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Use of Electrical Resistivity for Mapping the Leachate Distribution in Blang Bintang Sanitary Landfill, Aceh District

Zakia Masrurah[1], Akmal Muhni[2], Muhammad Yanis[2], Muzakir Zainal[1*]

[1] *Geophysical Engineering Department, Universitas Syiah Kuala, Darussalam-Banda Aceh, Indonesia.*

[2] *Geological Engineering Department, Universitas Syiah Kuala, Darussalam-Banda Aceh, Indonesia.*

Corresponding Author's E-mail: muzakirzainal@usk.ac.id

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Abstract

An increase in waste in urban areas, especially in landfills, can produce leachate that has the potential to pollute the environment. The Blang Bintang waste treatment facility, which uses a sanitary landfill system, is in a hilly area with complex geology dominated by andesite volcanic rocks. This study aims to identify and estimate the level of leachate contamination at the Blang Bintang landfill in Aceh using Electrical Resistivity Tomography (ERT). Four ERT profiles were measured in the leachate treatment facility area, spanning 180 meters in length and up to 30 meters in depth. ERT data analysis using the Res2dinv software produced an accurate model with an RMS error of 10%-20%. The modeling results indicate the presence of conductive zones (5–150 Ohm.m) near the surface layers of profiles 1 and 2, suggesting leachate contamination. The electrical resistivity tomography (ERT) model further demonstrates leachate accumulation in the subsurface, which poses a potential risk to groundwater quality. In Profile 3, conductive zones (5–200 Ohm.m) are observed along the underground leachate pipeline. For Profile 4, conductive layers (15–250 Ohm.m) are attributed to seepage from the first leachate pond, indicating substantial contamination. This study provides landfill managers with valuable data on subsurface contamination that cannot be identified from surface observations. It also advances geophysical methods for environmental impact assessments.

Introduction

The region's population growth and urbanisation drive increased development, generating large-scale waste. Generally, municipal waste in urban or developing regions is predominantly composed of food waste, plastic, bottles, and textiles [1]. Several factors, such as the area or city's level of development, public awareness, and the existing waste management system, contribute to the rising amount of waste. Integrated waste management in landfills effectively and efficiently reduces pollution from solid waste [2][3]. It readily decomposes into solid waste, producing organic and inorganic compounds that are readily decomposed by external fluids, which then form leachate liquid waste that has the potential to contaminate the environment around the waste management site [4]. The increased volume of waste managed and the lack of application of waste recycling techniques will result in increased pollution and greater leachate generation [5][6].

The Blang Bintang landfill is in Aceh Besar Regency, Aceh Province, Indonesia, and was designed with a sanitary landfill-based system. Facilities are built in hilly areas with higher topography than residential areas. The sanitary landfill system aims to isolate leachate waste to prevent adverse environmental impacts. Nevertheless, studies have shown that even sanitary landfills can pose risks of groundwater and soil contamination in the future if not properly managed [7]. Leachate waste, with other compounds that flow into the surrounding environment, can increase the risk of ecological disasters [2]. Research [4] Studies of subsurface contamination in landfills are essential to mitigate future environmental disasters. Leachate can infiltrate into subsurface layers and contaminate groundwater [5]. Groundwater contamination can be estimated using the leachate pollution index [8]. In addition, physicochemical analysis can also be applied to determine the level of contamination in landfill areas [9]. These risks may be exacerbated in the Blang Bintang landfill due to its location in a volcanic complex and its proximity to regional fault systems [10], which could provide preferential pathways for leachate migration. Direct discharge of post-treatment leachate may lead to percolation through the unsaturated zone, increasing the risk of aquifer contamination and harming the local hydrological environment.

Geophysical applications have become a major alternative in geoscience studies; this is supported by several factors, such as their non-destructive nature, relatively low operational costs, high accuracy, and time efficiency. Geophysical studies have been widely applied in geoscience and environmental case studies, such as the localisation of the Indrapatra Fort archaeological site [11], mapping geological structures in the Jaboi Volcano area [12], investigation of road damage [13], characterisation of soil [14] and sedimentary deposits [15] Prospective tools for studying sand deposits [16]. In other studies, the geophysical application of resistivity parameters also worked well in studying seawater intrusion in coastal areas [17], [18]. The electrical resistivity tomography (ERT) survey identified leachate at the sanitary landfill in Johor, Malaysia, as indicated by the distribution of low-resistivity values [19]. Resistivity parameters have also been successfully used to accurately detect leachate in West Nusa Tenggara [20]. Furthermore, the ERT method enables mapping of subsurface leachate seepage and detection of leakage around the protective lining of the waste pond in Belfort, France [21] and evaluating leachate seepage around the liner membrane of the waste pond in Palermo, Italy [22]. Although these studies demonstrate the effectiveness of ERT in landfill settings, they were primarily conducted in relatively homogeneous geological environments. The seismic refraction tomography (SRT) contrast model at the Blang Bintang landfill indicates a complex subsurface, shaped by lithology and highly weathered bedrock with few fractures or faults [23]. Therefore, this research uses electrical resistivity tomography (ERT) as an effective and efficient tool to map leachate seepage and estimate pollution levels by contrasting resistivity parameters. In addition, this application allows us to analyse the geological setting and hydrogeological system in detail in the Blang Bintang landfill area.

Basic Theory

Electrical Resistivity Tomography (ERT) is a non-invasive geophysical method used to model subsurface structures based on physical parameters. ERT calculates the response of resistivity and electrical conductivity values of the subsurface material based on the electrical current injected into the subsurface [24]. The ability to produce contrasting resistivity models makes this method successfully applied in several studies, such as the geometric analysis of landslides [25], [26], fault fracture mapping structure in the Jaboi Volcano [12], groundwater resource estimation in West Papua [27] and identifying ancient river sediment deposits in Banda Aceh [28]. On the other hand, the ERT method has a good ability to model the distribution of leachate with high pH and conductivity concentrations [4]. Therefore, ERT applications are relevant in several case studies of varying complexity.

The ERT application works by using four electrode components to obtain the apparent resistivity value; the components are used to obtain a qualitative subsurface resistivity distribution [29]. The apparent resistivity value can be calculated by estimating the intensity of the current injected into the subsurface (I), the measured potential difference (ΔV), geometric factors (K):

$$\rho_a = K\frac{\Delta V}{I} \tag{1}$$

Where K is determined based on the array and position of the four component electrodes and is represented by:

$$K = 2\pi\left[\frac{1}{AM} - \frac{1}{MB} - \frac{1}{AN} + \frac{1}{NB}\right]^{-1} \tag{2}$$

In this study, the Wenner-Schlumberger geoelectric configuration with geometry factors was used:

$$K_w = 2\pi a \tag{3}$$

$$K_s = \pi n\,(n+1)a \tag{4}$$

Where K_w is a Wenner electrode configuration with high sensitivity for identifying horizontal anomalies, K_s It is a Schlumberger electrode configuration that has a high sensitivity to vertical changes [30]. Therefore, combining both configurations produces a high-resolution model (ERT) that represents subsurface information in the measurement profile.

Methodology and Data Processing

Design Survey

This research was conducted at the Blang Bintang Regional Landfill (TPA), Aceh Besar Regency, Aceh Province, with geographical coordinates of 5°31.011'N and 95°28.431'E. The landfill, constructed in 2014, covers 200 hectares and is one of the largest in Indonesia. The development was also carried out in a hilly area with an altitude of 150 -180 meters above sea level, where the landfill facility is 5 km away from community settlements with lower topography. The facilities and capacity available can manage 250 tons of waste per day from Banda Aceh City and Aceh Besar District. A sanitary landfill system was preferred as an effective and efficient management solution, which has also been applied at landfills in Serbia [3] and Niger [31]. A control pond with an impermeable rubber coating manages leachate with a high pH level. The leachate management ponds at Blang Bintang landfill include 1 main collection pond, 3 leachate waste management ponds to reduce pH levels, and 12 leachate storage ponds with pH levels ranging from acidic to neutral (Figure 1).

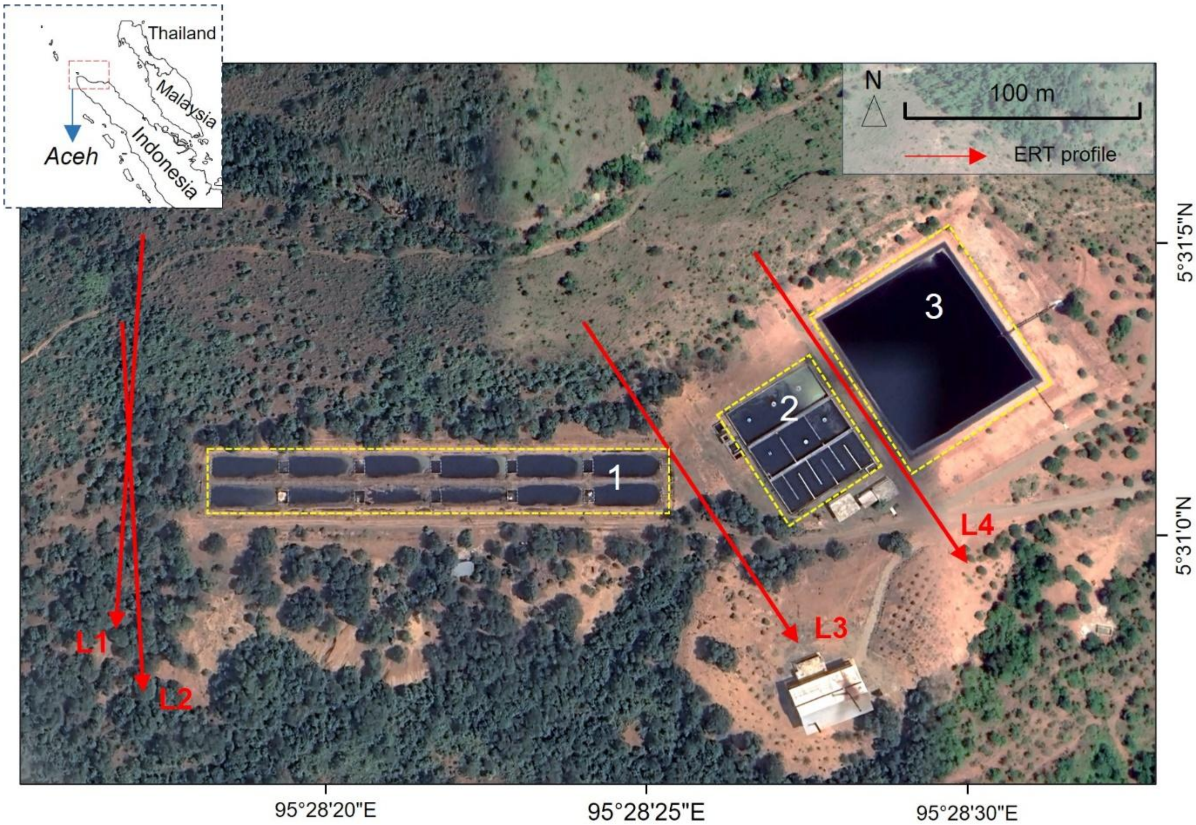

Figure 1. Map of the study site showing the ERT profile measurement design. Area (1) is a leachate storage pond with varying pH levels. (2) a leachate treatment pond to reduce pH levels, and (3) the first leachate collection pond from the landfill on the east side.

Four ERT profiles were measured at the Blang Bintang landfill covering the area of the leachate management ponds facility (Figure 1). Profiles 1 and 2 are located on the western side of the sanitary landfill and intersect, with the aim of obtaining more detailed information on contamination in the leachate disposal area and its surrounding environment. Profiles 3 and 4 were measured on the east side of the landfill, whereas profile three was measured between the leachate collection and treatment ponds. Profile 4 is measured between the treatment ponds and the first leachate collection from the landfill. The ERT profile is 180 meters long, obtained with a 3-meter inter-electrode spacing. On the other hand, field conditions make the distance between profiles vary. The MAE X612EM+ Resistivitymeter, developed by MAE Advanced Geophysics, was used to obtain high-resolution resistivity data. Multi-electrode data acquisition is performed with 60 auto-electrode components. In addition, a Wenner-Schlumberger configuration was used to produce a model with good resolution and contrast. In addition, the configuration has a good response to vertical and horizontal changes, which will increase the accuracy of interpretation [32].

Blang Bintang is an area with a complex geological setting shaped by the tectonic activity of the Sumatran fault. On the other side, the landfill area is close to the Seulimum segment fault line, which results in the distribution of local faults around the area. The presence of Seulawah Vulcano on the south side also significantly contributes to the distribution of volcanic rocks. The study area comprises rocks ranging from the Holocene to the Pleistocene. The centrally located QTvt unit represents the Lam Teuba volcanic formation and includes andesite to dacite, pumice breccia, tuff, agglomerate, and volcanic ash flows. Other units, such as Qvtl, Qh, and QTps, are distributed throughout the area and consist of younger volcanic and alluvial deposits. The Tuktp unit, found in the southeast, is characterized by deformed sedimentary rocks [10].

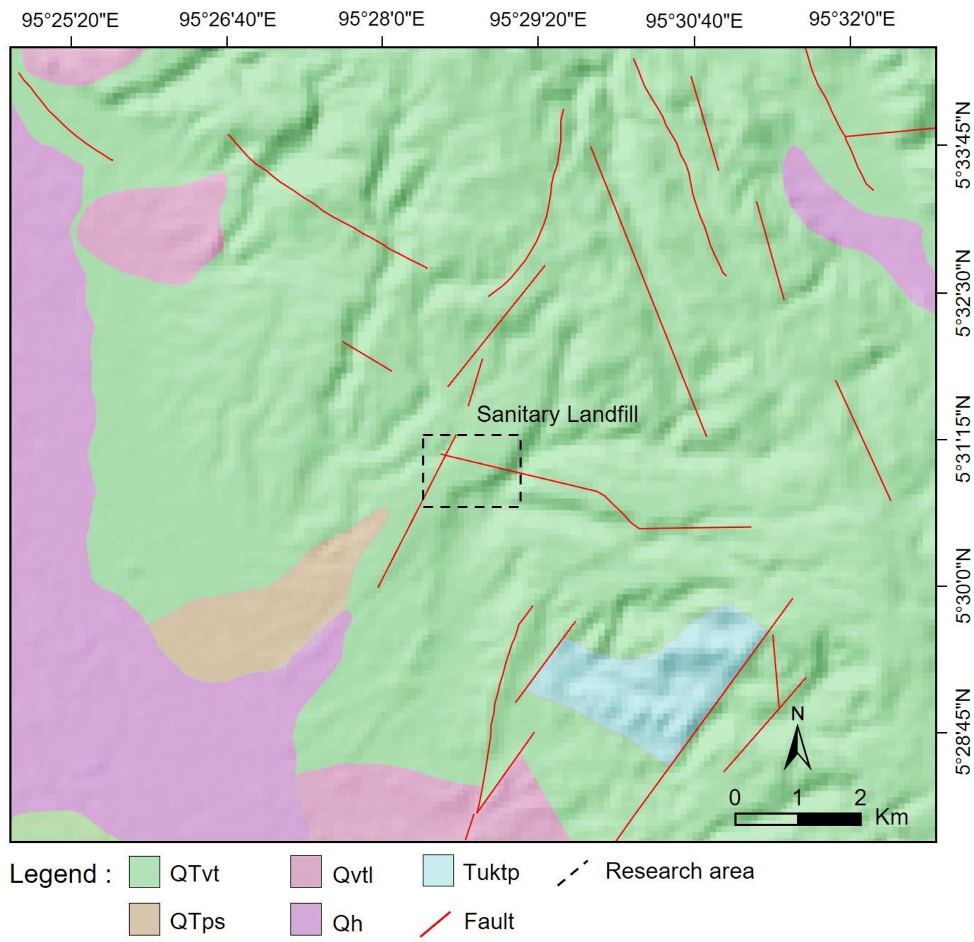

Figure 2. Geological map of the research area

Data Processing

The distribution of measured apparent resistivity values can generally be used to estimate subsurface information from the resulting pseudosection model. Still, it must allow for precise, accurate analysis and interpretation of subsurface anomalies [33]. ERT data is processed with the Res2dinv software developed by Geotomo to obtain resistivity values to the proper depth. Model inversion was performed using the least-squares method. [34]. This technique can optimise errors arising from differences in measured apparent resistivity values by performing an iterative calculation [35]. In addition, some conditions allow the presence of data noise obtained during measurement. In the analysis of resistivity data, noise is removed prior to inversion, thereby minimizing RMS error and improving model accuracy. The RMS error (root-mean-square error) estimates the range and evaluates the quality of the inversion at each iteration. Overall, the subsurface resistivity model in this study was obtained through three iterations, with iterations <4 minimizing distortion of the actual resistivity and limiting the error of the resulting model [36]. This study's ERT profile model has an RMS error value of 10-20%.

Although the location is in a mountain area with significant relief, topographic correction is important to improve the interpretation of the resistivity model [34]. It reduces ambiguity in interpreting the results. In addition, the application of topographic values has helped many studies in showing the suitability of the results obtained, such as landslide characterization in Blangkejeren, Aceh [37], detection of leachate distribution in sanitary landfill areas in Johor, Malaysia [38], and mapping of leachate migration in Banda Aceh, Indonesia [39].

Results and Discussion

The ERT survey in this study was conducted along parallel, south-oriented profiles. This orientation was designed to identify leachate seepage from an underground waste pipeline aligned west–east. In addition, Profiles 1 and 2 were arranged to intersect to obtain more detailed information on the waste-disposal area and its impact on the surrounding environment, particularly in zones with relatively low contamination levels. The measurements were carried out along four survey lines, each 180 m in length, providing an investigation depth of up to 30 m, sufficient to detect leachate. The first profile (Figure 3) obtained resistivity values ranging from 1 - 800 ohm.m. ERT modelling results indicate that subsurface conditions are dominated by conductive and resistive areas. In the northern sector, a conductive zone (C1) with resistivity values of 5-150 ohm.m was identified at depths of 0-50 m, with a layer thickness of 0-15 m. These low resistivity values indicate subsurface contamination from leachate, consistent with previous studies [40], [41]. Another conductive zone (C2) was detected at 60–90 m, extending from the surface to 30 m depth. The ERT model shows leachate seepage reaching deeper subsurface layers, which may contaminate the groundwater table and pose long-term environmental risks to nearby residential areas. A third conductive zone (C3) was found at 110-145 m, indicating leachate infiltration to a depth of about 10 m. The model also suggests deeper leachate migration toward the southern sector, but limited data prevent continuous modeling at greater depths. In contrast, a resistive zone (R1) with resistivity above 150 ohm.m was observed at 30-70 m, at depths of 5-30 m. This resistive response aligns with geological data and field observations of andesitic volcanic rocks, as shown on the geological map [42]. Another resistive zone (R2) was identified at 90-130 m, from the surface to 30 m depth. Steep topography in the northern area, about 50 m from the river channel, may direct leachate flow along the gradient, increasing the risk of broader environmental hazards.

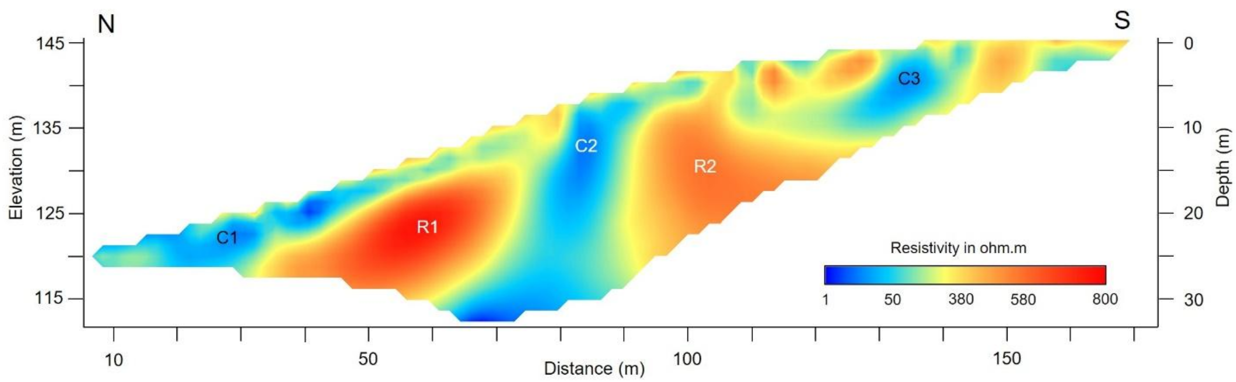

Figure 3. ERT model in profile 1, measured on the west side of the landfill and located outside the leachate storage pond facilities.

The second profile (Figure 4) was measured 15 meters from the first profile, where the second profile crossed the first profile at 60 meters. The observation field showed leachate flow at 50 meters from the waste pipeline, where the topography is flatter. The obtained ERT model shows a resistivity distribution ranging from 1 - 800 ohm.m, with conductive zones dominating the near-surface layers and resistive zones at greater depths. In the northern sector, a conductive zone (C1) with resistivity values of 10-140 ohm.m is distributed at depths of 0-15 m, interpreted as a response to leachate seepage near the waste pipeline. In addition, another conductive zone (C2) is identified at 90-120 m along the survey line, indicating leachate infiltration into deeper subsurface layers. In the southern sector, a conductive zone (C3) is also observed at 140-160 m, suggesting leachate migration to greater depths. However, the lack of resistivity distribution data in this area limits the interpretation at deeper levels. The ERT model further reveals a resistive zone (R1) with resistivity exceeding 140 ohm.m, located at 80 - 110 m and 0 - 10 m below the surface. Additionally, a deeper resistive zone (R2) is present at depths of 15-30 m, interpreted as the response of andesitic bedrock that dominates the study area.

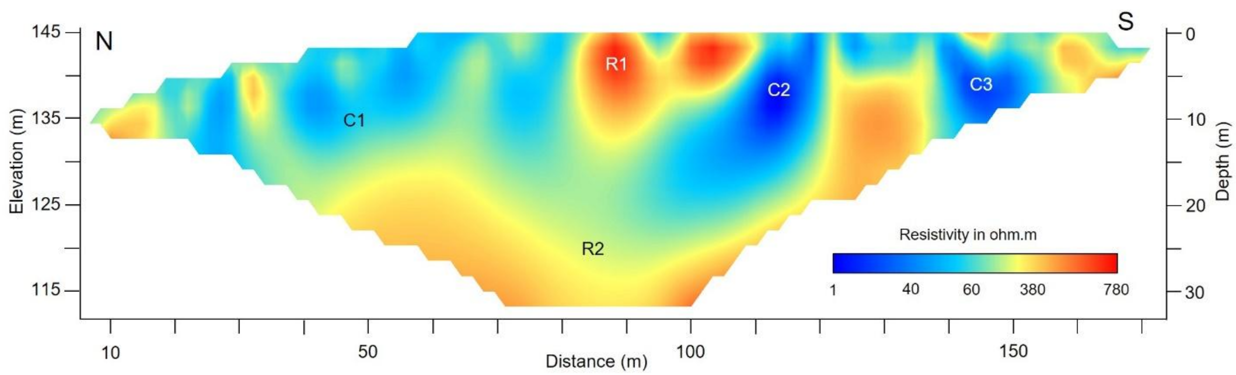

Figure 4. The ERT model in profile two was measured on the west side of the landfill, outside the leachate storage pond facilities.

Figure 5 shows the ERT model for the third profile, with a distribution of values ranging from 1 to 780 ohm.m, dominated by resistive areas. This condition is a response to the geological setting, which is dominated by andesite. In the northern sector, a conductive zone (C1) with resistivity values ranging from 5 to 200 ohm.m was identified at depths of approximately 15 - 25 m and at distances of 30 - 65 m from the surface. This response indicates the presence of leachate seepage near the underground waste pipeline. In addition, another conductive zone (C2) was detected at 70 - 90 m, with depths of 5 - 20 m, interpreted as a response to leachate infiltration around the waste pipeline. A further conductive zone was also observed at distances of 110 - 145 m and depths of 5 - 25 m, reflecting the influence of leachate presence near the pipeline. Conversely, the ERT model demonstrates a strong capability to locate the underground waste pipeline. Additional analysis indicates that leachate seepage affects the resistivity response in the surrounding pipeline area. Overall, this profile is dominated by volcanic andesitic rocks, as indicated by resistivity values exceeding 200 ohm.m.

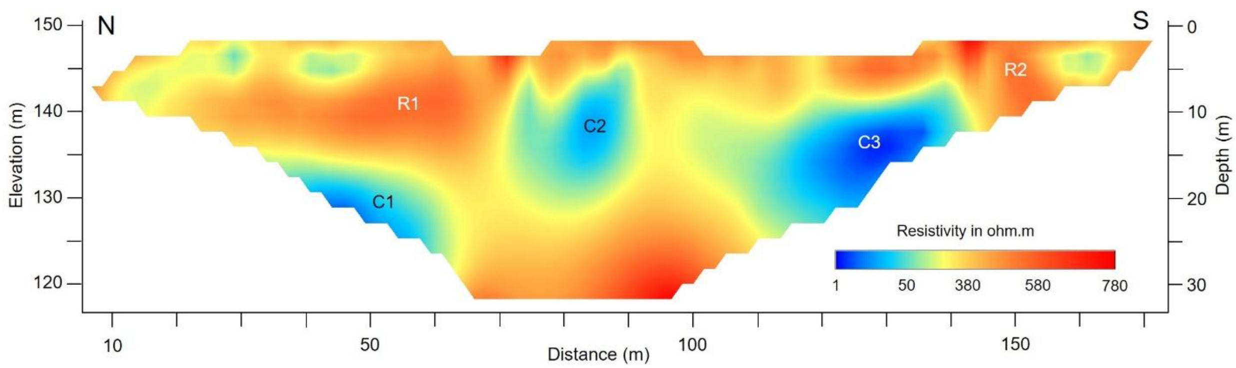

Figure 5. ERT model of profile three measured on the east side. Profile measured between the storage and process ponds.

Figure 6 shows the distribution of resistivity values in the fourth profile, ranging from 1 - 780 ohm.m, with conductive and resistive layers dominating the model results. The fourth profile was measured on the west side of the initial leachate collection pond at the landfill to assess contamination from seepage from the first pond, which had high pollutant levels. In the northern sector, a conductive zone (C1) with resistivity values ranging from 15 - 250 ohm.m is distributed at depths of 0 - 25 m and distances of 10 - 95 m below the surface. This conductive zone (C1) is interpreted as subsurface leachate seepage originating from the main leachate pond. In another section, a conductive zone (C2) is also identified at 105 - 140 m in depth and 0 - 20 m in depth, indicating additional leachate seepage from the same pond. Conversely, the ERT model reveals a resistive zone (R1) with resistivities exceeding 250 ohm.m, located at 60 - 125 m depth and 0 - 30 m depth. Furthermore, a resistive zone (R2) is observed at distances of 130 - 160 m along the survey profile, distributed from near the surface to depths of 0 - 10 m. The distribution of these resistive zones indicates that the ERT model is consistent with the geological conditions of the study area.

Based on the results obtained from the four profiles, it is assumed that there are conductive areas at different depths up to ± 25 m in the subsurface. These conditions indicate the presence of leachate seepage infiltrating into the subsurface following the local hydrological system. Furthermore, leachate flowing into the free environment after the neutralisation process was detected not only at the surface but also seeping deep into the subsurface. Based on the study location, the sanitary landfill area is situated at a considerable distance from residential settlements, with a radius of approximately 5–10 km; therefore, this condition does not directly impose environmental impacts on nearby communities. However, waste effluent discharged into the environment with relatively low contamination levels after the neutralization process still exhibits a strong geophysical response characterized by high conductivity values (5–150 ohm.m). This suggests that heavy metals may still be present and could contaminate the surrounding environment. Further investigations are required to confirm the composition and quality of the neutralized leachate.

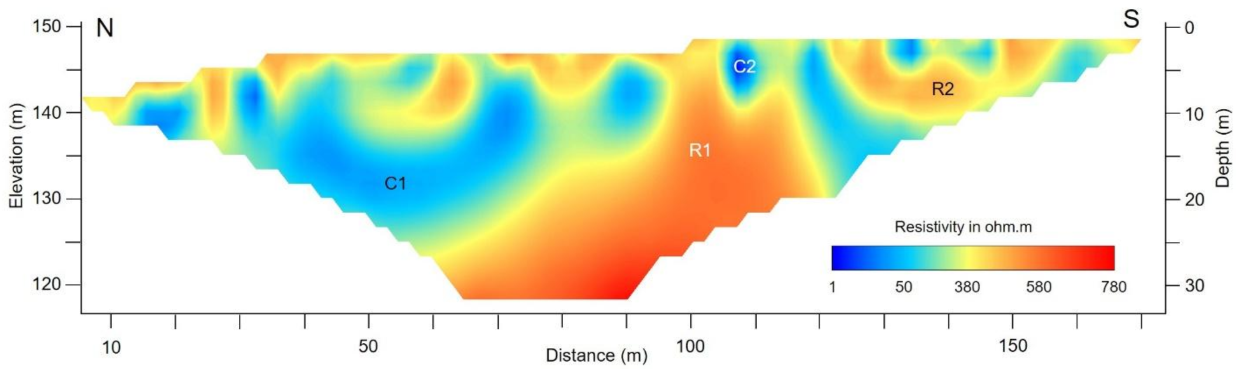

Figure 6. ERT model in profile four was measured on the east side of the landfill. Measurements were conducted between the initial containment and the process pond.

If observed on the path profile between the storage and processing ponds (Figure 4), there are three conductive zones (5-200 ohm.m) with different diameters. After being adjusted to the actual field conditions, it was found that the three zones were located at the flow pipe connecting the two ponds. However, the identified diameter is different from the actual pipe size. This could be due to leachate seeping around the pipes, which may have influenced the resistivity values obtained during data acquisition. Periodic inspection of leachate pipelines must be carried out as routine maintenance to anticipate leaks that could cause leachate to seep into the ground and potentially contaminate it.

Conclusion

The application of geophysical methods in environmental studies, as a continuous monitoring effort, can help mitigate environmental disasters in landfill areas. In this study, an ERT geophysical survey was applied to the Blang Bintang landfill area, Aceh Province; this survey can provide information on the extent and depth of leachate seepage below the surface and characterise soil conditions in the area. The ERT model reveals conductive zones with resistivity values ranging from 5 to 150 ohm.m, interpreted as leachate contamination. These anomalous responses are identified in the near-surface layers of Profiles 1 and 2. Furthermore, the ERT modeling results indicate that leachate contamination is not limited to shallow surface layers but has infiltrated into deeper subsurface layers. This condition suggests a potential risk of groundwater contamination in the study area. Profile 3 shows conductive zones (5–200 ohm.m) interpreted as leachate seepage around the waste transfer pipeline. In addition, Profile 4 presents a subsurface model dominated by conductive zones (15–250 ohm.m), interpreted as leachate seepage from the main leachate pond with a high level of contamination. The subsurface investigation using ERT effectively identified leachate in the Blang Bintang landfill area. In addition, this study highlights the importance of geochemical testing to accurately assess leachate contamination levels at the Blang Bintang sanitary landfill.

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