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Integrated Hydrogeophysical Characterization of Residual Landfill-Derived Contamination beneath the Reclaimed Keputih Municipal Solid Waste Landfill (Indonesia) Using Two-Dimensional Electrical Resistivity Tomography

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Abstract

Municipal solid waste (MSW) landfills remain potential sources of environmental contamination long after closure because residual leachate can continue to migrate through shallow aquifers for decades. Although many former landfill sites have been successfully rehabilitated into urban green spaces, the long-term persistence and spatial distribution of subsurface contamination beneath reclaimed land remain poorly understood, particularly in tropical coastal environments. This study investigates residual leachate beneath the former Keputih Municipal Solid Waste Landfill, Surabaya, Indonesia, approximately 24 years after landfill closure, using two-dimensional Electrical Resistivity Tomography (ERT) with a Wenner–Schlumberger array.

Six ERT profiles (80–100 m long; 5 m electrode spacing) were acquired across the reclaimed landfill and inverted using a smoothness-constrained least-squares algorithm implemented in RES2DINV. The inverted models reveal pronounced subsurface heterogeneity, with resistivity values ranging from 0.95 to 482 Ωm. Distinct low-resistivity anomalies (<10–15 Ωm), interpreted as residual leachate, are concentrated beneath Survey Lines 1–3, whereas Survey Lines 4 and 6 are dominated by relatively resistive materials. In contrast, the conductive anomaly identified along Survey Line 5 is spatially associated with a surface pond and is interpreted as water-saturated sediments rather than landfill-derived contamination. The distribution of conductive anomalies follows local topographic gradients and inferred groundwater-flow directions, indicating that hydrogeological conditions continue to govern contaminant migration long after landfill closure.

These findings demonstrate that high-resolution ERT provides a rapid, non-invasive, and cost-effective approach for long-term assessment of reclaimed landfill sites. More importantly, this study shows that integrating geophysical imaging with geological, hydrogeological, topographic, and groundwater-quality information substantially reduces interpretation uncertainty and enables more reliable identification of residual leachate in complex coastal alluvial settings. The proposed integrated interpretation framework provides a transferable methodology for post-

closure landfill assessment, environmental risk evaluation, and sustainable management of reclaimed landfill environments undergoing ecological restoration and urban redevelopment.

Keywords: Electrical Resistivity Tomography; Municipal Solid Waste Landfill; Residual Leachate; Wenner–Schlumberger Array; Environmental Geophysics; Post-Closure Monitoring; Tropical Coastal Environment

1 Introduction

Municipal solid waste (MSW) landfills can remain sources of subsurface environmental contamination long after active waste disposal has ceased. Although closure, capping, and surface rehabilitation can substantially reduce direct exposure to buried waste, they do not necessarily eliminate residual contaminant sources or the hydrogeological pathways through which dissolved constituents migrate. During prolonged degradation of the waste mass, dissolved organic compounds, ammonium, chloride, major ions, and trace elements may remain available for transport by groundwater. The composition and persistence of landfill-derived leachate depend on waste characteristics, degradation stage, infiltration, redox conditions, and hydrogeological setting (Christensen et al., 2001; Kamaruddin et al., 2017; Kjeldsen et al., 2002). Landfill closure should therefore be regarded as a transition from active waste management to long-term environmental stewardship rather than as the definitive termination of contamination risk.

This persistence is particularly important where former landfills overlie shallow and permeable aquifer systems. Groundwater can provide hydraulic pathways connecting residual waste, leachate-affected sediments, and downgradient receptors, while sedimentary heterogeneity can produce preferential routes and locally variable contaminant distributions. Long-term investigations have shown that contamination-related electrical and hydrochemical signatures may remain detectable after landfill closure and that their spatial distribution can be highly heterogeneous rather than forming a simple, continuous plume (Helene et al., 2020; Kondracka et al., 2021). As landfills mature, changes in waste degradation and leachate composition can further modify contaminant mobility and transport. These processes are particularly relevant at reclaimed sites, where substantial ecological restoration at the surface may coexist with persistent hydrogeochemical perturbations in the underlying subsurface.

Characterising residual contamination is challenging because its distribution reflects the coupled effects of waste degradation, sedimentary heterogeneity, groundwater flow, recharge, and local hydrogeological structure. Conventional monitoring wells and groundwater sampling provide direct information on water chemistry, but measurements are spatially discrete and may not adequately resolve the geometry, continuity, or preferential pathways of

contamination between sampling locations. Hydrogeophysical methods can complement such observations by providing spatially distributed information on subsurface physical properties. Electrical methods are particularly useful because bulk resistivity responds to pore-fluid conductivity, saturation, lithology, and pore structure, allowing hydrogeological contrasts associated with potentially contaminated zones to be investigated non-invasively (Binley et al., 2015; Loke et al., 2013).

Among these methods, Electrical Resistivity Tomography (ERT) has been widely applied to landfill investigations because ion-rich leachate can produce pronounced resistivity contrasts relative to surrounding materials. (Helene et al., 2020) demonstrated the use of ERT to identify leachate infiltration and infer preferential flow pathways, whereas (Maurya et al., 2017) showed that two- and three-dimensional resistivity imaging could delineate leachate-affected zones whose low-resistivity responses were consistent with ionic-strength measurements from monitoring wells. The principal value of ERT in such applications is therefore its ability to image the geometry and continuity of subsurface electrical contrasts between discrete sampling locations.

The interpretation of these contrasts is inherently non-unique, however, because low resistivity is not diagnostic of landfill leachate alone. Clay-rich sediments, saline groundwater, high saturation, mineralogical effects, and other naturally conductive materials can produce similar electrical responses. This ambiguity is particularly important in coastal environments, where salinity gradients and geological heterogeneity can influence both groundwater flow and bulk electrical properties (Greggio et al., 2018; Kreyns et al., 2020). Consequently, resistivity magnitude alone cannot establish the presence or origin of contamination. Conductive anomalies should instead be interpreted using multiple lines of evidence, including their magnitude, geometry, depth, lateral continuity, relationship to former waste-disposal areas, topographic position, hydrogeological setting, and consistency with independent hydrochemical observations.

Such integrated interpretation is particularly important for reclaimed landfill sites. Geophysical investigations of former waste deposits have demonstrated the value of combining complementary datasets to resolve subsurface heterogeneity and reduce interpretational uncertainty (Kondracka et al., 2021). Likewise, landfill ERT studies indicate that comparison of resistivity patterns with groundwater or leachate chemistry can strengthen the interpretation of conductive zones. ERT is therefore best regarded not as a direct chemical detector of leachate, but as a spatial imaging method whose environmental interpretation requires geological, hydrogeological, and hydrochemical constraints.

The former Keputih Municipal Solid Waste Landfill in eastern Surabaya, Indonesia, provides a

distinctive setting in which to investigate these issues. The landfill operated from approximately 1970 until permanent closure in 2001 and was subsequently transformed into the Keputih Bamboo Forest and Harmony Park through extensive ecological rehabilitation. The site therefore represents a long-closed landfill where substantial surface restoration has occurred while the buried waste mass and underlying hydrogeological system remain part of the subsurface environment. Available monitoring data have reported elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) in groundwater in the vicinity of the former landfill, indicating that environmental pressures may persist despite surface rehabilitation. Previous geophysical investigations have also identified conductive subsurface zones interpreted as potentially landfill-related. However, these investigations did not provide the high-resolution shallow two-dimensional resistivity imaging required to systematically examine the geometry, continuity, and possible controls on conductive anomalies beneath the restored landscape.

Three related knowledge gaps motivate the present study. First, field-based evidence concerning the persistence of potentially landfill-derived conductive fluids more than two decades after closure and ecological rehabilitation remains limited. Second, the shallow architecture and continuity of residual conductive zones beneath restored landfill surfaces remain insufficiently resolved by high-resolution geophysical imaging. Third, in tropical coastal environments, distinguishing landfill-derived electrical responses from those associated with lithological heterogeneity, groundwater saturation, and salinity remains a substantial interpretational challenge. Addressing these temporal, spatial, and attributional uncertainties is important for determining whether surface ecological rehabilitation is accompanied by corresponding subsurface recovery and for developing appropriate post-closure monitoring strategies.

To address these gaps, this study applies two-dimensional Electrical Resistivity Tomography using the Wenner–Schlumberger electrode configuration to characterise the shallow subsurface beneath the reclaimed Keputih Landfill. The Wenner–Schlumberger configuration provides a practical compromise between vertical and lateral sensitivity and has been widely used in near-surface electrical imaging where both signal strength and spatial resolution are important (Dahlin and Zhou, 2004; Loke et al., 2013). Six ERT profiles were distributed across representative sectors of the reclaimed site to: (i) characterise the spatial distribution and magnitude of subsurface resistivity; (ii) delineate conductive anomalies that may be associated with residual landfill-derived fluids; and (iii) evaluate the relationships between these anomalies and geological conditions, topographic gradients, groundwater-flow conditions, and available groundwater-quality data.

The working hypothesis is that conductive anomalies occurring beneath or hydraulically

connected to the former waste-disposal area may reflect electrically conductive pore fluids influenced by residual landfill-derived constituents, while their geometry and continuity are controlled by local lithological and hydrogeological conditions. This hypothesis is evaluated using a multi-criteria interpretation rather than a resistivity threshold alone. Specifically, conductive features are assessed according to their magnitude, geometry, depth, lateral continuity, spatial relationship to the former landfill boundary, topographic position, hydrogeological setting, and consistency with independent groundwater-quality observations. This approach explicitly recognises the non-uniqueness of ERT and distinguishes features supported by multiple independent observations from anomalies that may have alternative geological, saturation-related, or salinity-related explanations.

The principal contribution of this study is a site-scale hydrogeophysical framework for evaluating the distribution and probable origin of conductive anomalies beneath a reclaimed tropical landfill approximately 24 years after closure. By integrating high-resolution ERT with geological, hydrogeological, topographic, and groundwater-quality information, the study assesses the evidence for persistent landfill-related conductive fluids and examines the environmental controls governing their spatial organisation. Rather than treating resistivity anomalies as direct indicators of contamination, the proposed framework provides a process-oriented basis for evaluating competing explanations for subsurface electrical responses beneath an ecologically rehabilitated landfill. The results support targeted groundwater monitoring, post-closure environmental assessment, and land-use management, while providing a potentially transferable approach for reclaimed landfill sites in tropical coastal regions where lithological heterogeneity, shallow groundwater, and salinity gradients complicate the interpretation of electrical geophysical data.

2 Geological and Hydrogeological Setting

The study was conducted at the former Keputih Municipal Solid Waste (MSW) Landfill in Sukolilo District, eastern Surabaya, East Java, Indonesia (**Figure 1**). The landfill operated from approximately 1970 to 2001 and served as a major municipal waste-disposal facility for Surabaya before permanent closure. Following closure, the site underwent extensive ecological rehabilitation and was subsequently transformed into the Keputih Bamboo Forest and Harmony Park, which now form part of Surabaya's urban green-space network (Septiani, 2022; Tucunan et al., 2018). Although surface land use has changed substantially, the historical waste mass and the underlying subsurface environment remain. Previous investigations in and around the former landfill have reported elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) in groundwater, suggesting that groundwater quality remains affected in the vicinity of the former landfill (Masitoh and

Saifanto, 2024). More broadly, studies of historic and reclaimed landfills demonstrate that contaminant legacies can persist beyond active disposal and may continue to affect surrounding groundwater and coastal environments (O'Shea et al., 2018; Parvin and Tareq, 2021).

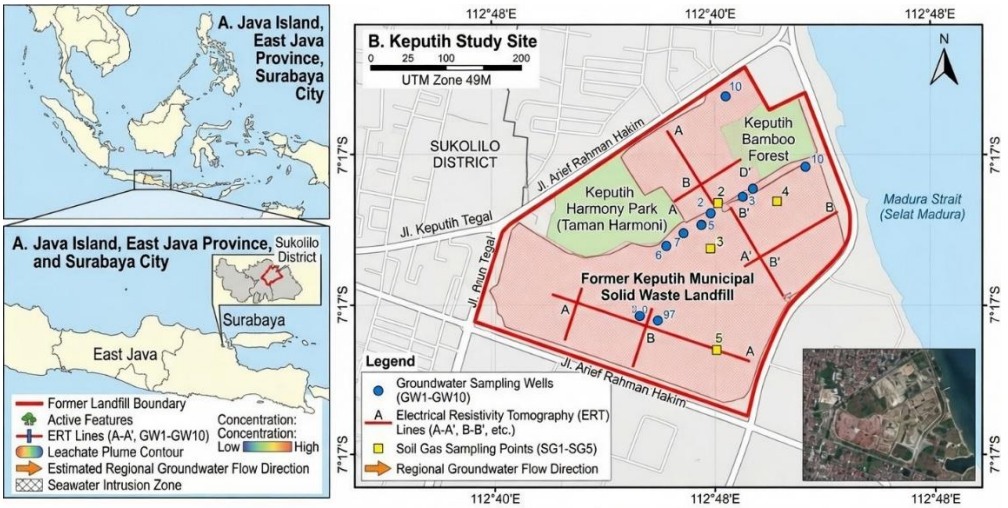


Fig. 1. Location of the former Keputih Municipal Solid Waste Landfill in Sukolilo District, eastern Surabaya, East Java, Indonesia, showing the six Electrical Resistivity Tomography (ERT) survey lines.

Geologically, the study area lies within the Quaternary alluvial deposits of the northern East Java Basin (**Figure 2**). The regional sequence comprises unconsolidated clay, silt, sand, and gravel, with locally developed organic-rich materials. Depositional processes associated with fluvial and coastal environments have produced pronounced lateral and vertical variability in grain size, porosity, permeability, and hydraulic conductivity. Fine-grained clay- and silt-rich horizons generally have lower hydraulic conductivity and may locally impede vertical groundwater movement, whereas sand- and gravel-rich intervals form comparatively permeable pathways for groundwater circulation and dissolved-solute transport. This sedimentary heterogeneity is particularly important for interpretation of the present ERT data because variations in lithology, saturation, pore-fluid conductivity, and pore structure can generate substantial resistivity contrasts independently of landfill-derived fluids (Hibbs, 2024; Javed et al., 2024; Loke et al., 2013).

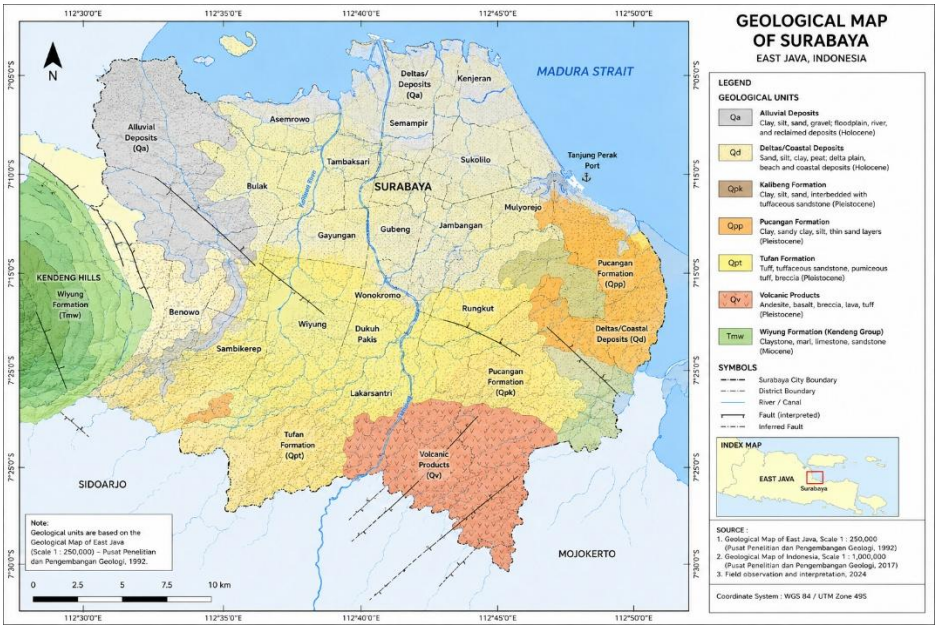


Fig. 2. Geological map of the Surabaya area showing the distribution of Quaternary alluvial deposits and the location of the former Keputih Landfill (modified from the Geological Map of Surabaya).

The shallow groundwater system constitutes a key component of the Keputih hydrogeological setting, as shown in **Figure 3.** The area is characterised by a shallow coastal aquifer in which groundwater occurs at relatively shallow depths. Hydrogeological assessment of the Sukolilo area reports groundwater levels of approximately 1.5 m below ground level, hydraulic conductivity of about 22 m day^{-1} over much of the study region, and a shallow-aquifer thickness generally below 10 m (Bahri et al., 2017). These characteristics indicate a relatively shallow and hydraulically responsive groundwater system in which recharge and groundwater movement can occur through the more permeable portions of the alluvial sequence.

Within this heterogeneous succession, hydraulically connected sand- and gravel-rich horizons may provide preferential pathways for groundwater and solute transport, whereas finer-grained layers can locally restrict vertical movement and promote lateral spreading along more permeable horizons. Such contrasts are directly relevant to ERT interpretation because the geometry of a conductive anomaly reflects the combined effects of pore-fluid conductivity, saturation, and the electrical properties and architecture of the host sediments. The presence of shallow groundwater and relatively permeable alluvial materials therefore creates conditions under which dissolved constituents released from historical waste deposits may remain mobile. Nevertheless, the magnitude and direction of contaminant transport cannot be inferred from the regional hydrogeological setting alone and require site-specific geological,

hydrochemical, and geophysical constraints (Dang et al., 2025; Hoque and Burgess, 2020).

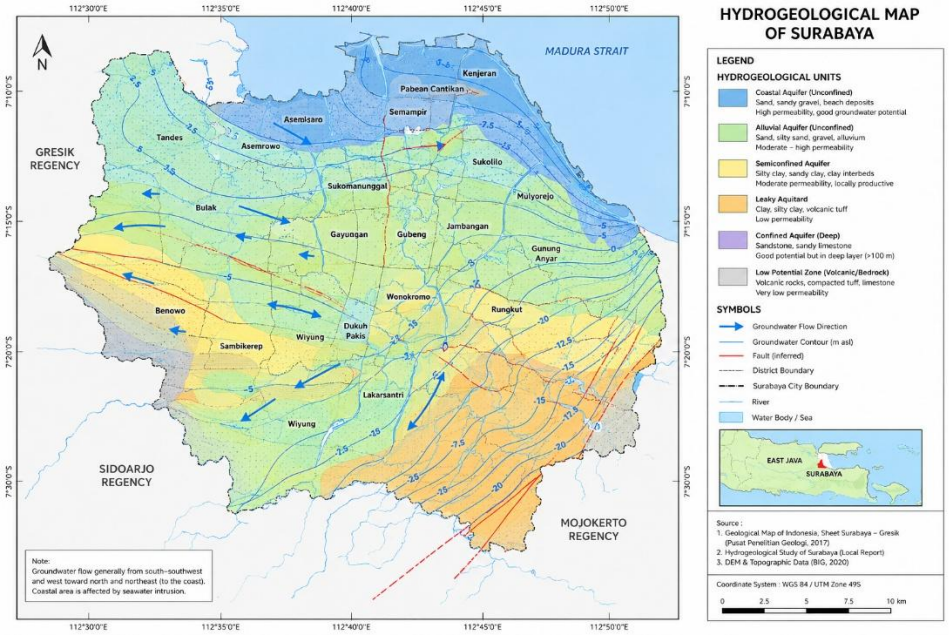


Fig. 3. Hydrogeological map of the Surabaya area showing regional groundwater flow direction, aquifer characteristics, and the location of the study area.

Regional hydrogeological information indicates a general groundwater-flow tendency toward the coastal zone and the Madura Strait. Investigations of the former Keputih landfill likewise indicate an overall eastward tendency toward the sea. This regional or site-scale pattern should not, however, be interpreted as evidence of a uniform groundwater-flow direction beneath the reclaimed landfill. Local groundwater movement may vary over relatively short distances in response to lithological heterogeneity, spatially variable recharge, topographic gradients, surface-water interactions, and local hydraulic conditions. Accordingly, the regional flow direction is treated in this study as a hydrogeological constraint rather than as direct evidence of the transport pathway of individual ERT anomalies. Residual landfill-derived fluids may instead be redistributed along preferential permeability pathways that are not resolved by regional groundwater-flow information alone.

The coastal position of Keputih introduces an additional constraint on interpretation of the electrical data. The landfill is located near the Madura Strait, and hydrogeochemical investigations indicate that both landfill-related inputs and coastal salinity may influence groundwater chemistry in the surrounding area (Mangimbulude et al., 2016). Groundwater-vulnerability assessments for Sukolilo also indicate susceptibility to seawater intrusion, with increasing electrical conductivity and chloride concentrations toward the coastal zone. These

conditions are particularly relevant to ERT because both saline or brackish groundwater and landfill-derived fluids increase pore-fluid conductivity and can consequently produce low-resistivity responses.

Low resistivity therefore cannot be regarded as definitive evidence of landfill-derived contamination at Keputih. Clay-rich sediments, high saturation, saline or brackish groundwater, and other naturally conductive materials may produce similar electrical signatures. Previous hydrogeophysical investigations have consequently emphasised the need to interpret resistivity distributions together with geological structure, groundwater conditions, topography, and hydrochemical information rather than relying on resistivity magnitude alone (Chang et al., 2023; Helene et al., 2020). This requirement is particularly important at Keputih, where both landfill-related hydrochemical impacts and coastal salinity provide plausible explanations for enhanced electrical conductivity.

In the present study, conductive anomalies are therefore evaluated using multiple lines of evidence, including resistivity magnitude, geometry, depth, lateral continuity, spatial relationship to the former landfill boundary, geological and lithological context, topographic position, regional hydrogeological setting, and consistency with available groundwater-quality observations. The objective is not to assign a landfill-related origin solely on the basis of low resistivity, but to determine whether individual conductive features are more consistent with residual landfill-derived pore fluids than with alternative explanations such as clay-rich materials, elevated saturation, or saline/brackish groundwater. This multi-evidence framework also distinguishes anomalies supported by independent geological or hydrochemical observations from those for which the geophysical interpretation remains inherently ambiguous.

The reclaimed surface is dominated by mature bamboo vegetation associated with the ecological rehabilitation of the former landfill. Vegetation can influence shallow electrical properties through evapotranspiration, root-water uptake, and the accumulation and decomposition of organic matter, thereby modifying near-surface moisture conditions. These processes may contribute to local variability in the shallowest portions of the ERT models. However, because spatially resolved soil-moisture measurements were not available, the magnitude of vegetation-related effects cannot be independently quantified. Interpretation therefore does not attribute shallow resistivity variations to vegetation alone but considers them together with lithology, groundwater conditions, saturation, and possible landfill-derived pore fluids.

The combination of historical waste deposits, heterogeneous Quaternary alluvial sediments, shallow groundwater, coastal hydrogeological conditions, and extensive post-closure

ecological rehabilitation makes Keputih a particularly informative setting for investigating the persistence and spatial organisation of subsurface conductive anomalies more than two decades after landfill closure. The site also provides a useful test of ERT interpretation because landfill-derived fluids and saline or brackish groundwater represent competing sources of enhanced pore-fluid conductivity. By explicitly incorporating the geological framework, groundwater conditions, coastal setting, topography, and available hydrochemical evidence, the present study establishes the basis for evaluating whether conductive features identified by ERT are more consistent with residual landfill-derived fluids or with alternative geological and hydrogeological controls. This framework is subsequently applied to the six ERT profiles to interpret the observed subsurface patterns and assess their implications for post-closure environmental monitoring.

3 Methodology

3.1 Research Design

This study adopted a non-invasive hydrogeophysical approach based on two-dimensional Electrical Resistivity Tomography (ERT) to characterise the shallow subsurface beneath the reclaimed Keputih Municipal Solid Waste Landfill and to identify conductive zones that may be associated with residual landfill-derived fluids. ERT is well suited to environmental investigations because it provides spatially distributed information on subsurface electrical resistivity while requiring minimal surface disturbance, an important consideration at a rehabilitated landfill site (Chao et al., 2024; Helene et al., 2020; Song et al., 2023; Tsai et al., 2021). In landfill environments, measured resistivity reflects the combined effects of lithology, saturation, pore-fluid conductivity, and subsurface structure. Conductive responses may therefore provide useful evidence of leachate-affected materials, but they cannot be interpreted independently of the geological and hydrogeological setting (Capa-Camacho et al., 2022; Maurya et al., 2017; Song et al., 2023).

The methodological workflow comprised four sequential stages: (i) survey design and field acquisition of ERT data; (ii) quality control and inversion of apparent-resistivity measurements; (iii) interpretation of the inverted resistivity models; and (iv) integration of the geophysical results with geological, hydrogeological, topographic, and groundwater-quality information. This integrated approach was adopted to address the inherent non-uniqueness of resistivity interpretation, particularly in heterogeneous coastal environments where low-resistivity responses may originate from lithological, saturation-related, salinity-related, or anthropogenic sources (Ali et al., 2025; Binley et al., 2015; Loke et al., 2013; Mendecki et al., 2025).

3.2 ERT Survey Design and Data Acquisition

Six ERT profiles were established across representative sectors of the reclaimed landfill to investigate spatial variations in subsurface electrical properties under contrasting site conditions (**Table 1**; **Figure 4**). Profile lengths ranged from 80 to 100 m, with a constant electrode spacing of 5 m. This configuration yielded an approximate investigation depth of 15–20 m while retaining adequate lateral resolution for characterising shallow subsurface heterogeneity (Dahlin and Zhou, 2004; Loke et al., 2013).

Table 1. Locations and acquisition parameters of the six ERT survey profiles, including WGS 84 geographic coordinates, survey orientations, and profile lengths used for subsurface imaging at the reclaimed Keputih Municipal Solid Waste Landfill, Surabaya, Indonesia

Survey Line	Start Coordinate (WGS 84)		End Coordinate (WGS 84)		Survey Orientation	Profile Length (m)
	Latitude (°)	Longitude (°)	Latitude (°)	Longitude (°)		
Line 1	-7.29454	112.80292	-7.29461	112.80389	West–East	100
Line 2	-7.29423	112.80244	-7.29436	112.80332	West–East	100
Line 3	-7.29580	112.80793	-7.29520	112.80807	South–North	80
Line 4	-7.29570	112.80423	-7.29599	112.80479	West–East	100
Line 5	-7.29575	112.81551	-7.29487	112.81567	South–North	100
Line 6	-7.29567	112.80528	-7.29480	112.80543	South–North	100

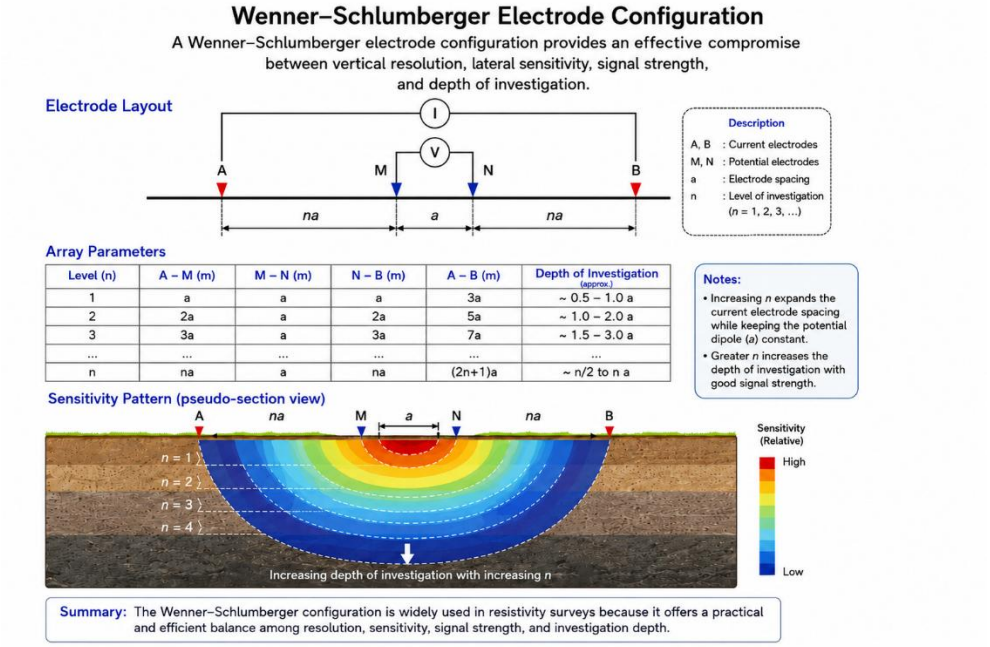


Fig. 4. Wenner–Schlumberger electrode configuration used for the Electrical Resistivity Tomography (ERT) survey. The array combines constant potential-electrode spacing with progressively increasing current-electrode separation, providing a balanced compromise

between vertical resolution, lateral sensitivity, signal strength, and depth of investigation. The lower panel illustrates the corresponding pseudo-sensitivity distribution with increasing investigation depth

A Wenner–Schlumberger electrode configuration was selected because it offers a practical balance between vertical and lateral sensitivity, signal strength, and investigation depth (Al-Saady et al., 2022; Dahlin and Zhou, 2004; Okpoli, 2013). This configuration was considered appropriate for the reclaimed landfill environment, where abrupt variations in lithology, saturation, pore-fluid conductivity, and subsurface structure may occur over short distances. It also provides sensitivity to both shallow conductive features and broader resistivity contrasts within the heterogeneous alluvial sequence.

Electrical current was injected through two current electrodes, while the resulting potential difference was measured between two potential electrodes using a multi-electrode resistivity system with automated electrode switching. Apparent resistivity (ρ_a) was calculated as

$$\rho_a = K\frac{\Delta V}{I} \quad (1)$$

Where K is the geometric factor determined by the electrode configuration, ΔV is the measured potential difference (V), and I is the injected current (A). Automated switching generated a dense set of quadrupole measurements at different electrode separations, providing spatially distributed apparent-resistivity data for subsequent inversion (Loke et al., 2013; Papadopoulos et al., 2009).

3.3 Data Processing and Interpretation

Apparent-resistivity data were processed and inverted using RES2DINV following established procedures for two-dimensional electrical imaging (Loke and Barker, 1996). Prior to inversion, the dataset was subjected to quality control to identify measurements affected by poor electrode contact, unstable current injection, or excessive electrical noise. Measurements considered unreliable were removed to minimise their influence on the resulting resistivity models.

The filtered data were inverted using a smoothness-constrained least-squares approach. The inversion iteratively minimises the difference between measured and calculated apparent resistivities while imposing spatial smoothness, thereby producing a stable representation of the subsurface resistivity distribution (Loke and Barker, 1996). Forward modelling was performed using the finite-element method to simulate current flow through the heterogeneous subsurface (Loke et al., 2013; Sasaki, 1992).

Model convergence was evaluated from the reduction and stabilisation of the root-mean-square (RMS) misfit during successive iterations. Final RMS errors ranged from 1.98% to 10.1% among the six profiles (**Table 3**). These values indicate generally acceptable agreement between measured and calculated apparent resistivities for the intended environmental interpretation. However, the profile with the highest RMS error was treated with greater interpretational caution because RMS error alone does not establish the uniqueness or geological validity of an inverted model (Loke et al., 2013; Loke and Barker, 1996). The principal acquisition and inversion parameters are summarised in **Table 2**, and profile-specific inversion statistics are provided in **Table 3**.

Table 2. Principal ERT acquisition and inversion parameters.

Parameter	**Specification**
Survey technique	Two-dimensional Electrical Resistivity Tomography (ERT)
Study objective	Delineation of residual landfill leachate
Number of survey profiles	6
Profile length	80–100 m
Electrode spacing	5 m
Electrode configuration	Wenner–Schlumberger
Investigation depth	Approximately 15–20 m
Data acquisition	Multi-electrode automatic switching
Measured parameter	Apparent resistivity (Ωm)
Inversion software	RES2DINV
Inversion algorithm	Smoothness-constrained least-squares
Forward modelling	Finite-element method
Convergence criterion	Stabilization of successive iterations and RMS error
Output	Two-dimensional inverted resistivity model

Table 3. Inversion Statistics for Individual ERT Profiles

Survey Line	Profile Length (m)	Electrode Spacing (m)	Maximum Investigation Depth (m)	Number of Iterations	Final RMS Error (%)
Line 1	100	5	~20	4	3.2%
Line 2	100	5	~20	4	1.98%
Line 3	80	5	~15	4	4.6%
Line 4	100	5	~20	4	5.9%
Line 5	100	5	~20	4	6.8%
Line 6	100	5	~20	4	10.1%

3.4 Interpretation framework

Interpretation of the inverted resistivity models followed a multi-evidence framework rather than a fixed resistivity-threshold approach. Although strongly conductive zones may be consistent with pore fluids of elevated ionic conductivity, similar electrical responses can arise from clay-rich sediments, saline or brackish groundwater, high saturation, and other naturally conductive materials. Resistivity magnitude was therefore treated as an indicator of electrical conductivity rather than as direct evidence of contamination (Dauda and Ali, 2024).

Each conductive anomaly was evaluated using several complementary criteria, including resistivity magnitude, geometric form, depth distribution, lateral continuity, geological and lithological context, spatial relationship to the former waste-disposal area, topographic position, inferred groundwater-flow conditions, and consistency with available groundwater-quality information. Particular attention was given to whether the geometry and continuity of an anomaly were compatible with preferential groundwater movement through permeable horizons or with the accumulation or migration of conductive pore fluids.

The coastal setting of Keputih was also explicitly considered because saline or brackish groundwater represents a plausible alternative source of enhanced electrical conductivity. An anomaly was regarded as more strongly consistent with residual landfill-derived fluids only when several independent observations converged. Features that could reasonably be explained by lithological boundaries, saturation, or coastal salinity were treated as ambiguous unless supported by additional evidence. This approach recognises the inherent non-uniqueness of ERT and avoids assigning a contaminant origin solely on the basis of resistivity magnitude (Basheer et al., 2025; Cong-Thi et al., 2024; Helene et al., 2020; Kondracka et al.,

2021).

3.5 Validation Using Groundwater-Quality Information

Previously reported groundwater-quality data from the study area were used as independent contextual information to assess the environmental significance of the ERT anomalies. The available parameters included biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS). These parameters provide indicators of groundwater-quality degradation and may be associated with landfill-derived impacts in settings affected by leachate migration; however, they were not treated as unique tracers of landfill leachate (Huang et al., 2024; Wen et al., 2025).

Because the available groundwater sampling locations did not spatially coincide with all ERT profiles, no quantitative statistical correlation was attempted between the hydrochemical and geophysical datasets. Instead, groundwater-quality information was evaluated qualitatively in relation to the location and geological setting of the interpreted conductive features. Agreement between the two datasets was therefore regarded as supporting contextual evidence rather than definitive validation of individual anomalies.

The integration of ERT with groundwater-quality observations provides a more conservative basis for environmental interpretation than either dataset considered independently. Similar integration of geophysical and hydrochemical information has been used to reduce ambiguity in the interpretation of conductive subsurface anomalies and to improve confidence in environmental assessments of contaminated or potentially contaminated sites (Adiat et al., 2024; Hasan and Shang, 2022). The resulting framework allows conductive features supported by converging geological, hydrogeological, geophysical, and hydrochemical evidence to be distinguished from anomalies for which alternative explanations remain plausible. It also provides a basis for identifying locations where future groundwater sampling could be targeted to test the interpreted conductive zones and improve assessment of residual contamination beneath the reclaimed landfill.

4 Results

4.1 Topographic Characteristics of the Study Area

The reclaimed Keputih Municipal Solid Waste (MSW) Landfill exhibits gently undulating topography with several localised depressions distributed across the rehabilitated landscape (**Figure 5**). The six Electrical Resistivity Tomography (ERT)

survey lines were positioned to sample the principal geomorphological settings within the bamboo forest and adjacent reclaimed areas. Surface elevation decreases gradually from west to east, consistent with the regional topographic gradient of eastern Surabaya and the general direction of shallow groundwater flow reported in previous hydrogeological studies of the region (Baud et al., 2021; Toulier et al., 2019).

Although local elevation differences are modest, shallow depressions are evident in the central and eastern sectors of the site. These low-lying areas provide an important spatial context for evaluating the distribution of subsurface resistivity because topography can influence surface runoff, infiltration, and the accumulation and redistribution of shallow groundwater within unconsolidated alluvial deposits (Gnann et al., 2025; Warix et al., 2023).



Fig. 5. Topographic map of the reclaimed Keputih Municipal Solid Waste Landfill showing the locations of the six Electrical Resistivity Tomography (ERT) survey lines.

4.2 Groundwater Quality Characteristics

Available groundwater-quality data from previous environmental monitoring in the Keputih area indicate that groundwater surrounding the reclaimed landfill is characterised by elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS) relative to Indonesian groundwater-quality standards (Dahlia and Warmadewanthi, 2025; Imron et al., 2021). These observations indicate persistent

groundwater-quality degradation in portions of the study area.

The hydrochemical measurements were not incorporated into the ERT inversion process and therefore do not constitute direct constraints on the resistivity models. Instead, they are used as independent contextual information to support the interpretation of the inverted resistivity models presented in the Discussion. In particular, the groundwater-quality observations provide an external line of evidence against which the spatial distribution of conductive zones can subsequently be evaluated.

4.3 Overall Resistivity Characteristics

The inverted resistivity models reveal pronounced lateral and vertical heterogeneity beneath the reclaimed landfill (**Figures 6**–**11**). Estimated resistivity values range from 0.95 to 482 Ω·m and encompass conductive (<10–15 Ω·m), intermediate (15–100 Ω·m), and resistive (>100 Ω·m) domains. Low-resistivity materials occur predominantly within the upper 2–10 m of the subsurface, whereas intermediate- and high-resistivity materials become increasingly dominant at greater depths or toward the margins of several profiles.

The geometry, thickness, and continuity of conductive zones vary markedly among the six ERT profiles. Survey Lines 1–3 contain the most extensive conductive regions and generally exhibit relatively high lateral continuity. In contrast, Survey Lines 4 and 6 are dominated by intermediate- and high-resistivity materials, with conductive features restricted mainly to isolated shallow intervals. Survey Line 5 contains a comparatively localised conductive feature beneath the central portion of the profile. Collectively, these observations demonstrate that the subsurface electrical structure is highly heterogeneous across the reclaimed landfill rather than laterally continuous.

4.4 Interpretation of Individual ERT Profiles

4.4.1 Survey Line 1

The inverted resistivity model for Survey Line 1 (**Figure 6**) shows resistivity values ranging from approximately 0.95 to 220 Ω·m. A broad low-resistivity domain (<10 Ω·m) occupies the central portion of the profile and extends from near the ground surface to depths of approximately 8–10 m. Intermediate resistivity values (10–50 Ω·m) surround the conductive region, whereas values exceeding 100 Ω·m occur locally at greater depths.

The conductive zone displays high lateral continuity and constitutes one of the most extensive low-resistivity features identified in the survey. Resistivity increases progressively toward both ends of the profile, producing a clear contrast between the central conductive region and the more resistive margins.

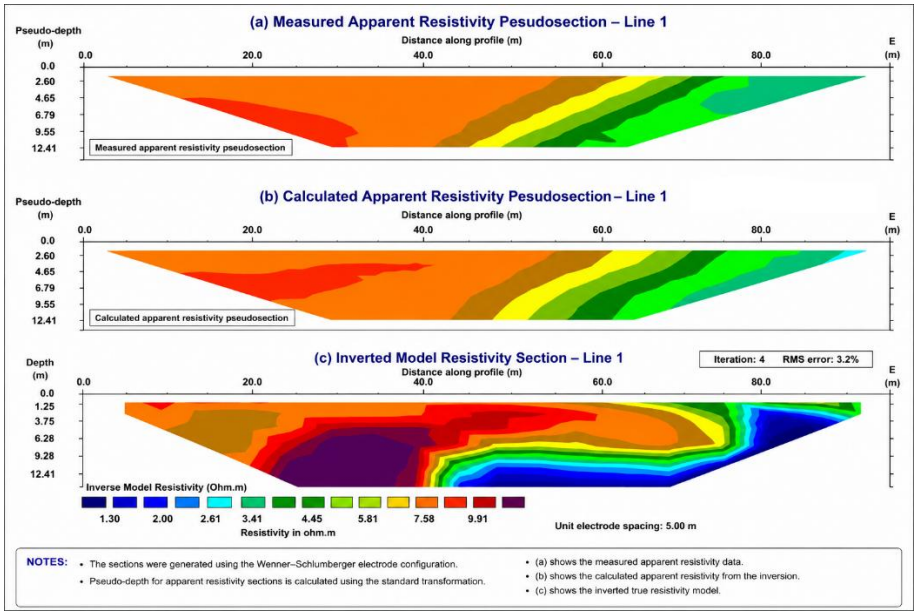


Fig. 6. Electrical Resistivity Tomography results for Survey Line 1 showing (a) measured apparent-resistivity pseudosection, (b) calculated apparent-resistivity pseudosection, and (c) inverted resistivity model (Iteration = 4; RMS error = 3.2%).

4.4.2 Survey Line 2

Survey Line 2 (**Figure 7**) exhibits resistivity values ranging from approximately 1.5 to 250 Ω·m. A laterally continuous low-resistivity region (<10–15 Ω·m) occupies the central part of the profile and extends to depths of approximately 8–10 m. Intermediate- and high-resistivity materials occur predominantly toward both ends of the profile and become increasingly abundant with depth.

Compared with Survey Line 1, the conductive region has a similar lateral extent but occurs slightly deeper within the central section. The resistivity distribution is characterised by a well-defined conductive core bordered by progressively more resistive materials.

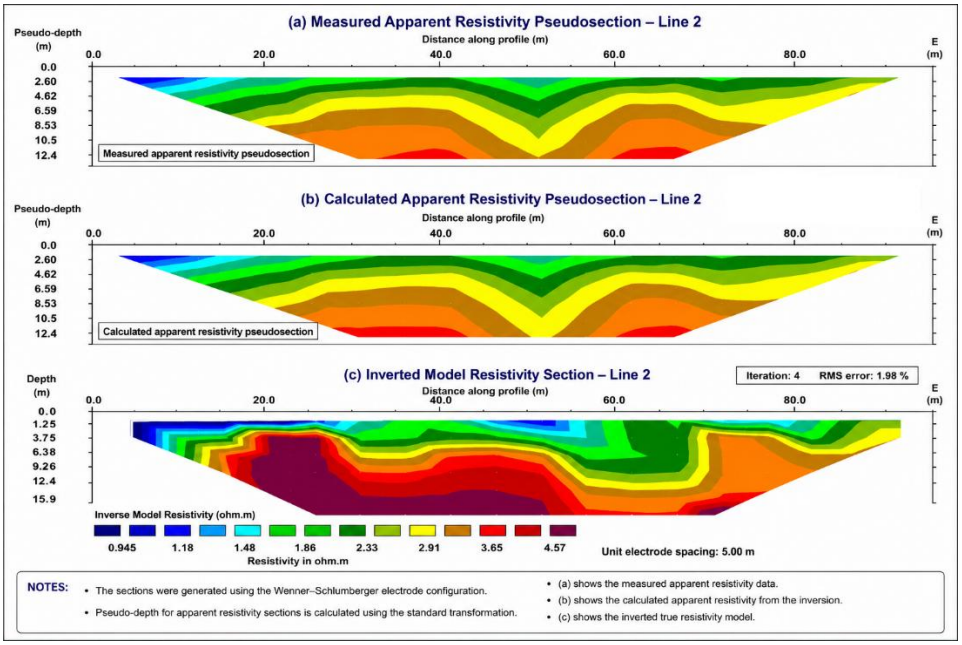


Fig. 7. Electrical Resistivity Tomography results for Survey Line 2 showing (a) measured apparent-resistivity pseudosection, (b) calculated apparent-resistivity pseudosection, and (c) inverted resistivity model (Iteration = 4; RMS error = 1.98%).

4.4.3 Survey Line 3

The inverted model for Survey Line 3 (**Figure 8**) shows resistivity values ranging from approximately 2 to 300 Ω·m. Low-resistivity materials (<15 Ω·m) dominate the central portion of the profile and extend vertically through much of the investigated depth. High-resistivity zones are restricted to localised shallow intervals and isolated deeper regions.

Among the six profiles, Survey Line 3 exhibits the greatest vertical continuity of conductive materials and contains one of the largest conductive regions identified during the investigation.

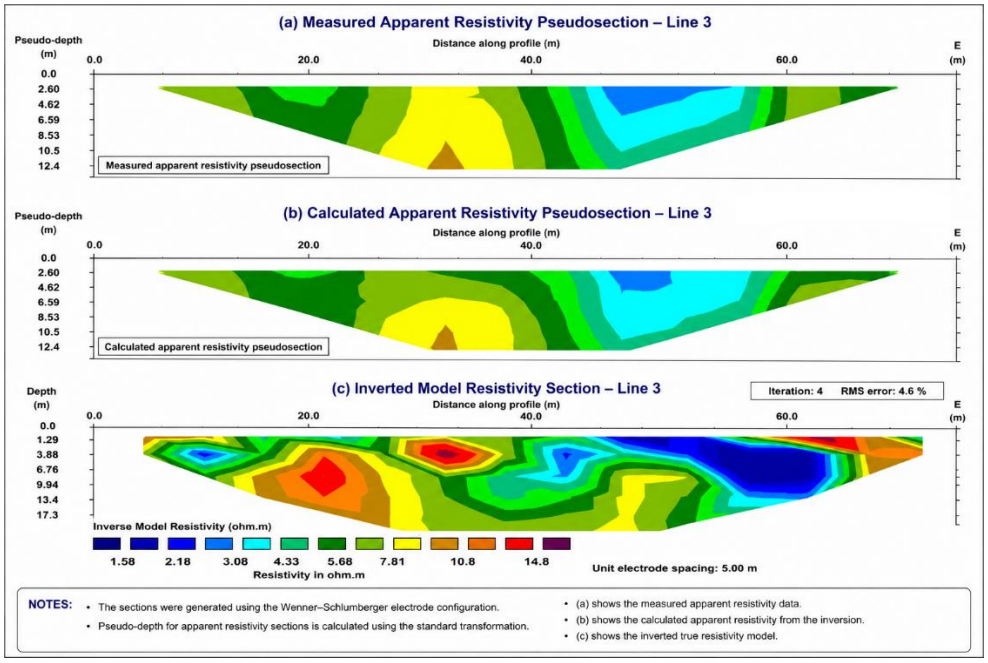


Fig. 8. Electrical Resistivity Tomography results for Survey Line 3 showing (a) measured apparent-resistivity pseudosection, (b) calculated apparent-resistivity pseudosection, and (c) inverted resistivity model (Iteration = 4; RMS error = 4.6%).

4.4.4 Survey Line 4

Survey Line 4 (**Figure 9**) differs markedly from Survey Lines 1–3. Resistivity values range from approximately 12 to 350 Ω·m, with intermediate- and high-resistivity materials dominating most of the profile. Low-resistivity features are limited to several isolated shallow intervals and exhibit relatively restricted lateral continuity.

Overall, the profile is characterised by a more resistive electrical structure than Survey Lines 1–3.

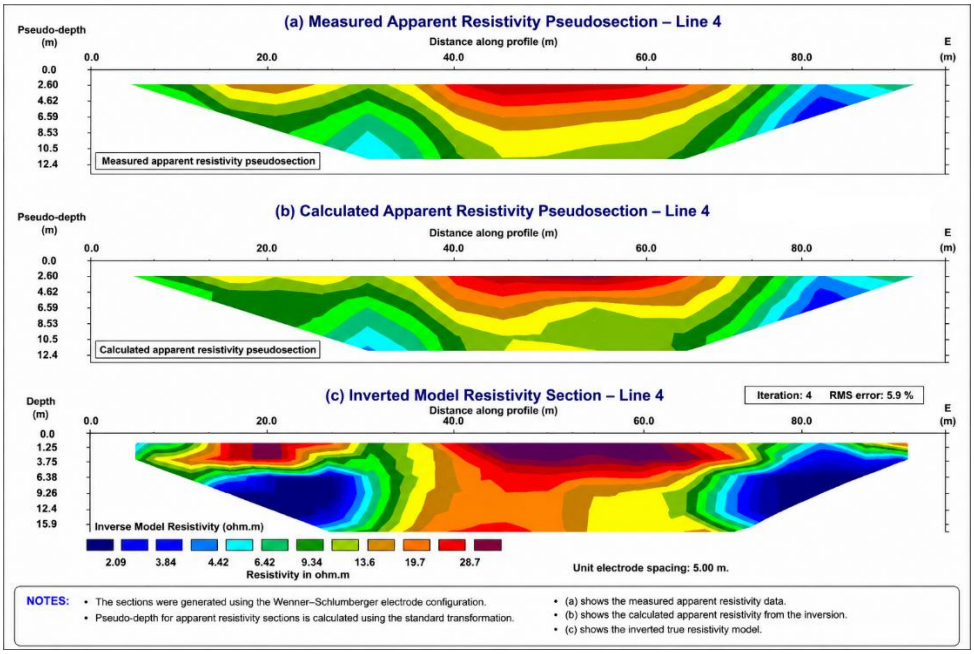


Fig. 9. Electrical Resistivity Tomography results for Survey Line 4 showing (a) measured apparent-resistivity pseudosection, (b) calculated apparent-resistivity pseudosection, and (c) inverted resistivity model (Iteration = 4; RMS error = 5.9%).

4.4.5 Survey Line 5

The inverted resistivity model for Survey Line 5 (**Figure 10**) exhibits resistivity values ranging from approximately 3 to 200 Ω·m. A localised low-resistivity feature occurs beneath the central part of the profile adjacent to the surface pond, whereas intermediate- and high-resistivity materials dominate the surrounding subsurface.

The conductive feature displays limited lateral continuity. Resistivity increases progressively away from the ponded area, producing a gradual transition from conductive to more resistive conditions.

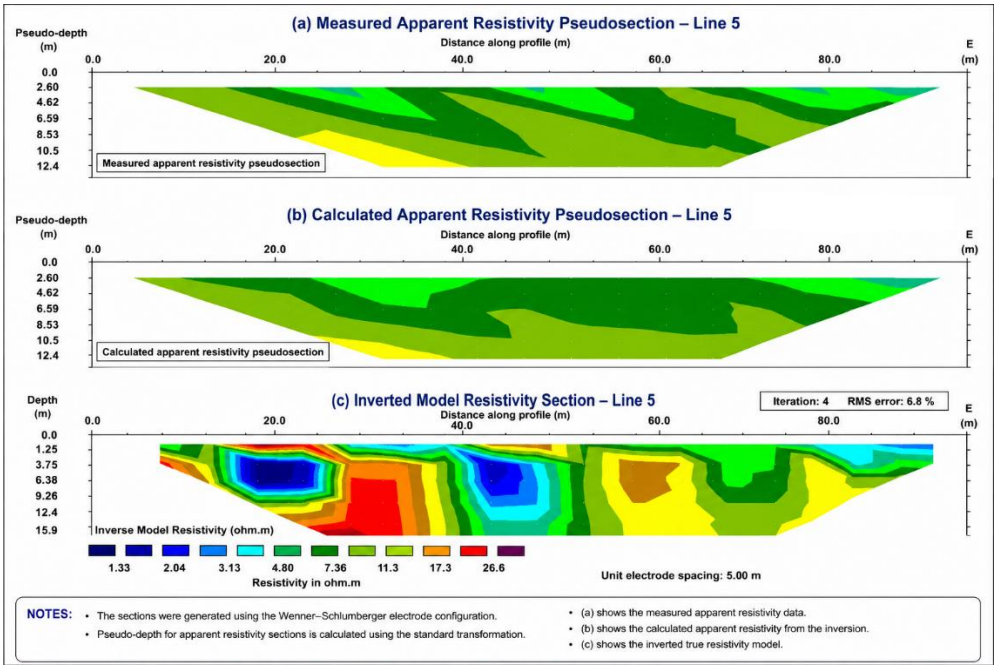


Fig. 10. Electrical Resistivity Tomography results for Survey Line 5 showing (a) measured apparent-resistivity pseudosection, (b) calculated apparent-resistivity pseudosection, and (c) inverted resistivity model (Iteration = 4; RMS error = 6.8%).

4.4.6 Survey Line 6

Survey Line 6 (**Figure 11**) exhibits the highest overall resistivity range among the six profiles, with values from approximately 20 to 482 Ω·m. Intermediate- and high-resistivity materials dominate the profile, whereas conductive features are restricted to several isolated shallow intervals with limited lateral continuity.

Compared with Survey Lines 1–3, Survey Line 6 displays a substantially more resistive and spatially less heterogeneous electrical structure.

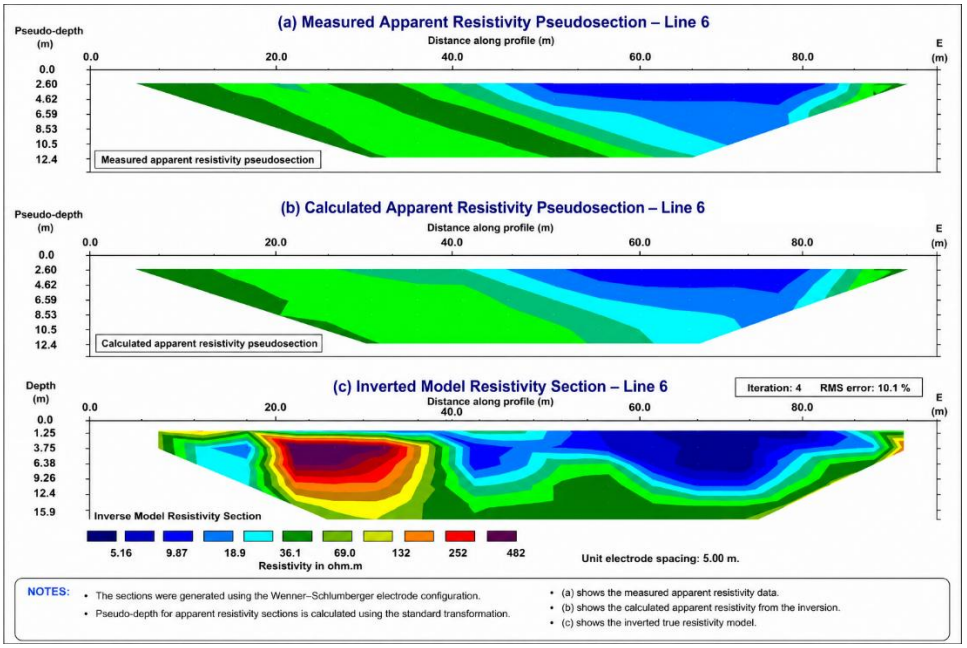


Fig. 11. Electrical Resistivity Tomography results for Survey Line 6 showing (a) measured apparent-resistivity pseudosection, (b) calculated apparent-resistivity pseudosection, and (c) inverted resistivity model (Iteration = 4; RMS error = 10.1%).

4.5 Spatial Distribution of Low-Resistivity Zones

Comparison of the six inverted resistivity sections reveals marked spatial variability in the distribution of low-resistivity materials across the reclaimed landfill. Survey Lines 1–3 contain the largest and most laterally continuous conductive domains, extending predominantly within the upper 2–10 m of the subsurface. In contrast, Survey Lines 4 and 6 are dominated by intermediate- and high-resistivity materials, with conductive features restricted mainly to isolated shallow intervals. Survey Line 5 displays a localised conductive response confined to the vicinity of the surface pond.

The observed conductive regions occur as discrete bodies of variable thickness, depth, and lateral continuity rather than as a single continuous subsurface feature. The distribution is therefore spatially heterogeneous, with substantial differences in the extent and vertical persistence of conductive materials among the six profiles.

The strongest conductive responses are concentrated in Survey Lines 1–3, whereas the remaining profiles exhibit either more restricted conductive features or predominantly intermediate- to high-resistivity conditions. This spatial variability provides an important basis for the subsequent assessment of the geological, hydrogeological, and hydrochemical controls on the observed resistivity patterns.

4.6 Summary of Resistivity Characteristics

The principal observations derived from the six ERT profiles are summarized in **Table 4**.

Table 4. Summary of the principal resistivity characteristics observed along the six ERT survey lines.

Survey Line	Resistivity Range (Ωm)	Dominant Resistivity Pattern	Approximate Depth (m)	Lateral Continuity
Line 1	0.95-220	Broad shallow conductive domain with isolated deep resistive bodies	2–10	High
Line 2	1.5-250	Continuous central low-resistivity region	3–10	High
Line 3	2-300	Extensive conductive region with strong vertical continuity	2–11	High
Line 4	12–350	Predominantly intermediate- to high-resistivity materials	2–20	Moderate
Line 5	3–200	Localized conductive feature beneath the central profile	1–5	Low
Line 6	20–482	Predominantly resistive subsurface with isolated shallow conductive intervals	2–20	Low

Collectively, the six ERT profiles demonstrate pronounced lateral and vertical heterogeneity in the subsurface electrical properties of the reclaimed Keputih landfill. Survey Lines 1–3 contain the most extensive and laterally continuous conductive domains,

whereas Survey Lines 4 and 6 are characterised predominantly by intermediate- to high-resistivity materials and Survey Line 5 contains a comparatively localised conductive feature. These results establish the geophysical basis for the subsequent Discussion, where the observed resistivity patterns are evaluated in relation to lithological heterogeneity, groundwater conditions, coastal salinity, topographic setting, and available groundwater-quality information.

Importantly, the Results presented here describe the spatial and geometric characteristics of the resistivity distributions without assigning a unique contaminant source to individual conductive anomalies. The environmental significance and possible origins of these features are assessed in the Discussion using the combined geological, hydrogeological, topographic, and hydrochemical evidence.

5 Discussion

5.1 Electrical Resistivity Characteristics of the Reclaimed Landfill

The Electrical Resistivity Tomography (ERT) survey demonstrates substantial heterogeneity in the shallow subsurface beneath the reclaimed Keputih Municipal Solid Waste (MSW) Landfill more than two decades after closure. Inverted resistivity values range from 0.95 to 482 Ω·m, indicating pronounced spatial variability in bulk electrical properties. Such variability may reflect the combined effects of lithological heterogeneity, pore-water chemistry, moisture content, residual waste composition, and post-closure biogeochemical processes. In mature landfill systems, these factors may continue to evolve after waste disposal has ceased as decomposition, differential settlement, groundwater circulation, and contaminant attenuation progressively modify subsurface conditions (Rowe, 2005; Soupios and Ntarlagiannis, 2017).

The strongest conductive anomalies occur beneath Survey Lines 1–3, whereas Survey Lines 4 and 6 are dominated by intermediate- to high-resistivity materials. The distribution therefore does not support the presence of a single, laterally continuous conductive plume across the reclaimed landfill. Instead, conductive zones occur as spatially discrete bodies with variable thickness, depth, and lateral continuity. Such heterogeneity is consistent with the complex internal architecture of landfill deposits and the heterogeneous geological setting in which contaminant transport occurs. Variations in waste emplacement, sediment texture, permeability, saturation, and groundwater flow can all contribute to spatially variable electrical responses (Guinea et al., 2022; Morita et al., 2023).

An important observation is the localised conductive anomaly identified along Survey Line 5. Unlike the extensive conductive bodies beneath Survey Lines 1–3, this feature is spatially associated with a surface pond and is therefore interpreted primarily as a response to elevated water saturation rather than as evidence of residual landfill-derived fluids. Increased pore-water saturation enhances electrolytic conduction and can consequently reduce bulk resistivity, even in the absence of contamination (Liu et al., 2020). This distinction underscores an important limitation of resistivity-based investigations: low resistivity alone cannot uniquely identify contaminant sources because similar electrical responses may arise from different geological and hydrogeological conditions.

The observed resistivity architecture also provides insight into the long-term evolution of the reclaimed landfill. Although ecological rehabilitation has restored the land surface, the subsurface remains electrically heterogeneous, indicating that post-closure hydrogeological and biogeochemical processes continue to influence shallow pore-water conditions. Consequently, environmental recovery of reclaimed landfill ecosystems should not be inferred solely from surface restoration. The persistence of subsurface electrical anomalies highlights the value of geophysical imaging for identifying conditions that may not be apparent from surface observations or limited groundwater monitoring (Alao et al., 2024).

5.2 Identification of Residual Landfill-Derived Fluids

A principal objective of this study was to evaluate whether the conductive anomalies identified by ERT are consistent with residual landfill-derived fluids persisting beneath the reclaimed site. The extensive low-resistivity zones (<10–15 Ω·m) beneath Survey Lines 1–3 are interpreted as the most probable locations of residual leachate accumulation. These zones coincide spatially with the historical waste-disposal area, exhibit relatively strong lateral continuity, and occur predominantly within the shallow subsurface where groundwater-mediated contaminant transport is expected. Low resistivity is commonly associated with increased pore-fluid conductivity in leachate-affected environments because dissolved ionic constituents enhance electrolytic conduction. Similar relationships between conductive ERT anomalies and landfill-derived contamination have been reported in previous hydrogeophysical investigations (Helene et al., 2020; Wang et al., 2025).

The interpretation, however, does not rely on resistivity thresholds alone. In coastal alluvial environments such as eastern Surabaya, low electrical resistivity may also arise from clay-rich sediments, saline or brackish groundwater, and highly saturated

deposits. Because of this inherent non-uniqueness, the conductive anomalies were evaluated within a multi-evidence framework incorporating geological conditions, hydrogeological setting, topographic gradients, historical landfill boundaries, anomaly geometry, and available groundwater-quality information. Such an integrated approach is preferable to interpreting resistivity values in isolation because the electrical response represents the combined effects of lithology, pore-fluid properties, and saturation rather than contaminant concentration alone. The importance of integrating geophysical observations with independent geological and hydrogeological constraints has been emphasized in previous landfill investigations (Helene et al., 2020; Kondracka et al., 2021).

Independent hydrochemical observations provide additional supporting evidence. Previous groundwater monitoring around the reclaimed landfill reported elevated biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total suspended solids (TSS), indicating that groundwater quality remains affected in portions of the study area (Dahlia and Warmadewanthi, 2025; Imron et al., 2021). Although ERT cannot directly quantify contaminant concentrations or identify individual chemical species, the correspondence between the groundwater-quality evidence and the principal conductive anomalies increases confidence that at least some of the low-resistivity zones are associated with residual landfill-derived fluids. The complementary use of geophysical and hydrochemical information provides a stronger basis for assessing landfill-related groundwater impacts than either dataset considered independently (Kim et al., 2024; Wang et al., 2025).

The conductive anomalies are also spatially discontinuous, occurring as discrete bodies with variable thickness, depth, and lateral continuity rather than as a single continuous plume. This distribution is consistent with the heterogeneous nature of reclaimed landfill systems, in which variations in waste composition, sediment permeability, groundwater circulation, and contaminant attenuation can produce localized zones of persistent contamination. Spatially heterogeneous contaminant distributions have likewise been observed in mature landfill environments, where groundwater transport and natural attenuation progressively modify the extent and connectivity of leachate-affected zones (Bolhari and Sale, 2023).

Taken together, these observations indicate that the principal conductive anomalies beneath Survey Lines 1–3 are consistent with residual landfill-derived fluids, but they should not be regarded as definitive evidence of leachate based on resistivity alone. The interpretation is strengthened by the convergence of geophysical,

hydrogeological, topographic, historical, and groundwater-quality evidence. This multi-evidence framework provides a more defensible basis for identifying residual contamination beneath a reclaimed landfill, particularly in coastal settings where several natural and anthropogenic processes can generate comparable low-resistivity responses (Kondracka et al., 2021).

5.3 Influence of Hydrogeological Conditions on Residual Contaminant Distribution

The spatial distribution of conductive anomalies indicates that residual contaminant distribution beneath the reclaimed Keputih landfill is controlled not only by the historical waste body but also by the local hydrogeological framework. Electrical resistivity in landfill environments reflects the combined effects of pore-fluid conductivity, groundwater saturation, sediment properties and hydraulic connectivity. Consequently, geoelectrical anomalies should be interpreted in conjunction with geological and hydrogeological information rather than treated as direct indicators of contaminant concentration (Guinea et al., 2022; Helene and Moreira, 2021).

The study area is underlain by heterogeneous Quaternary alluvial deposits comprising interbedded clay, silt, sand and gravel. Such lithological variability can produce substantial contrasts in hydraulic conductivity and, consequently, influence both groundwater circulation and contaminant transport. Fine-grained clay-rich horizons generally restrict advective flow and may promote contaminant retention, whereas sandy and gravelly units provide more permeable pathways for groundwater movement and dissolved constituent transport. At the same time, clay-rich materials can contribute to lower bulk resistivity through their electrical surface-conduction properties. The alternating conductive and resistive domains observed in the ERT sections are therefore interpreted as the combined expression of lithological heterogeneity and variations in pore-water conditions rather than as a direct reflection of waste distribution alone (Yabusaki et al., 2011).

Regional hydrogeological information indicates a general groundwater-flow tendency from the western part of the study area toward the coastal zone and the Madura Strait. This regional flow pattern provides a plausible hydraulic framework for the observed spatial distribution of conductive anomalies. The extensive conductive domains beneath Survey Lines 1–3 occur within the portion of the site where residual conductive fluids may be retained or redistributed along hydraulically favourable pathways, whereas the predominantly resistive conditions beneath Survey Lines 4 and 6 may reflect lower contaminant accumulation, more effective groundwater flushing,

lower saturation, or differences in subsurface material. The distribution therefore suggests that residual conductive fluids occur as spatially discrete compartments rather than as a single continuous plume, consistent with the heterogeneous contaminant distributions reported in mature and post-closure landfill systems (Wen et al., 2025; Xiang et al., 2024).

An additional source of uncertainty arises from the coastal setting of eastern Surabaya. Saline or brackish groundwater can generate low-resistivity responses because elevated concentrations of dissolved ions increase pore-fluid electrical conductivity. Consequently, a low-resistivity anomaly cannot be attributed uniquely to landfill-derived contamination without independent geological, hydrogeological or hydrochemical constraints. In the present study, the integration of ERT results with groundwater-flow patterns, topographic information, historical landfill boundaries and available groundwater-quality observations reduces this ambiguity. The spatial correspondence among these independent datasets supports the interpretation that the principal conductive anomalies beneath Survey Lines 1–3 are more consistent with residual landfill-derived fluids than with saline or naturally conductive groundwater alone (Moulds et al., 2023).

Overall, the results indicate that hydrogeological conditions exert an important control on the persistence and spatial distribution of residual contaminants beneath the reclaimed landfill. The ERT-derived resistivity pattern should therefore be regarded as the electrical expression of interacting lithological, hydraulic and pore-water processes rather than as a direct map of contaminant concentration. This interpretation highlights the importance of integrating geophysical imaging with hydrogeological and hydrochemical information when evaluating contaminant persistence in heterogeneous tropical coastal landfill environments.

5.4 Long-Term Persistence of Landfill -Derived Contamination

One of the principal findings of this study is that pronounced conductive anomalies remain detectable beneath the reclaimed Keputih landfill approximately 24 years after closure. The persistence of these anomalies indicates that ecological rehabilitation of the land surface has not necessarily been accompanied by complete recovery of the shallow subsurface environment. Although the former landfill has been transformed into the Keputih Bamboo Forest and Harmony Park, localized low-resistivity zones remain within portions of the shallow subsurface, particularly beneath Survey Lines 1–3. Such observations are consistent with the broader recognition that the environmental legacy of municipal solid waste landfills can persist well beyond the

operational lifetime of the facility because waste-derived constituents and altered hydrogeological conditions may remain within the subsurface after closure (Rong et al., 2017).

Long-term persistence of conductive pore fluids is also consistent with the continued biogeochemical transformation of buried municipal solid waste. Following landfill closure, residual organic matter can continue to undergo microbial degradation, while dissolved constituents released during this process may remain in pore water and groundwater. The persistence and redistribution of these constituents depend on groundwater circulation, sediment permeability, moisture conditions and the degree of hydraulic connection between preferential flow pathways and less permeable zones. Consequently, attenuation is unlikely to occur uniformly throughout an old landfill, and localized zones of elevated pore-fluid conductivity may remain even after active waste disposal has ceased (Salam et al., 2025).

The spatial pattern observed at Keputih further suggests that residual conductive conditions are not distributed uniformly across the reclaimed site. The extensive conductive domains beneath Survey Lines 1–3 contrast with the predominantly intermediate- to high-resistivity conditions observed along Survey Lines 4 and 6. This contrast may reflect differences in waste thickness, sediment permeability, groundwater residence time, moisture retention and the effectiveness of natural flushing. The localized nature of the anomalies is therefore consistent with a heterogeneous post-closure system in which residual landfill-derived fluids may persist within hydraulically favourable or relatively poorly flushed zones rather than forming a single continuous plume. Comparable spatial heterogeneity has been reported in investigations of mature landfill systems, where geophysical and hydrogeological conditions continue to influence the distribution of residual contamination after closure (Helene and Moreira, 2021; Song et al., 2023).

The results also have important implications for interpreting ecological rehabilitation. Surface revegetation and redevelopment can indicate successful restoration of the visible landscape, but these indicators do not necessarily demonstrate complete recovery of subsurface environmental conditions. At Keputih, the persistence of localized low-resistivity anomalies beneath an extensively rehabilitated landscape illustrates the value of complementary subsurface assessment. High-resolution ERT can provide spatial information on subsurface heterogeneity that may not be apparent from surface observations alone and can help identify locations requiring more targeted hydrochemical or hydrogeological investigation (Ahaneku, C.V. et al., 2025).

From a post-closure management perspective, the findings support continued monitoring of reclaimed landfill environments even after substantial ecological restoration has been achieved. ERT should not be regarded as a direct measure of contaminant concentration; rather, it provides a spatially resolved indicator of variations in bulk electrical properties that can be evaluated alongside groundwater chemistry, geology and hydrogeological conditions. An integrated monitoring strategy is therefore more appropriate than reliance on any single indicator. Such an approach can help identify persistent subsurface anomalies, prioritize locations for groundwater-quality assessment and support risk-informed management of reclaimed landfill sites.

5.5 Quantitative Evaluation of Resistivity Anomalies

To complement the qualitative interpretation of the ERT sections, the inverted resistivity models were evaluated quantitatively in terms of resistivity magnitude, depth distribution and lateral continuity. Across the six profiles, inverted resistivity values range from 0.95 to 482 Ω·m, demonstrating substantial electrical heterogeneity within the shallow subsurface. Such variability is expected in reclaimed landfill environments, where bulk resistivity is controlled by the combined effects of lithology, moisture content, pore-water conductivity and the heterogeneous distribution of residual waste and associated materials (Steiner et al., 2022).

The most prominent conductive anomalies are characterised by resistivity values below approximately 10–15 Ω·m. These low-resistivity domains are concentrated mainly beneath Survey Lines 1–3 and occur predominantly within the upper 2–10 m. Their magnitude and spatial persistence are consistent with resistivity responses commonly reported from leachate-affected landfill environments, where elevated pore-fluid conductivity can substantially reduce bulk resistivity (Singh et al., 2024). Nevertheless, these values should be regarded as site-specific indicators rather than universal thresholds for identifying landfill contamination, because clay-rich sediments, high saturation and saline or brackish groundwater can generate comparable electrical responses.

Marked differences are evident among the six ERT profiles. Survey Lines 1–3 contain the largest and most laterally continuous conductive bodies, whereas Survey Lines 4 and 6 are dominated by intermediate- to high-resistivity materials with only limited conductive intervals. Survey Line 5 is distinct because its conductive response is spatially restricted to the vicinity of the surface pond. The contrast among profiles demonstrates that conductive materials are distributed as discrete and spatially

variable subsurface bodies rather than as a continuous electrical anomaly across the reclaimed landfill. Similar spatial heterogeneity has been observed in landfill investigations in which variations in waste emplacement, sediment properties and groundwater conditions influence the geometry of conductive zones (Dauda and Ali, 2024; Maurya et al., 2017).

The vertical distribution of the anomalies provides an additional constraint on their interpretation. Most low-resistivity zones occur within approximately 2–10 m below ground level, broadly corresponding to the shallow groundwater-bearing interval identified for the study area. At greater depths, resistivity generally becomes more variable and locally increases, which may reflect changes in saturation, lithological composition, pore-water conductivity or the degree of interaction between groundwater and residual waste materials. Depth-dependent variations of this type have also been reported in landfill environments where post-closure contaminant transport is controlled by groundwater circulation and heterogeneous subsurface architecture (Igboama et al., 2022).

Taken together, the quantitative distribution of resistivity provides a consistent spatial framework for distinguishing the principal conductive domains from the more resistive portions of the reclaimed landfill. The concentration of low-resistivity anomalies beneath Survey Lines 1–3, their shallow occurrence and their relatively high lateral continuity support their classification as priority zones for further hydrochemical and hydrogeological investigation. In contrast, the predominantly resistive character of Survey Lines 4 and 6 indicates lower electrical evidence for extensive conductive pore-fluid accumulation in those areas. Because ERT provides an indirect measure of bulk electrical properties rather than contaminant concentration, these quantitative observations should be interpreted as indicators of subsurface environmental heterogeneity and potential areas of concern rather than as direct measurements of leachate concentration.

5.6 Comparison with Previous Studies

The results obtained from the reclaimed Keputih Landfill are broadly consistent with previous hydrogeophysical investigations showing that landfill-affected zones commonly exhibit lower electrical resistivity than surrounding uncontaminated materials. This response is generally attributed to the increased electrical conductivity of pore fluids containing dissolved ionic constituents derived from waste degradation. The low-resistivity anomalies identified beneath Survey Lines 1–3, particularly those below approximately 10–15 Ω·m, are therefore within the range of electrical

responses reported for leachate-affected landfill environments (Helene et al., 2020; Maurya et al., 2017). However, the present results also demonstrate that such low-resistivity values cannot be interpreted independently of local geological and hydrogeological conditions.

A notable feature of the Keputih results is the pronounced spatial heterogeneity of the conductive zones. Rather than forming a single continuous anomaly, low-resistivity bodies occur with different degrees of lateral continuity and depth among the six survey lines. This pattern is consistent with observations from other landfill investigations in which heterogeneous waste emplacement, variable sediment properties and groundwater flow pathways produce spatially complex resistivity distributions (Guinea et al., 2022). The strong contrast between Survey Lines 1–3 and the predominantly resistive character of Survey Lines 4 and 6 therefore appears to reflect local subsurface controls rather than a uniform distribution of landfill-derived fluids.

The age of the Keputih landfill provides an additional point of comparison. Unlike many ERT studies focused on active or recently closed landfills, the present investigation examines a site approximately 24 years after closure and after substantial ecological rehabilitation. The persistence of shallow conductive anomalies indicates that post-closure environmental processes may continue long after waste emplacement has ceased. Long-term studies of municipal solid waste landfills have similarly shown that waste degradation, contaminant release and subsurface transport can continue for extended periods after closure, particularly where heterogeneous hydrogeological conditions limit complete flushing and attenuation (Rong et al., 2017; Song et al., 2023).

The present study also differs from approaches based solely on resistivity thresholds by explicitly considering the geological, hydrogeological and hydrochemical context of the anomalies. This is particularly important in the coastal setting of eastern Surabaya, where clay-rich sediments, high saturation and saline or brackish groundwater may produce electrical responses comparable to those associated with landfill-derived fluids. An integrated interpretation framework therefore provides a more defensible basis for distinguishing potential contamination from natural or hydrogeological sources of low resistivity, consistent with previous recommendations for combining geophysical and hydrogeological evidence in complex subsurface environments (Kondracka et al., 2021).

Overall, the Keputih results are consistent with the established understanding that landfill-derived fluids commonly generate conductive anomalies, but they also

highlight the importance of site-specific interpretation. The principal contribution of the present study is not simply the identification of low-resistivity zones, but the demonstration that such anomalies remain spatially heterogeneous and detectable more than two decades after landfill closure despite extensive surface rehabilitation. This finding extends the application of ERT from the investigation of active or recently closed landfills to the assessment of long-term subsurface conditions beneath reclaimed urban landfill sites.

5.7 Environmental Implications for Post-Closure Landfill Management

The present findings demonstrate that successful ecological rehabilitation of a closed municipal solid waste landfill does not necessarily indicate complete recovery of subsurface environmental conditions. Although the Keputih landfill has been transformed into an urban bamboo forest and public recreational area, the persistence of localised conductive anomalies suggests that residual landfill-derived pore fluids remain within portions of the shallow subsurface more than two decades after closure. This observation is consistent with evidence that waste-derived contaminants and associated geochemical processes can persist beyond landfill closure because degradation, contaminant release and subsurface transport continue under post-closure conditions (Bozkurt et al., 2000; Rong et al., 2017; Rowe, 2005).

These results emphasise the importance of incorporating subsurface assessment into post-closure landfill management rather than relying exclusively on surface ecological indicators. In the present study, ERT provides spatially continuous information between survey lines and identifies subsurface zones that warrant closer hydrochemical or hydrogeological investigation. Geophysical monitoring can therefore complement conventional groundwater-based approaches by helping to delineate areas of elevated environmental concern and supporting more targeted monitoring strategies (O'Shea et al., 2018; Rani and Cassiani, 2022). However, ERT should be regarded as a screening and spatial-characterisation tool rather than a direct measurement of contaminant concentration.

The interpretation is particularly important in the coastal and heterogeneous hydrogeological setting of eastern Surabaya, where clay-rich sediments, variable saturation and saline or brackish groundwater may generate low-resistivity responses that overlap with those associated with landfill-derived fluids. Consequently, post-closure monitoring should integrate geophysical observations with geological, hydrogeological and groundwater-quality information to reduce interpretational

uncertainty. Such integrated approaches are especially relevant where multiple natural and anthropogenic sources can contribute to subsurface electrical conductivity (Greggio et al., 2018; Minarto et al., 2025; Tiwari et al., 2024).

From a management perspective, the spatially heterogeneous distribution of conductive anomalies identified at Keputih suggests that monitoring intensity need not be uniform across the reclaimed site. Areas associated with persistent, laterally continuous conductive anomalies—particularly beneath Survey Lines 1–3—could be prioritised for targeted groundwater sampling, hydraulic assessment and, where appropriate, repeat geophysical surveys. Conversely, the predominantly resistive conditions observed along Survey Lines 4 and 6 indicate comparatively lower electrical concern, although they should not be interpreted as definitive evidence of the absence of contamination. This risk-based approach can improve the efficiency of post-closure monitoring while retaining sufficient spatial coverage to detect changes in subsurface conditions.

More broadly, the Keputih landfill illustrates an important challenge associated with the redevelopment of former waste-disposal sites in rapidly urbanising tropical regions. Surface rehabilitation can substantially improve ecological and social functions while subsurface environmental processes continue beneath the restored landscape. The present results therefore support the inclusion of long-term subsurface assessment within management frameworks for reclaimed landfills, particularly where former disposal areas have been converted to public, recreational or other land uses. High-resolution ERT, combined with targeted hydrochemical and hydrogeological monitoring, provides a practical framework for identifying areas requiring further investigation and for supporting groundwater protection and sustainable post-closure management.

5.8 Study Limitations and Future Perspectives

Despite demonstrating the utility of two-dimensional ERT for delineating potential residual landfill-derived fluids beneath the reclaimed Keputih landfill, several limitations should be acknowledged. First, electrical resistivity is an indirect measure of subsurface electrical properties and cannot uniquely distinguish landfill-derived fluids from other conductive materials, including clay-rich sediments, highly saturated deposits and saline or brackish groundwater. Consequently, the interpretation of low-resistivity anomalies remains inherently non-unique and requires supporting geological, hydrogeological and hydrochemical information. This limitation is fundamental to the application of electrical methods in complex landfill environments and reinforces the importance of integrated interpretation rather than reliance on

resistivity thresholds alone (Kondracka et al., 2021; Soupios and Ntarlagiannis, 2017).

Second, the present investigation represents a single ERT survey campaign and therefore provides a spatial snapshot rather than a direct assessment of temporal changes in subsurface conditions. Groundwater levels, recharge, moisture distribution and contaminant transport may vary seasonally and can influence the measured resistivity response. Consequently, the observed distribution of conductive anomalies should not be interpreted as a static representation of contaminant migration. Repeated geophysical and hydrochemical observations would be required to distinguish persistent anomalies from responses associated with transient hydrological conditions (Ali et al., 2025; Mao et al., 2015).

Third, the use of two-dimensional ERT profiles limits the ability to resolve fully three-dimensional subsurface structures between survey lines. Although the six profiles provide important spatial information on the distribution of conductive zones, conductive bodies may extend laterally or vertically beyond the dimensions captured by individual profiles. Three-dimensional resistivity imaging would therefore provide a more comprehensive representation of anomaly geometry and could improve the identification of preferential groundwater-flow pathways and potential contaminant accumulation zones.

Future investigations should consequently combine time-lapse ERT, three-dimensional resistivity imaging, direct groundwater-quality measurements and quantitative hydrogeological modelling. Time-lapse ERT would allow changes in subsurface electrical properties to be evaluated under different hydrological conditions, while three-dimensional imaging could better resolve the spatial continuity of conductive bodies. Integration with groundwater chemistry would further enable geophysical anomalies to be tested against direct measurements of contaminant indicators, thereby reducing the ambiguity inherent in resistivity-based interpretation (Kondracka et al., 2021; Soupios and Ntarlagiannis, 2017).

A further priority is the development of an integrated hydrogeological–geophysical monitoring framework for the reclaimed Keputih site. Rather than treating ERT as a standalone diagnostic method, future monitoring should use repeat ERT surveys to identify areas of temporal change and targeted groundwater sampling to determine whether those changes correspond to variations in contaminant concentrations or groundwater chemistry. Such an approach would provide a stronger basis for distinguishing persistent landfill-derived anomalies from changes driven by seasonal saturation, groundwater flow or other natural processes.

Overall, the limitations identified here do not diminish the value of the present ERT investigation; rather, they define the level of certainty that can reasonably be assigned to the interpretation. The current results provide a spatial framework for identifying areas of potential environmental concern, while future time-lapse, three-dimensional and hydrochemical investigations can progressively reduce uncertainty and improve understanding of long-term contaminant behaviour beneath reclaimed landfill environments.

6 Conclusion

This study demonstrates the utility of two-dimensional Electrical Resistivity Tomography (ERT) using the Wenner–Schlumberger array to characterise the long-term subsurface environmental conditions of the reclaimed Keputih Municipal Solid Waste Landfill, Surabaya, Indonesia, approximately 24 years after closure. The inverted resistivity models reveal pronounced subsurface heterogeneity, with values ranging from 0.95 to 482 Ω·m. These variations reflect the combined influence of lithology, groundwater saturation and pore-water electrical conductivity. Extensive low-resistivity anomalies (<10–15 Ω·m) occur beneath Survey Lines 1–3, whereas Survey Lines 4 and 6 are dominated by intermediate- to high-resistivity materials. The localised conductive anomaly along Survey Line 5 is spatially associated with a surface pond and is therefore more consistent with elevated water saturation than with residual landfill-derived fluids. This contrast underscores the importance of interpreting resistivity anomalies within their hydrogeological context rather than on resistivity magnitude alone.

Integration of the ERT results with geological, hydrogeological, topographic and groundwater-quality information indicates that the principal conductive anomalies are most consistent with residual landfill-derived fluids within the shallow subsurface. These conductive zones occur as spatially discrete bodies influenced by lithological heterogeneity, groundwater-flow pathways and local topographic gradients, rather than as a continuous contaminant plume. The findings demonstrate that post-closure contaminant distribution can remain governed by natural hydrogeological processes long after waste disposal has ceased and that successful surface rehabilitation does not necessarily imply complete recovery of subsurface environmental conditions.

Beyond the site-specific results, this study demonstrates the value of high-resolution ERT combined with complementary geological and hydrochemical evidence for reducing the inherent ambiguity of resistivity interpretation in heterogeneous coastal alluvial settings. The multi-evidence approach improves the ability to distinguish conductive anomalies potentially associated with landfill-derived fluids from alternative sources of low

resistivity, including clay-rich sediments, highly saturated soils and saline or brackish groundwater. This integrated interpretation provides a stronger basis for evaluating subsurface environmental conditions than resistivity magnitude alone.

The broader significance of the study lies in its implications for the sustainable management of reclaimed landfill landscapes undergoing ecological restoration and urban redevelopment. Long-term environmental monitoring should incorporate subsurface hydrogeophysical assessment alongside conventional surface ecological evaluation because residual contamination may persist beneath apparently restored landscapes long after landfill closure. The integrated methodology presented here provides a practical, non-invasive and transferable framework for groundwater protection, environmental risk assessment and adaptive post-closure management of reclaimed landfill systems, particularly in tropical urban and coastal environments.

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Data availability

The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Author contributions

E. Minarto (Corresponding Author)**:** Conceptualization, methodology design, supervision, manuscript drafting, refinement, interpretations of results, manuscript review, and approval of the final version. A. I. Achsov: Field data acquisition, preprocessing, inversion analysis, interpretations of results, and visualization. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Declarations

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