles using a Wenner-Schlumberger configuration with 30 electrodes spaced 6 m apart, with a profile length of 174 m and an effective investigation depth of ±30 m. The resistivity data was then processed using RES2DINV software with a smoothness-based least-squares inversion algorithm, producing a stable subsurface model with an inversion error (RMS error) of between 1.6% and 10.9%. Interpretation revealed a low resistivity zone (<10 Ωm) in the landfill body extending to the rice fields and residential areas, indicating both horizontal and vertical leachate migration. As verification, groundwater and leachate quality tests were conducted at five sampling points with parameters of pH, chemical oxygen demand (COD), biochemical oxygen demand (BOD₅), and dissolved oxygen (DO). The analysis results showed that wells located 25–50 m from the landfill had COD values exceeding the quality standards, while wells located further away showed relatively better water quality. The spatial relationship between the low resistivity zone and the increase in organic pollution indicators confirmed the influence of landfill leachate on the shallow water system. Overall, the integrated approach between the ERI method and groundwater quality analysis is effective in reducing the uncertainty of geophysical interpretation and providing a reliable preliminary evaluation framework for monitoring the impact of landfills on shallow aquifers, particularly in tropical regions with complex hydrogeological conditions.

Keywords: electrical resistivity, leachate, quality testing groundwater, landfill pollution.

INTRODUCTION

Population growth and urban activities in developing regions have led to a significant increase in solid waste production. The increase in the amount and diversity of waste generated from household activities, trade, public facilities, and industry generally ends up in final processing sites (TPA). In many tropical regions, TPAs are still managed as open dumps, which have the potential to cause serious environmental pollution. (Chaerunnisa et al., 2025), especially with regard to shallow groundwater systems used by

communities as a source of clean water (Suresh et al., 2025; Yaashikaa et al., 2022)

One of the main impacts of landfill sites is the formation of leachate, which is liquid resulting from the infiltration of rainwater that interacts with waste deposits and carries dissolved organic and inorganic compounds (Abdel-Shafy et al., 2024). In landfills that are not equipped with impermeable liners and adequate leachate collection systems, leachate has the potential to migrate into the soil and contaminate shallow aquifers. This process is influenced by local hydrogeological conditions, such as soil permeability, lithological heterogeneity, and groundwater depth, making it difficult to directly identify the migration path of leachate below the surface (Gyabaah et al., 2024)

Various studies have examined the physicochemical characteristics of leachate and its impact on groundwater quality. In Indonesia, (Sanjaya et al., 2025). shows that the pH, BOD, and COD parameters in the well water of residents around the landfill exceed water quality standards. Global studies also report that leachate characteristics vary greatly between locations and are influenced by the age of the landfill and its management system, with BOD, COD, and TDS parameters showing a strong correlation with pollution levels (Lindamulla et al., 2022; Ma et al., 2022) However, a water quality-based approach alone cannot explain the spatial distribution patterns and migration pathways of leachate beneath the surface.

In addition to environmental chemistry approaches, geophysical methods, particularly resistivity geophysical methods, have been widely used to identify zones that conduct electricity easily and are associated with the presence of leachate. Several studies have shown that leachate tends to accumulate or migrate in certain layers characterised by low resistivity values, using both Schlumberger and Wenner configurations. (Trujillo-romero et al., 2025). However, some of these geoelectric studies were not accompanied by water quality testing for validation, so the interpretation of low resistivity zones remains potentially ambiguous and difficult to directly correlate with actual groundwater contamination levels. (Suryadi et al., 2020)

This condition indicates a research gap in the form of a lack of an integrated approach that links subsurface spatial information obtained from geophysical methods with the physicochemical

characteristics of groundwater. Without such integration, understanding of the leachate migration mechanism and its impact on shallow aquifers remains partial, especially in tropical regions with heterogeneous geological conditions and high community dependence on shallow groundwater (Obiri-Nyarko et al., 2023)

One location that has the potential to experience this problem is the Cadika TPA in Gowa Regency, South Sulawesi. This TPA has been operating since 1996 and is located very close to residential areas, thereby increasing the potential risk of environmental pollution. Geologically, the Cadika landfill is located on relatively permeable alluvial deposits from a former quarry, which has the potential to facilitate leachate movement towards shallow aquifers. No research on leachate in this area has ever been conducted. Previous studies have only examined water pollution, particularly metal content, so the analysis was limited to a single water quality parameter. These conditions have not been able to provide a comprehensive picture of the level of pollution and the migration pathways of leachate (Riadi et al., 2021)

Therefore, this study combines two-dimensional resistivity geophysical methods with laboratory analysis of groundwater quality to identify the distribution of leachate and evaluate its impact on shallow aquifers around the Cadika landfill. Specifically, this study aims to (1) map the distribution of low resistivity zones indicated as leachate distribution below the surface, and (2) evaluate the quality of residents' wells based on selected physicochemical parameters to assess the potential for groundwater contamination. This integrated approach is expected to improve the reliability of geophysical interpretation and provide a stronger scientific basis for assessing the risk of groundwater contamination in the landfill area.

Based on this framework, this study is based on the hypothesis that zones with low resistivity values identified through the geoelectric method are spatially related to increased indicators of organic pollution, particularly chemical oxygen demand (COD) and biochemical oxygen demand (BOD_5), in shallow aquifer systems around the Cadika TPA.

MATERIALS AND METHODS

Study area

The research location is at the Cadika TPA, Gowa Regency, South Sulawesi Province, Indonesia. This area was chosen as the research site because the Cadika TPA has been operating for a long time with a non-engineered management system and is located very close to residential areas. These conditions increase the potential risk of contamination of shallow groundwater, which is used by the community as their main source of raw water.

The Cadika landfill stands on a former quarry site with geological characteristics consisting of alluvial deposits comprising gravel, sand, clay and silt. The area surrounding the landfill is dominated by rice fields, ponds and residential areas. The presence of shallow aquifers in relatively permeable alluvial material makes this area prone to leachate migration into the groundwater system.

The majority of residents around the Cadika landfill still rely on dug wells and shallow bore wells to meet their daily domestic water needs. Therefore, this location represents the typical conditions of landfill areas in tropical regions that face serious challenges in leachate management and groundwater quality protection. The research location and surrounding environmental conditions are shown in Figure 1.

Mapping lindi distribution using the geophysical method (spatial verification)

The two-dimensional (2D) resistivity geophysical method with a Wenner-Schlumberger configuration was used to monitor leachate distribution. This configuration was chosen because it has balanced sensitivity to lateral and vertical resistivity variations and a stable signal-to-noise ratio (Godio and Chiampo, 2023). These characteristics make the Wenner-Schlumberger configuration effective for delineating conductive zones associated with leachate in heterogeneous subsurface environments, such as in non-engineered landfill systems in tropical regions.

Electrical resistivity measurements were conducted on seven transects covering the landfill body, leachate pond, rice fields, and surrounding residential areas. Each line used 30 electrodes with a spacing of 6 metres between electrodes, resulting in a measurement line length of 174 metres. With this configuration, the effective investigation depth obtained was approximately ±30 metres, which was considered sufficient to represent the shallow aquifer conditions at the study site.

The orientation of the traverses was adjusted to the field conditions and potential direction of leachate migration, with four north-south traverses and three west-east traverses. Data acquisition was carried out using a Geomative GD-10 Supreme multi-electrode geoelectric system, with
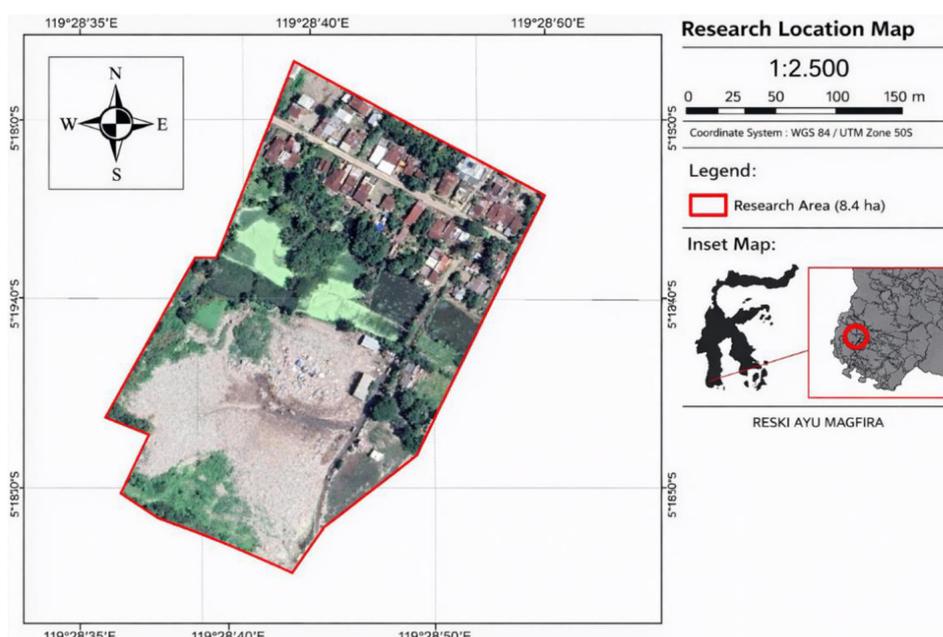

Figure 1. Research location map

measurements of electric current (I) and potential difference (ΔV) to obtain the apparent subsurface resistivity value. The geoelectric survey activities in the field are presented in Figure 2 as evidence of data acquisition and measurement configuration at the research site.

Geophysical data processing and inversion

The apparent resistivity data obtained from the measurements was processed using RES2D-INV software to produce a two-dimensional subsurface resistivity distribution model. The inversion process was carried out using a smoothness-constrained least squares algorithm until a sufficient level of convergence was achieved between the measured data and the calculated data.

Topographic correction was applied to profiles with significant elevation differences, namely profiles 5, 6, and 7. The inversion error values (root mean square/RMS error) obtained ranged from 1.6–2.7% on Traverses 1–4, 4.5–6.4% on Traverse 5, 8.1–10.9% on Traverse 6, and 2.4–5.1% on Traverse 7. These RMS values indicate a good level of agreement between the measured data and the inversion model, so the interpretation results are considered reliable.

Zones with low resistivity values (<10 Ωm) (Muzambiq et al., 2023) interpreted as a conductive zone potentially affected by the presence of leachate, in accordance with the resistivity characteristics of leachate and contaminated groundwater in previous landfill studies.

Water quality testing as laboratory validation (quantitative proof)

Water quality testing was conducted as a final stage to validate the results of subsurface mapping using the resistivity geophysical method and to examine the relationship between low resistivity zones and groundwater pollution conditions. Water samples were collected at five points, consisting of three community wells located around the low resistivity zone resulting from geoelectric interpretation, one leachate pond, and one water reservoir pond in the TPA area. The community wells used as sampling points were located at a distance of approximately ±25 metres, ±50 metres, and more than 100 metres from the TPA boundary. Groundwater and leachate sampling in the field is presented in Figure 3 to show the sampling procedure carried out directly at the research site.

Water samples were collected using sterile containers in accordance with national standards and analysed at the accredited laboratory of the Faculty of Fisheries and Marine Sciences, Hasanuddin University. The water quality parameters analysed included pH, chemical oxygen demand, five-day biochemical oxygen demand, and dissolved oxygen. After laboratory testing, the pH, COD, BOD₅, and DO values at each sampling point were spatially mapped by compiling a distribution map for each parameter. The distribution map was created based on the sample location coordinates (Arif and Syamsuddin, 2025), so that water quality variation patterns can be visualised and directly compared with low resistivity zones resulting from geoelectric interpretation. BOD and COD parameters are used as the main indicators of organic pollution that potentially originates from leachate seepage through shallow groundwater systems (Koda et al., 2017; Qian et al., 2024). This water quality testing evaluation was conducted based on Indonesian National Standards, whereby water quality was analysed using SNI 6989. 11: 2019, 6989.2: 2019, and 6989.72: 2009, but DO and

Figure 2. (a) Geophysical instrument inspection process (b) Geomative GD-10 Supreme geophysical instrument

Figure 3. Water sampling process

BOD$_5$ were only limited to values for determining BOD$_5$. Water quality values were analysed by comparing them to Class I water quality standards based on Government Regulation No. 22 of 2021, while leachate quality was compared to leachate quality standards in accordance with Minister of Environment and Forestry Regulation No. P.59 of 2016. The results of this water quality test were used as quantitative validation to confirm the relationship between the results of geophysical resistivity interpretation and the actual level of pollution in the field.

Integration of geophysical data and water quality

Data integration was performed by spatially correlating the well location and water sampling point with the area of low resistivity interpretation of geoelectric results. Wells located within or close to the conductive zone were evaluated for pollution level using parameters such as pH, COD, and BOD$_5$. The appropriateness of the low resistivity areas and the increasing organic pollutant parameters were used to assess the relationships between the geophysical response and the actual groundwater pollution conditions. The integrated approach is aimed at reducing the ambiguity of the geoelectric data interpretation and enhancing the reliability of the melanin migration assessment toward the shallow aquifer system in the engineered landfill environment.

RESULTS AND DISCUSSION

Characteristics of subsurface resistivity and indications of leachate migration

An investigation of subsurface conditions around the Cadika landfill was conducted using a resistivity geophysical approach with a Wenner–Schlumberger configuration on seven measurement lines. Each line was 174 m long with 6 m electrode spacing and 30 electrodes. The location and orientation of all lines relative to the landfill body, leachate pond, rice fields, and residential areas are shown in Figure 4.

The two-dimensional inversion results show that, in general, the subsurface resistivity distribution is divided into three main groups, namely high resistivity (±40–150 Ωm), medium resistivity (±10–40 Ωm), and low resistivity (<10 Ωm). Based on local geological conditions dominated by alluvial deposits, high resistivity is interpreted as layers of sand and gravel saturated with fresh water, while medium resistivity is interpreted as sandy clay saturated with fresh water. Low resistivity zones (<10 Ωm) (Muzambiq et al., 2023; Ali et al., 2025) interpreted as a conductive medium associated with the presence of leachate or aquifers that have been affected by leachate.

On Trajectory 1 and Trajectory 2, which are located in the northern part of the study area and relatively far from the landfill body, no low resistivity zones were found. The resistivity cross-sections on both trajectories were dominated by high to medium resistivity, indicating shallow aquifers that were still saturated with fresh water
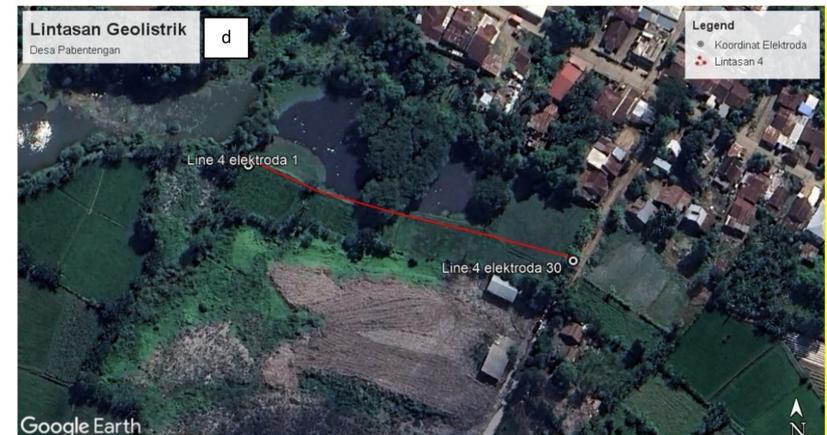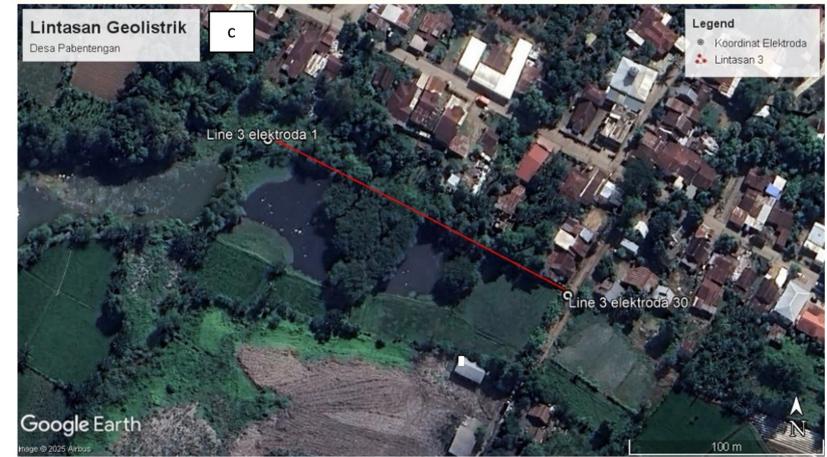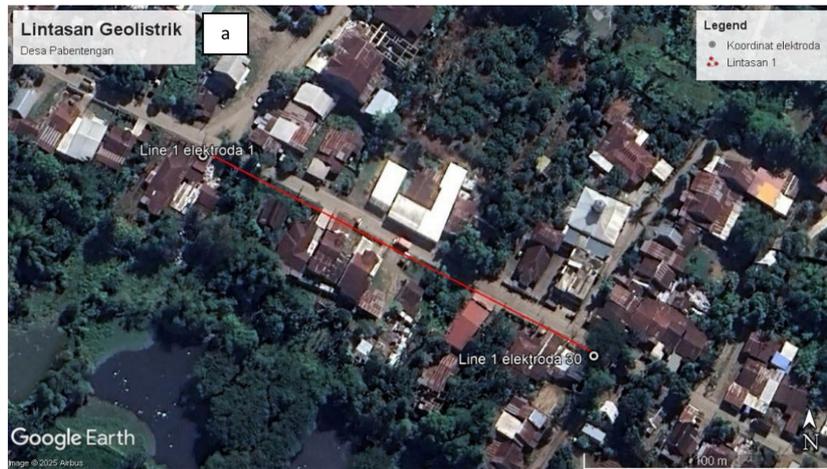
Figure 4. Traverse locations at TPA Cadika, Pabbentengan village: (a) traverse 1, (b) traverse 2, (c) traverse 3, (d) traverse 4, (e) traverse 5, (f) traverse 6, (g) traverse 7

and showed no signs of leachate contamination. A representative cross-section of the zone relatively unaffected by leachate is shown in Figure 5. These findings indicate that leachate migration has not developed northwards from the landfill site.

Conversely, indications of leachate presence began to be identified on the transect located in the transition zone between the landfill and the surrounding environment. On transect 3, located near the water pond, a low resistivity zone (<10 Ωm) was detected in the middle of the cross-section at a depth of approximately 15–20 m. On section 4, which is in the rice field area between the landfill and the residential area, a low resistivity anomaly also appeared at a depth of approximately 20 m. A similar pattern was found in section 5,
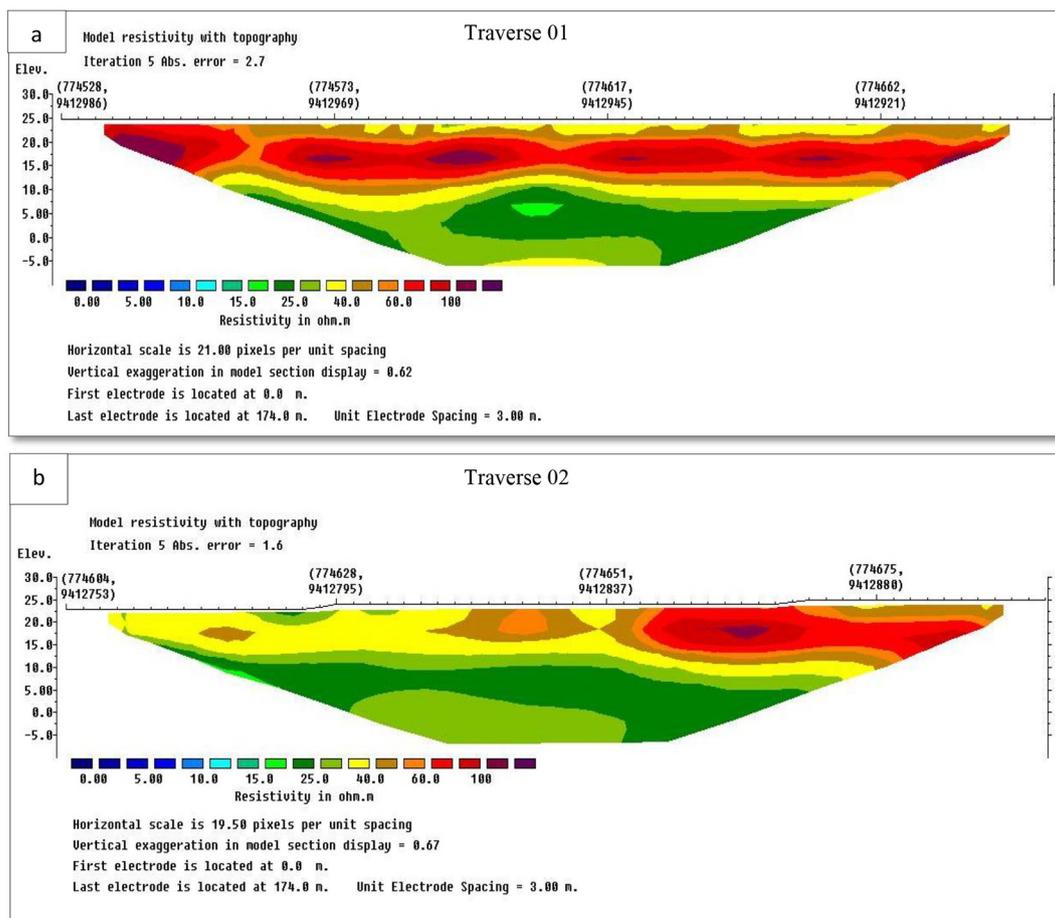
Figure 5. a) 2D resistivity traverse I using RES2DINV, (b) 2D resistivity traverse II using RES2DINV

with a more developed low resistivity zone at a depth of 5–20 m. The resistivity cross-sections of the transects representing indications of leachate migration outside the landfill body are shown in Figures 6, 7, and 8. The appearance of conductive zones in transects 3, 4, and 5 indicates horizontal migration of leachate from the landfill area to the surrounding environment, particularly towards rice fields and shallow water-saturated zones.

Indications to the source and the accumulation of leachate are most obvious in two traverse that located directly within the TPA boundary, i.e. traverse 6 and traverse 7. In traverse 6 low resistivity zone (<10 Ωm) is clearly defined on the top and the bottom of waste pile, from a depth of about 0 to 20m. These conductive zones are interpreted as leachate accumulation trapped in mining pit subsidence basin and at the bottom of the waste pile. A resistivity section of this traverse is shown in Figure 9.

On Traverse 7, in addition to a similar pattern of leachate accumulation at shallow depths (0–20 m), a continuous low resistivity zone was also identified at greater depths, namely around 10–30 m in the middle of the cross-section. This pattern indicates vertical leachate migration towards deeper aquifer layers. The resistivity cross-section of traverse 7 is presented in Figure 10 and provides important evidence of the potential for vertical leachate seepage beneath the landfill body.

The inversion results for the entire traverse show good quality, with absolute error values ranging from 1.6% to 8.1%. The evaluation of the quality of the geoelectric data inversion for traverses 1 to 7 is presented in Figure 11, which shows good agreement between the measured resistivity data and the inversion model. These relatively low error values increase the level of confidence in the interpretation of subsurface lithology and the delineation of conductive zones associated with the presence of leachate.

Overall, the geoelectric results confirm that the Cadika landfill is the main source of leachate accumulated within the landfill body. The results also show that leachate has migrated horizontally to the surrounding area and show indications
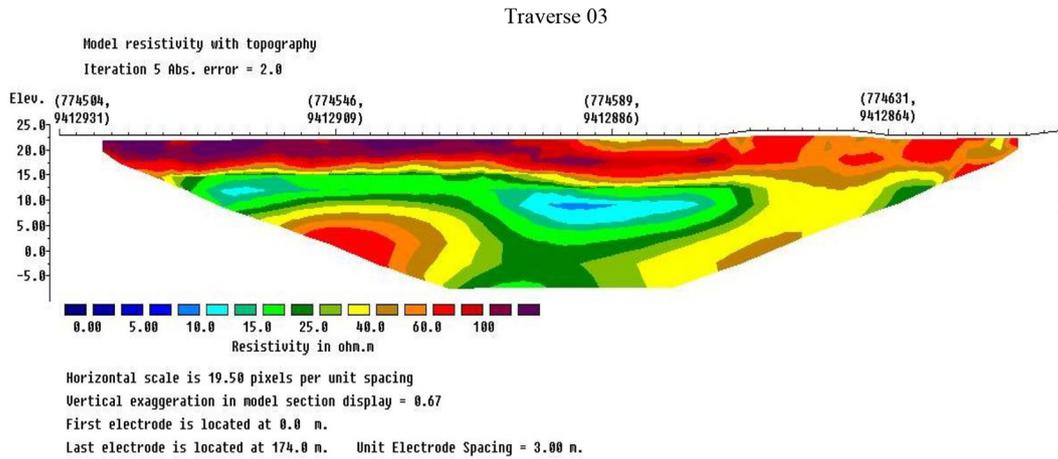
Traverse 03

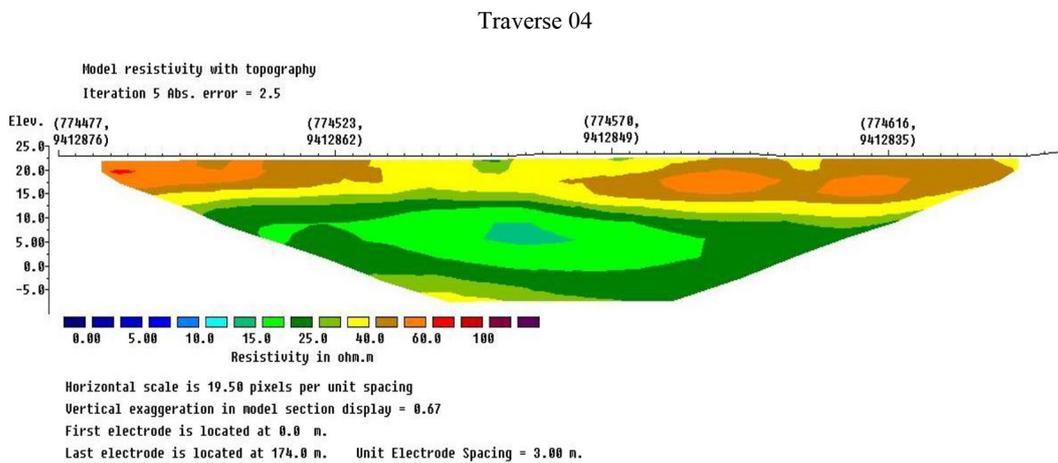**Figure 6.** Resistivity 2D traverse III using RES2DINV

Traverse 04

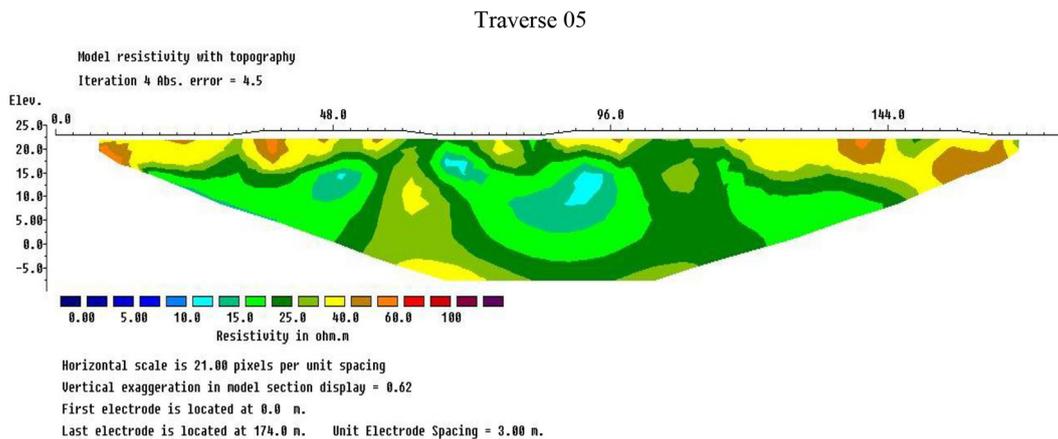**Figure 7.** Resistivity 2D traverse IV using RES2DINV

Traverse 05

Figure 8. Resistivity 2D traverse V using RES2DINV

of vertical migration towards deeper aquifers. This distribution pattern is an important basis for further validation through groundwater and leachate quality testing, which is discussed in the next subsection.

Groundwater quality as laboratory validation

The results of groundwater quality tests show variations in pH, COD, BOD, and DO values between sampling locations around the Cadika
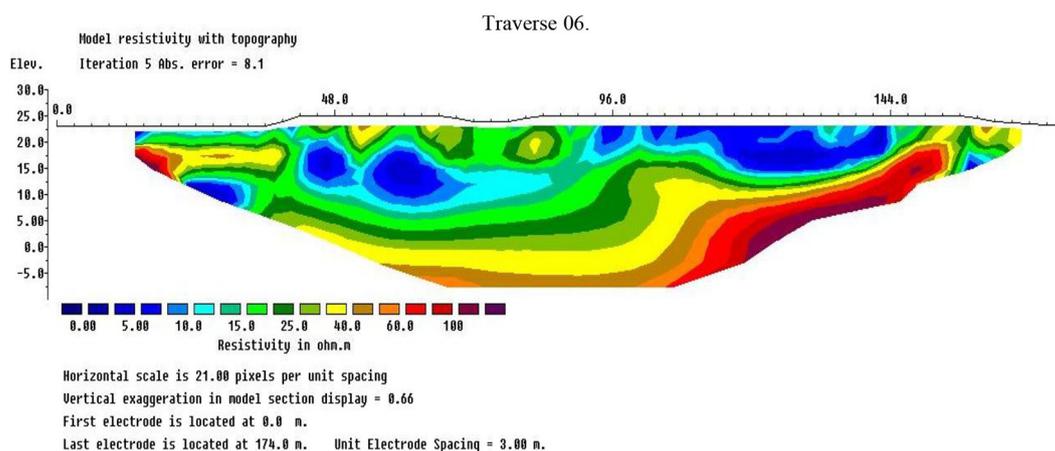
Traverse 06.

Figure 9. Resistivity 2D traverse VI using RES2DINV
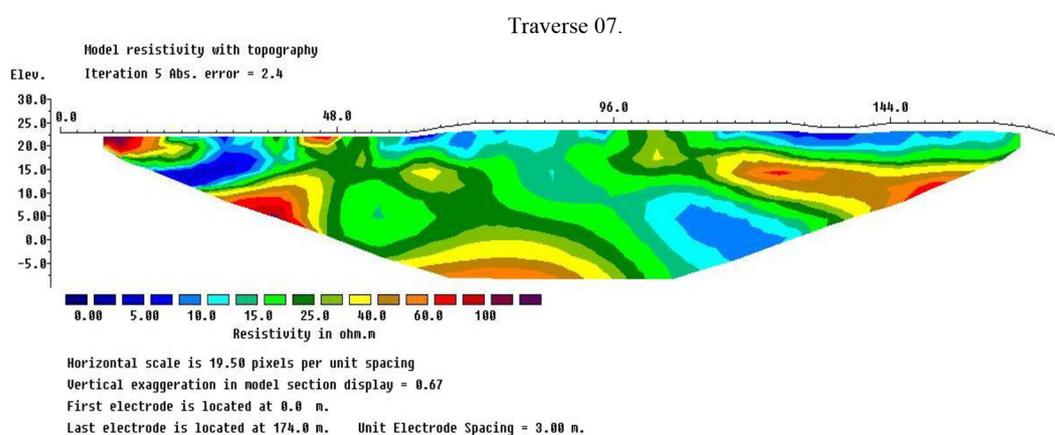
Traverse 07.

Figure 10. Resistivity 2D traverse VII using RES2DINV

landfill (Table 1). These variations reflect differences in water chemistry and organic pollutant loads in shallow aquifers used by the community as a source of domestic water.
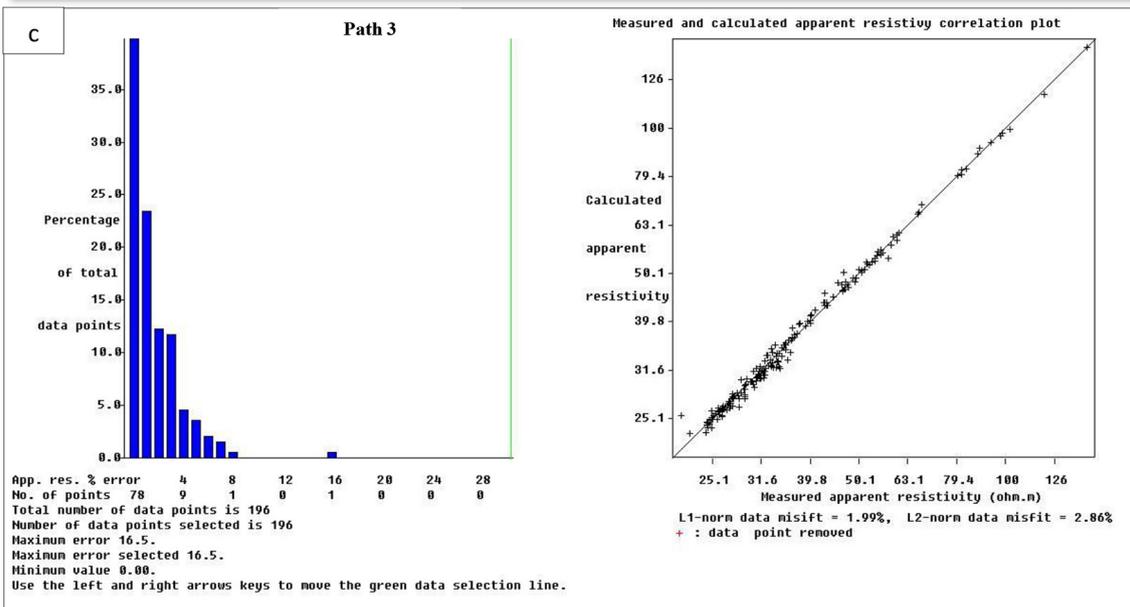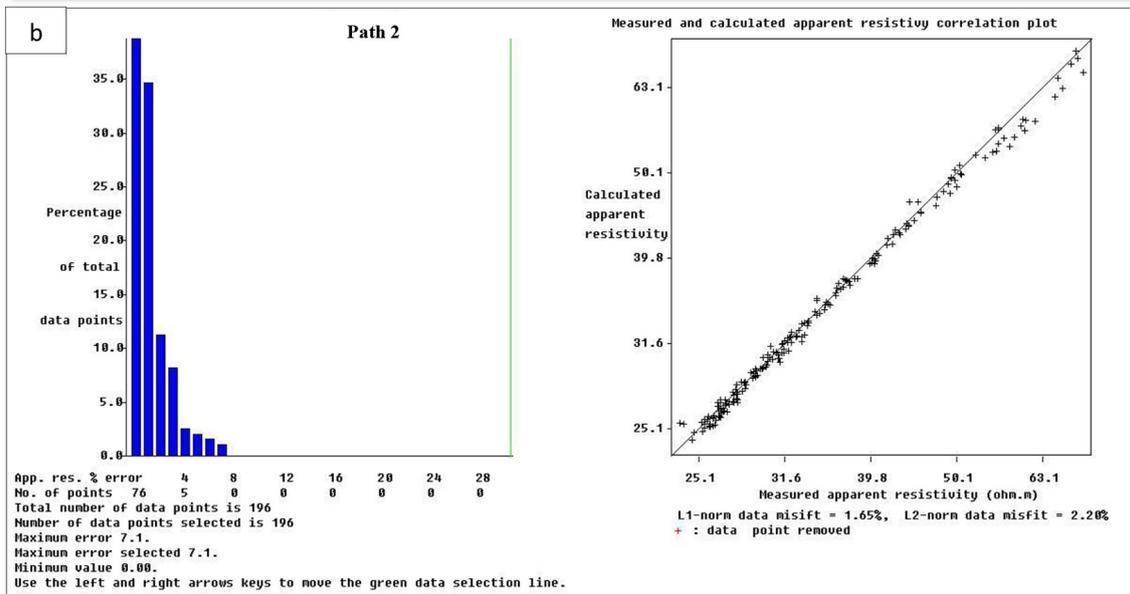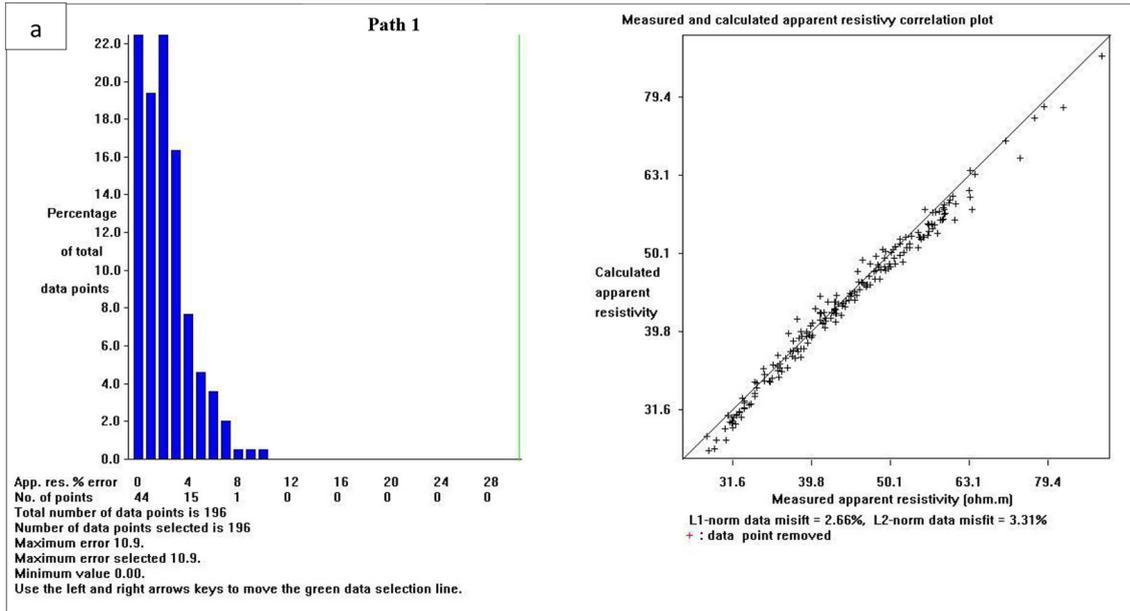
Characteristics of soil water pH

Based on laboratory test results, the pH value of residents' well water ranged from 6.55 to 7.03, while the pH of leachate and retention ponds ranged from 7.28 to 7.49. The distribution of pH values is visualised in the soil water pH distribution map (Figure 12). All pH values are still within the water quality standards based on Government Regulation No. 22 of 2021, so that in general the acidity level of water in the study area is classified as neutral to slightly alkaline.
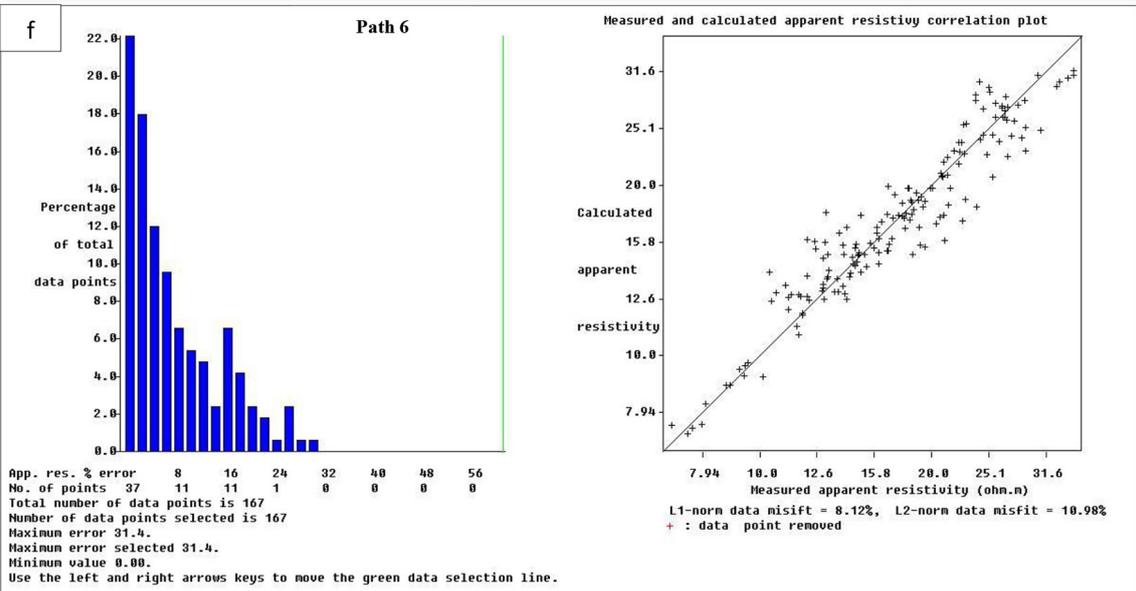
There were no significant differences in pH between locations, indicating that leachate infiltration had no significant effect on changes in groundwater acidity. The natural buffering capacity of the local alluvial soil material, which is able to neutralise chemical changes in water at the early stages of contamination, is thought to be responsible for this condition.

Characteristics of groundwater COD

Unlike pH, the COD parameter shows more contrasting variations between sampling locations. Two community wells located relatively close to the landfill, at a distance of approximately ±25 metres and ±50 metres, had COD values of 17.5 mg/L and 31.0 mg/L, which exceeded the Class I water quality standard based on Government Regulation No. 22 of 2021. Conversely, the residential well located further away from the landfill (±200 metres) showed a much lower COD value of 4.5 mg/L, which still meets the water quality standard. The spatial distribution of groundwater COD values is visualised in the groundwater COD distribution map (Figure 13).

a

Path 1

Measured and calculated apparent resistivy correlation plot

App. res. % error   0   4   8   12   16   20   24   28
No. of points   44   15   1   0   0   0   0   0
Total number of data points is 196
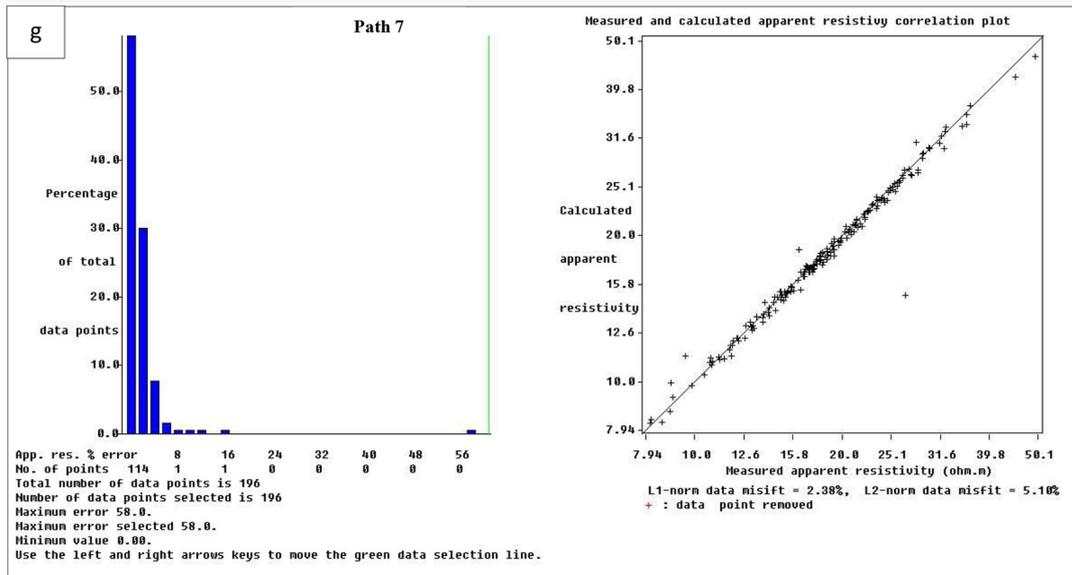Number of data points selected is 196
Maximum error 10.9.
Maximum error selected 10.9.
Minimum value 0.00.
Use the left and right arrows keys to move the green data selection line.

L1-norm data misift = 2.66%, L2-norm data misfit = 3.31%
+ : data point removed

b

Path 2

Measured and calculated apparent resistivy correlation plot

App. res. % error   4   8   12   16   20   24   28
No. of points   76   5   0   0   0   0   0
Total number of data points is 196
Number of data points selected is 196
Maximum error 7.1.
Maximum error selected 7.1.
Minimum value 0.00.
Use the left and right arrows keys to move the green data selection line.

L1-norm data misift = 1.65%, L2-norm data misfit = 2.20%
+ : data point removed

c

Path 3

Measured and calculated apparent resistivy correlation plot

App. res. % error   4   8   12   16   20   24   28
No. of points   78   9   1   0   1   0   0   0
Total number of data points is 196
Number of data points selected is 196
Maximum error 16.5.
Maximum error selected 16.5.
Minimum value 0.00.
Use the left and right arrows keys to move the green data selection line.

L1-norm data misift = 1.99%, L2-norm data misfit = 2.86%
+ : data point removed

Figure 11. Inverse path quality graph: (a) path 1, (b) path 2, (c) path 3, (d) path 4, (e) path 5, (f) path 6, (g) path 7

Table 1. Results of soil water, leachate, and retention pond quality tests around the Cadika landfill site

No	Sample location	pH	COD (mg/L)	DO (mg/L)	BOD (mg/L)	Notes on applicable quality standard
1	Community well (approximately 200 metres from the landfill site)	7.03	4.5	6.40	4.16	COD meets standards, BOD exceeds water quality standards
2	Community well (approximately 50 metres from the landfill site	6.55	31.0	3.84	1.92	COD does not meet water quality standards
3	Community well (approximately 25 metres from the landfill site)	6.93	17.5	3.20	1.60	COD does not meet water quality standards
4	Landfill leachate pond	7.49	25.2	4.80	3.20	Meeting the quality standards for lindi
5	Storage pond	7.28	25.0	5.76	2.56	Meets effluent quality standards, BOD exceeds water quality standards

Note: Groundwater quality standards refer to Government Regulation No. 22 of 2021 (Class I) (Indonesian Government, 2021). Leachate quality standards refer to Minister of Environment and Forestry Regulation No. P.59 of 2016.(Indonesia, 2016).
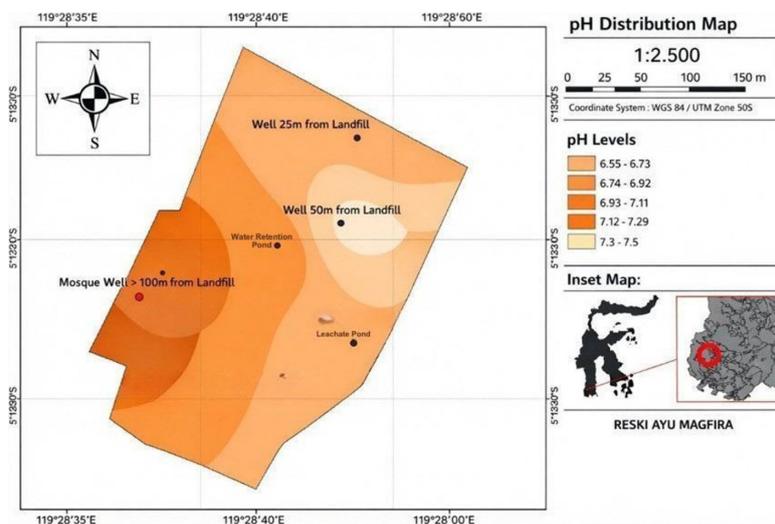

Figure 12. pH distribution map

Higher COD values in wells adjacent to the landfill indicate an increase in oxidised organic and inorganic matter in shallow groundwater. These findings show that the COD parameter is more sensitive in detecting the impact of landfill activity on groundwater quality than pH, and may be related to leachate infiltration or the accumulation of organic matter from the landfill's surrounding environment.

The relationship between BOD and DO n water quality assessment

The results of BOD and DO testing provide a more in-depth picture of the biochemical processes occurring in groundwater (Allawi et al., 2024). The BOD value of residents' wells ranged from 1.60 to 4.16 mg/L, while the DO value ranged from 3.20 to 6.40 mg/L. When compared to Class I water quality standards, the maximum permissible BOD value is 2 mg/L, meaning that several wells do not meet these standards. The distribution of groundwater BOD values is visualised in the groundwater BOD distribution map (Figure 14).

The DO parameter is analysed as an integral part of groundwater quality assessment and is used as a basis for calculating BOD values (Mohammad et al., 2024). The distribution of groundwater DO values is shown in the groundwater DO distribution map (Figure 15).

The relatively low DO values in wells located near the landfill reflect high oxygen consumption due to microbial activity in decomposing dissolved organic matter (Sefa-Ntiri et al., 2020). This condition is reflected in increased BOD values and indicates that the decline in groundwater quality involves active biochemical processes in the shallow aquifer, not just physical changes (Khadra et al., 2024).

However, the relatively high BOD values in wells located ±200 metres from the landfill do not directly indicate the influence of leachate. This is indicated by low COD values and high DO levels, which suggest that the organic matter at these locations is localised and easily degradable, possibly originating from domestic activities around the wells. These findings indicate that the BOD parameter does not always follow the distance gradient to the landfill, but is also influenced by local environmental conditions.

Comparison with the quality of runoff water and retention ponds

The results of leachate water quality tests from the leachate pond showed higher BOD and COD values than the residents' well water, but these values were still below the leachate water quality threshold based on Minister of Environment and Forestry Regulation No. P.59 of 2016 (Table 2).

This indicates that, in regulatory terms, the quality of the leachate still meets standards, despite containing a relatively high organic load.

The storage pond exhibits different characteristics because, in addition to functioning as part of the leachate management system, it is also used by
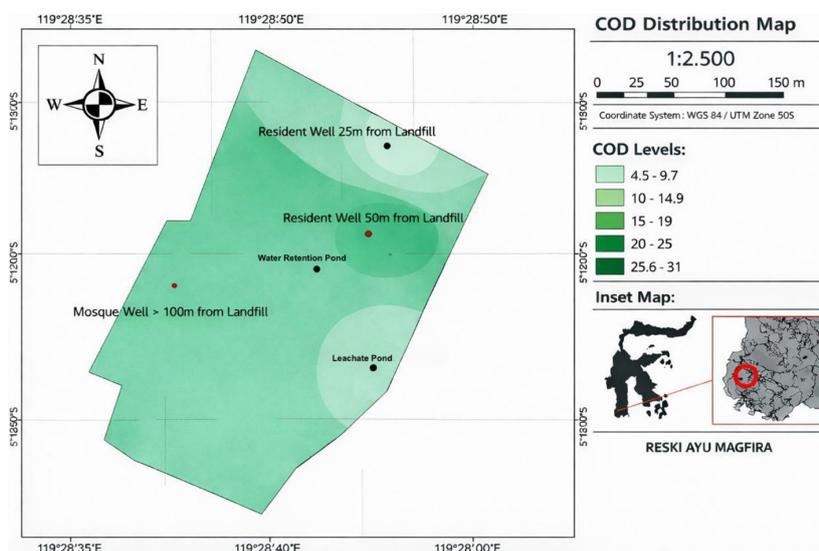
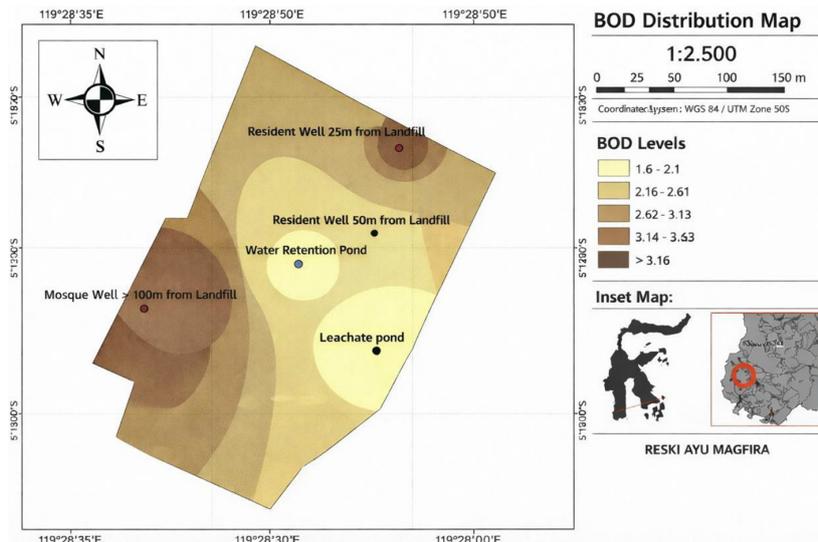

Figure 13. COD distribution map
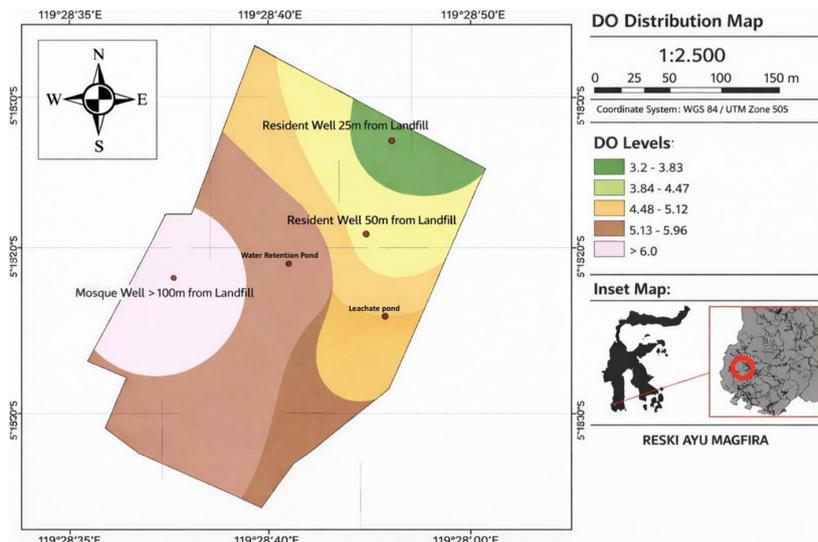
Figure 14. BOD distribution map

Figure 15. DO distribution map

Table 2. Results of leachate water quality tests and retention ponds at the Cadika landfill

No	Sample location	pH	BOD (mg/L)	COD (mg/L)	Compliance with leachate quality standards	Compliance with water quality standards
1	Landfill leachate pond	7.49	3.20	25.2	Fulfilling	Irrelevant
2	Storage pond	7.28	2.56	25.0	Fulfilling	The BOD does not meet

the local community for fishing and fish consumption. Therefore, the quality of the storage pond water needs to be evaluated not only based on leachate quality standards, but also compared to Class I water quality standards. BOD values in storage ponds that exceed water quality standards indicate a potential environmental and health risk if the water and aquatic biota are used continuously.

The correlation between high COD values in leachate, increased COD in wells adjacent to the landfill, and decreased DO in several locations reinforces the interpretation that leachate acts as a potential source of organic pollutants that can affect the quality of shallow groundwater around the Cadika landfill, although the intensity and characteristics of the pollution still vary locally.

CONCLUSIONS

This study confirms the effectiveness of an integrated approach that combines two-dimensional electrical resistivity methods – electrical resistivity imaging (ERI) with groundwater quality analysis in monitoring shallow aquifer conditions around the Cadika TPA in Gowa regency, south Sulawesi. The application of the Wenner-Schlumberger configuration produced a fairly accurate subsurface image, allowing conductive zones with low resistivity (<10 Ωm) to be clearly identified as an indication of the presence and movement of leachate. The distribution pattern of these low resistivity zones shows that the Cadika FDS is the main source of leachate, with migration occurring horizontally towards rice fields and residential areas, as well as vertically through deeper aquifer layers.

In the context of environmental monitoring, the ERI method has proven capable of capturing the diversity of subsurface conditions in complex tropical alluvial environments, where surface observations alone are insufficient to detect groundwater movement pathways. The main advantage of the electrical resistivity technique is its ability to map subsurface conditions non-invasively, covering a wide area, and providing continuous spatial information on zones potentially exposed to contamination.

The integration of geoelectric results with laboratory analysis of groundwater quality significantly improves the accuracy of interpretation. The high COD values in residents' wells located 25–50 meters from the landfill indicate a consistent spatial relationship with the low resistivity zone resulting from geoelectric modelling. These findings confirm that leachate infiltration plays a role in reducing the quality of shallow groundwater around the Cadika landfill, while also proving that combining geophysical data with hydrogeochemistry can reduce the ambiguity of interpretation that often arises in resistivity surveys without additional data support.

Although this approach shows good results, there are a number of limitations. Groundwater quality assessment is still limited to a relatively small number of sampling points and does not yet consider temporal variations. Dynamic factors such as seasonal rainfall intensity, groundwater level fluctuations, and changes in leachate characteristics over time have also not been included in the analysis. Therefore, further research is recommended to integrate multi-temporal geoelectric monitoring with time-based water quality

assessment to obtain a more comprehensive understanding of leachate migration dynamics.

Overall, this study provides a strong scientific basis for landfill management and groundwater resource protection in tropical regions. The integrated framework between resistivity geophysical methods and groundwater quality analysis is applicable and transferable to other locations, thus having the potential to be used as an early warning system to support pollution mitigation, spatial planning, and sustainable environmental management in landfill sites with similar geomorphological and hydrogeological conditions.

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