



Characterization of an inactive dumpsite using electrical resistivity tomography and hydrochemical data: a case study in Brazil

Leonides Guireli Netto^{1,2} · Camila Camolesi Guimarães² · Alexandre Muselli Barbosa^{2,3} · Otávio Coaracy Brasil Gandolfo²

Received: 11 March 2023 / Accepted: 8 October 2023 / Published online: 19 October 2023
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2023

Abstract

Open dumping is one of the most common solid waste disposal methods in developing countries. As they lack planning and basic environmental protection engineering measures, dumpsites represent environmental and health risks that should be investigated. However, several dumpsites are abandoned without appropriate land-use management, difficulting their proper environmental assessment. The use of non-invasive methods for waste mass delimitation and preliminary screening of contamination plumes, such as geophysical methods, is an interesting alternative for the study of the environmental impacts caused by dumpsites. The aim of the present study is to apply electrical resistivity tomography (ERT) for the delimitation of the waste mass and the identification of anomalies related to the presence of alterations in the physical and chemical properties of soils and groundwater in an inactive dumpsite in the municipality of Miracatu, State of São Paulo, Brazil. The study was based on the use of the python software *ResIPy*, which uses an R family of ERT inversion codes. The 3D inversion of data showed a good correlation between the most electrically conductive anomalies and the delimitation of the waste mass. The behavior of these anomalies, associated with the presence of waste, was confirmed by the physical characterization of the geological materials obtained from drillings and installation of monitoring wells. The present study shows that the ERT inversion code for electrical data can be an interesting open-source alternative for data processing in complex scenarios: environments that present considerable anthropic interference, such as dumpsites.

Keywords Dumpsite · Geophysics · Electrical resistivity tomography · Contamination

Introduction

Solid waste management faces a range of complex challenges worldwide due to increases in urbanization and waste production (Das et al. 2019). Several factors contribute to the complexity of this challenge, including environmental, social, economic, and public health issues (Kaza et al. 2018). In many parts of the world, traditional waste disposal methods such as landfills are reaching their maximum capacity, resulting in a shortage of suitable sites for safe waste disposal (Bharadwaj et al. 2020). Additionally, the lack of proper infrastructure in some regions hinders the implementation of modern waste management practices such as selective collection and recycling.

Open dumping is one of the most common solid waste disposal methods in developing countries (ISWA 2016). Open dumps, or dumpsites, are inadequate waste disposal sites, where the deposit of materials happens with either no or very limited measures to control the operation and

✉ Leonides Guireli Netto
leonidesnetto@ipt.br

Camila Camolesi Guimarães
camilacg@ipt.br

Alexandre Muselli Barbosa
muselli@ipt.br

Otávio Coaracy Brasil Gandolfo
gandolfo@ipt.br

¹ Geosciences and Exact Sciences Institute (IGCE), São Paulo State University (UNESP), Rio Claro 13506-900, Brazil

² Cities, Infrastructure and Environment Department, Institute for Technological Research (IPT), São Paulo, Brazil

³ Department of Chemical Engineering, University of São Paulo (USP), São Paulo, São Paulo State, Brazil

protect the surrounding environment (ISWA 2016). In Latin America, approximately 45% of the total generated waste is directed to inadequate final disposal sites, with more than 10,000 dumpsites currently operating in Latin American countries (UNEP 2021). Brazil is the largest and most populated country in Latin America. The country has more than 1500 dumpsites still in operation, which received 9.6 million tons of urban solid waste in 2021 (SNIS 2022). Besides the active dumpsites, most Brazilian municipalities have inactive inadequate waste disposal sites that operated in the past, especially until the first decade of the twenty-first century, when environmental legislation and requirements from environmental agencies became stronger, leading to the interdiction of some of these areas (Guimarães et al. 2019).

As they lack planning and basic environmental protection engineering measures, both active and inactive dumpsites represent environmental and health risks that should be investigated. The environmental, social, and economic impacts caused by dumpsites include the contamination of soils, surface, and groundwater resulting from leachate percolation; generation of greenhouse gases from the decomposition of organic waste; attraction of insect and rodent vectors; explosion risks; reduction of land values; and limitation of urban expansion and agricultural practices (ISWA 2015; Krook et al. 2012; Massoud et al. 2022). The Brazilian National Solid Waste Plan (MMA 2020) establishes the elimination and recovery of dumpsites until 2024, a process that involves the assessment and remediation of environmental contaminations in these areas. However, several dumpsites are abandoned without appropriate land-use management, being covered by vegetation, flooded, or occupied by irregular housing, making it difficult to properly identify and delimitate these areas, hampering post-closure management, and increasing contaminants spreading and ecological/public health risks (Morita et al. 2021).

In this scenario, the use of non-invasive methods for waste mass delimitation and preliminary screening of the extension of contamination plumes, such as geophysical methods, is an interesting alternative for the study of the environmental impacts caused by dumpsites. Geophysical surveys can be applied to highly anthropized areas whose history of operation is unclear, allowing the identification of alterations in the physical environment that evidence potential impacts resulting from these areas. Morita et al (2021) analyzed environmental assessments of 104 different dumpsites and non-sanitary landfills in Brazil and found that only 29% of the studies included geophysical surveys, which may lead to erroneous interpretations about the location of monitoring wells and delimitation of contamination plumes. This highlights the opportunities for the development of the use of geophysical methods for the assessment of active and inactive dumpsites, to strengthen the environmental characterization and recovery process of these sites.

In this way, the present study aims to apply the geophysical technique of electrical resistivity tomography (ERT) for the delimitation of the waste mass and the identification of anomalies related to the presence of alterations in the physical and chemical properties of soils and groundwater in an inactive dumpsite in the municipality of Miracatu, located in the southwest of the State of São Paulo, Brazil. The study was based on the use of the python software *ResIPy* (Blanchy et al. 2020), which uses an R family of ERT inversion codes, which had not previously been applied for the analysis of dumpsites, areas that present considerable anthropogenic interferences.

Location and history of use of the study area

The study area is the old and deactivated municipal solid waste dumpsite in the municipality of Miracatu, in the southwestern region of the state of São Paulo, Brazil, about 130 km from the capital. The dumpsite is located 2 km from the city center and has an area of approximately 35,000 m². It was operated for approximately 20 years, from the mid-1980s to early 2007. In its southern portion, the area is crossed by the São Lourenço River. The surroundings are characterized by areas of secondary forest and agricultural areas (mainly banana cultivation) (Fig. 1).

Based on the analysis of legal documents provided by the municipality, as well as restricted documents consulted at the local environmental agency, it was observed that the first inspections of the Miracatu solid waste dumpsite were carried out in the early 1990s and that disposal activities began in the mid-1980s (Fig. 2). Initially, waste disposal was open-air, without compaction, leveling, or covering with inert material. Waste coverage started in 1993. In 1997, the deactivation of the left portion of the landfill, initially used for waste disposal, with cover was verified. In 1999, an agreement was established between the city hall and the environmental company of the state of São Paulo regarding the landfill.

According to an inspection carried out in 2001, two-thirds of the landfill had the waste covered and a soil layer was made at the bottom and side of the dumpsite to delimit the area, as well as to prevent the advance of waste disposal and erosion. In November 2001, a barbed wire fence was installed at the edge of the landfill and the presence of waste was discovered only at the work front. About a quarter of the area had been closed, with eucalyptus plantations. In a survey carried out in 2006, a large amount of waste disposed of in the open and the irregular operation of the landfill were found. In October 2008, an inspection by the state environmental agency confirmed that activities at the landfill had ended.

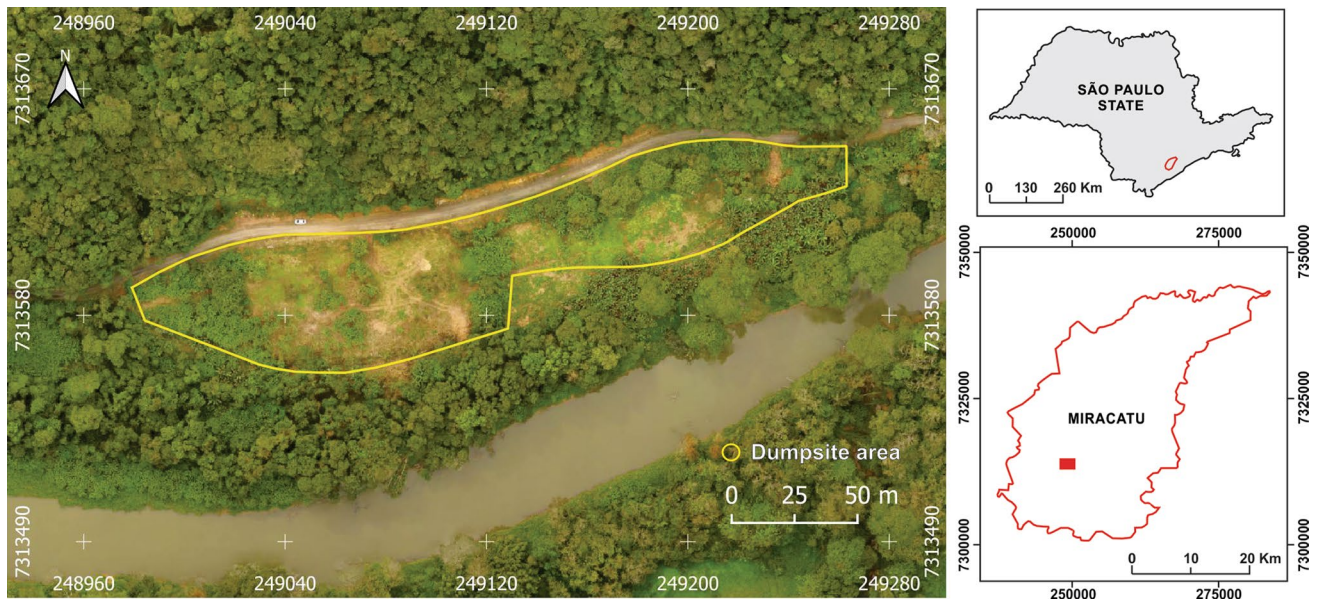


Fig. 1 Location of the study area



Fig. 2 Historical evolution of aerial images of the dumpsite. Source: Google Earth and personal file

Physiographic classification of the study area

In geological terms, the area of the territory of the municipality of Miracatu is characterized by the occurrence of

rocks and included features of different natures, which are grouped into two large crystalline domains, in addition to recent sediments. The first domain is represented by the association of older rocks, consisting of metamorphic

rocks. The second domain is represented by tectonically and chemically undifferentiated granitoid. The composition of the granitoid is, for the most part, granitic to granodiorite (Passarelli et al. 2010). In recent sediments, alluvial deposits are found. These are deposits on the banks, channel bottoms, and floodplains of rivers, consisting of sand, gravel, silt, clay, and, locally, turf, resulting from erosion, transport, and deposition processes from different source areas (Gimenez Filho et al. 1987) (Fig. 3). According to the geomorphological classification by Ross and Moroz (2011), the municipality of Miracatu is inserted in a unit characterized by plains and river terraces, altitudes not exceeding 70 m above sea level, and slopes of less than 2%. The municipality has a small portion of high hills with sharp and convex tops. Altimetry ranges from 200 to 800 m and slopes from 20 to 40%. This type of terrain presents, in general, a dendritic pattern, influenced by the direction of important fractures present in the area (Fig. 3).

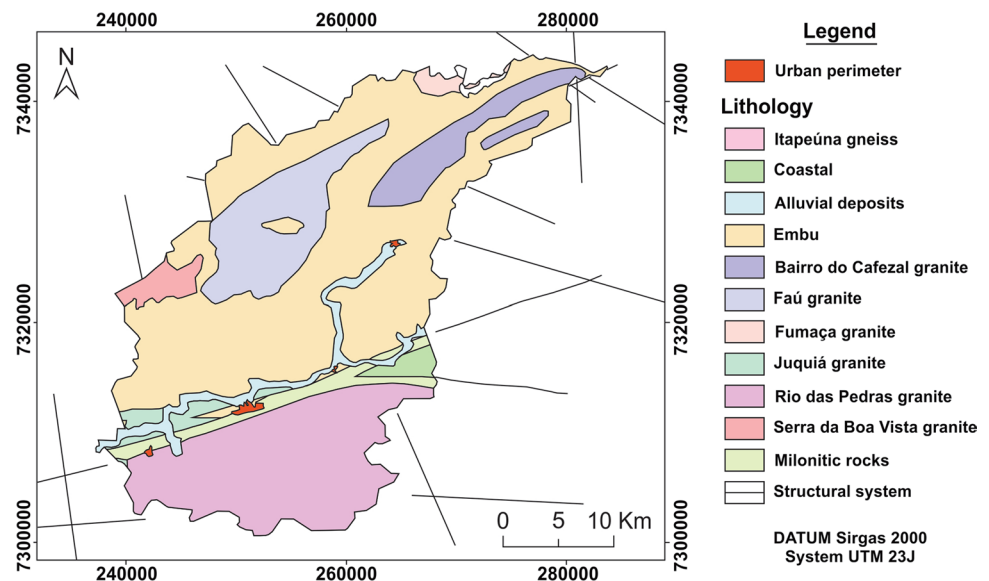
The hydrogeological context of the municipality of Miracatu is characterized by the presence of a fractured crystalline aquifer of regional extension, composed of the oldest rocks in the State of São Paulo. This aquifer is divided into different units according to the type of fissure porosity that develops in the rocks. In the municipality's area, wells were observed that capture water in the Precambrian aquifer unit. This unit has fissure porosity represented only by fractures in the rock and occupies the largest area of occurrence in the north, northeast, and southeast sectors of the State of São Paulo (Garpelli and Gastmans 2020). Another important aquifer in the region is the coastal one, characterized by a sedimentary aquifer, of limited extent, composed of varied and intercalated sediments, such as sandstones, siltstones, claystone, and conglomerates (Shubo et al. 2020).

Geophysical, environmental, and geotechnical investigations

Geoenvironmental investigation techniques provide information about various physicochemical parameters of the soil. These parameters are crucial for interpreting the stratigraphic characterization of the study area and the distribution of contaminants in the subsurface (Koda et al. 2020). However, since most techniques provide point data from boreholes, the information is strictly limited to the location where the test was conducted. Determining the contamination source through this type of invasive investigation can lead to the need for implementing an extensive grid of tests, which increases the cost of the contaminated area management project (Issaoui et al. 2023).

The use of geophysical methods in contaminated areas is well established in the literature, with numerous studies applied primarily to contaminant plume mapping and flow (Atekwana et al. 2000; Kaya et al. 2007; Guireli Netto et al. 2020), the stratigraphic characterization of the investigated area (Abbaspour et al. 2000; Abreu et al. 2016), and the monitoring of environmental remediation techniques (Caterina et al. 2017; Morita et al. 2020). The geophysical investigation in the decommissioned dump area made use of the electroresistivity method. This geophysical method performs non-invasive readings of apparent electrical resistivity (ρ_a) of the environment. There are different techniques for data acquisition. As the objective of the geophysical investigation was to obtain values of the physical parameter both laterally and in-depth the electrical resistivity tomography (ERT) technique was adopted (ERT). Data were processed using the open-source software *ResIPy* (Blanchy et al. 2020).

Fig. 3 Geological map of the municipality of Miracatu and points of urban perimeters



The electrical resistivity of materials is a physical parameter that expresses the difficulty encountered by the electric current to propagate in each geological material (Parasnis 1997). Changes in the physicochemical properties of materials lead to alterations in the ability of geological materials to facilitate the flow of electrical current within their interior (Lesmes and Friedman 2005). In rocks and soils, current propagation can occur by two conduction mechanisms: electronic (through the rock or soil matrix) and ionic or electrolytic (through ions existing in the water contained in the pores and voids of the materials). In environmental studies, regions with the presence of subsurface contaminants (waste and/or percolated liquid) alter the natural electrical resistivity values of the physical environment and, therefore, can be identified using geophysics (Atekwana et al. 2000; Cardarelli and Di Filippo 2009; Helene et al. 2020; Guireli Netto et al. 2021).

In this method for field acquisition, an artificial source of direct current, or very low frequency (I), was used, which was introduced into the soil through a pair of electrodes, called A and B. The potential difference (V) established in response to this current injection can be measured using two other electrodes, named M and N. The geometry related to the disposition of the four electrodes A, B, M, and N at the moment of the measurement defines the geometric factor (K), that has dimensions of distance. The apparent electrical resistivity value (ρ_a) of the investigated volume was calculated using the relationship

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

The acquisition lines were defined to allow the processing of a three-dimensional model of electrical resistivity through a robust finite-element mesh, covering the entire study area. The relationship between the length of Electrical Resistivity Tomography (ERT) acquisition lines and the depth of investigation plays a crucial role in the resolution and detection capability of subsurface structures (Parasnis 1997). In this way, 8 lines were arranged both longitudinally (L1 to L4) and transversely (T1 to T4) to the waste disposal area. The length of the acquisition lines is shown in Table 1.

Some geoelectrical arrays are more established in the literature due to their extensive application in various geophysical investigation studies. The main technical differences between these arrays, as well as the conditioning factors for their selection or non-selection based on the investigation objectives, include: the depth penetration capability of the array and whether it can maintain good resolution at greater depths, as well as its ability to provide high-resolution imaging of horizontal or vertical geological features (Gandolfo 2007; Moreira et al. 2019). The dipole–dipole array was chosen, because it provides good resolution of the lateral variations of subsurface electrical resistivity, desirable in

Table 1 Length and directions of geophysical acquisition lines in the study area

Longitudinal lines (direction E–W)	Length (m)	Transverse lines (direction N–S)	Length (m)
L1	230	T1	105
L2	290	T2	90
L3	290	T3	75
L4	300	T4	70

studies of detection of geological contacts, fracture zones, contamination plumes, and other bodies or structures that present as lateral resistivity heterogeneities (Furman et al. 2003; Moreira et al. 2016). The electrodes were spaced 5 m apart horizontally and 5 depth investigation levels were investigated. Figure 4 shows the positioning of the 8 lines and the electrodes display in the landfill area.

The determination of the location of the drillings for soil sampling and construction of the groundwater monitoring wells was carried out from the results of anomalies obtained in the geophysical study, as well as the distribution and limit of the mass of residues, to contemplate the extension of the potential sources of contamination identified. Six groundwater monitoring wells were installed and 6 capillary fringe samples were collected for physical–chemical characterization of the soil in this horizon. All groundwater monitoring wells were built following the guidelines of the standard (ABNT/NBR 15.495-1/2007). The construction characteristics of the monitoring wells are presented in Table 2.

In the profile sampled during the installation of the well, a visual tactile description of the material was performed. Some characteristics were collected, such as texture, color, consistency, and odor, in addition to external materials present. The soil horizons were classified and individualized; in this way, it was possible to generate descriptive subsoil profiles that supported the construction of the geological–geotechnical sections. Soil samples for physical–chemical characterization were collected from the capillary fringe using the direct push method, with multifunction mechanized equipment through the continuous driving of a probe containing disposable samplers (liners). The drilling was carried out until the water level was reached. The sampling procedure followed the guidelines of the ABNT/NBR 16.435/2015.

Electrical resistivity tomography (ERT)

The location of data acquisition lines in parallel and perpendicular lines to each other made it possible to acquire data throughout the area covered by the dumpsite. The data were entered into open-source software: *ResIPy* (Blanchy

Fig. 4 Location of geophysical acquisition lines, groundwater monitoring wells, and geological–geotechnical sections in the study area

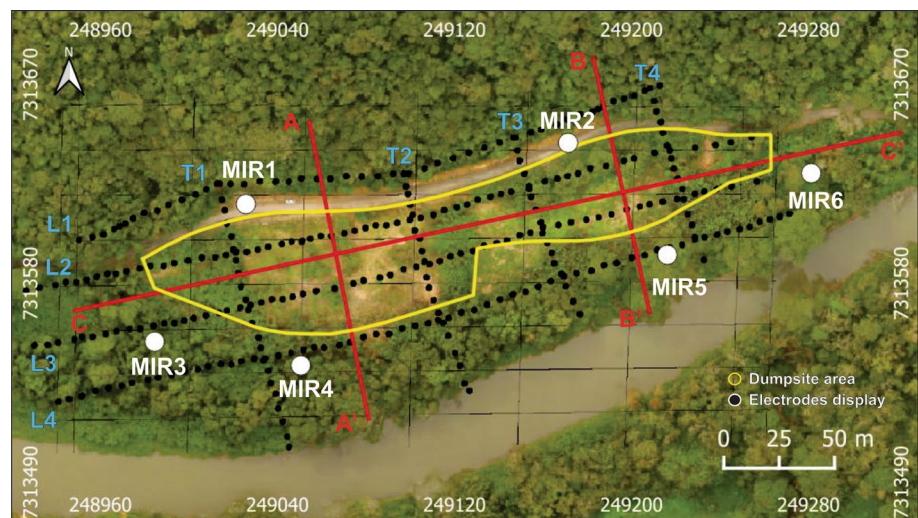


Table 2 Characteristics of monitoring wells in the study area

Groundwater monitoring well	Well depth (m)	Well installation filter depth (m)	Water level depth (m)
MIR1	9.0	8.8	6.9
MIR2	6.3	5.7	2
MIR3	4.5	4.4	2.3
MIR4	9.0	8.7	3.7
MIR5	4.5	4.4	2.2
MIR6	7.5	7.2	4.8

et al. 2020). The python software makes use of an R family of ERT inversion codes (Binley 2015) and has already been used in some environmental studies focusing on contamination (Ciampi et al. 2022; Mohammed Nazifi et al. 2022; Jefayinfa et al. 2023). However, studies have not yet been carried out in dumpsites, environments that present considerable anthropic interference in the physical environment, where waste disposal happens with very limited measures to control the operation and protect the surrounding environment.

Before the start of the data inversion stage, the coordinates and topography of each of the electrodes and control points inside the dumpsite were inserted to build a finite-element mesh consistent with the physiographic aspects of the study area. Filtering of the collected apparent electrical resistivity data was performed. In this step, all acquisition lines are analyzed individually to remove duplicate data—this can occur when current electrodes (A and B) are read as potential electrodes (M and N). Discordant values, which may occur mainly due to the increase in contact resistance between the electrode and the ground, were also removed (Blanchy et al. 2020). After analyzing the quality of the data, a robust three-dimensional finite-element mesh was

generated in the *ResIPy* software, with a good number of elements laterally and in-depth for geophysical inversion (Fig. 5A). In three-dimensional models, the software makes use of tetrahedral elements, since this geometry is better suited to terrain with considerable topographic variations (Boyd et al. 2019; Doyoro et al. 2022). The size of the nodes around the electrodes was the smallest available in the software (1/2). This value is the default of *ResIPy*. The node growth factors in depth were 8 and 3 near the surface. In this way, the generated mesh presented many nodes around the electrodes and in-depth (Fig. 5A).

The inversion of electrical resistivity data made use of the R3t inversion code for three-dimensional electric current flow in a tetrahedral finite-element mesh. The code uses an Occam-like solution that is based on a regularized objective function combined with weighted least squares (Binley 2015). As the acquisition lines were arranged close to each other and the longitudinal lines (E–W direction) have lengths of 275 m on average, the geostatistical relationship of distances between the interpolated lines and the total length of the ERT line (10–20%) was respected (Chiles and Delfiner 1999). Five iterations were performed and the difference between the apparent electrical resistivity data measured in the field and the resistivity of the model's tetrahedral elements (Root Mean Square—RMS) was less than 2 (Fig. 5B). Root Mean Square is a metric used in electrical resistivity tomography processing to quantify the discrepancy between the resistivity values calculated by the model and the values measured during the data acquisition process. The lower the RMS value, the more accurate the correspondence between theoretical values and experimental measurements, indicating a better fit of the model to the electrical behavior of the subsurface. This is crucial for assessing the reliability of reconstructed resistivity images and for interpreting the geological and hydrogeological features present

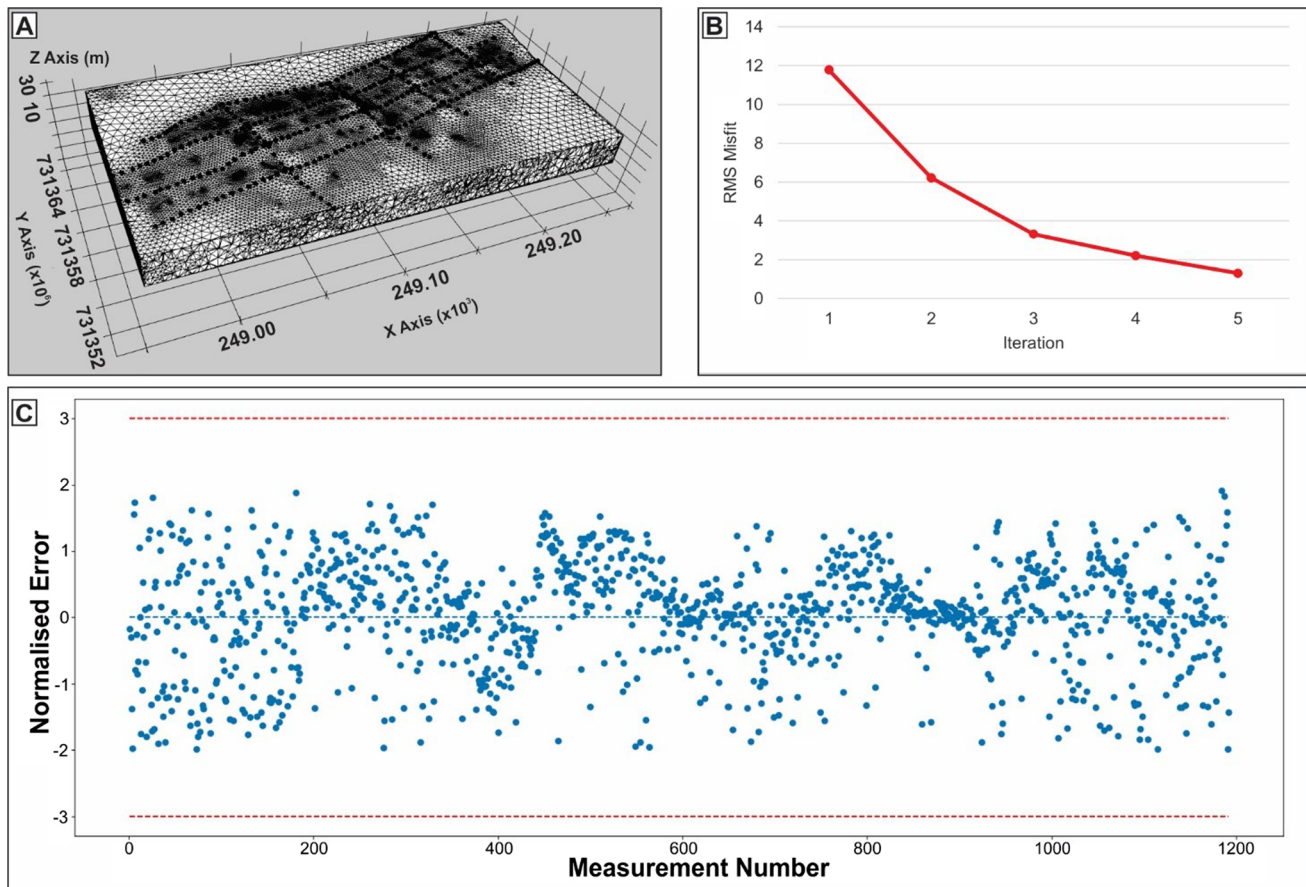


Fig. 5 **A** Tetrahedral finite-element mesh used in data processing, **B** RMS \times iterations, and **C** normalized inversion error

in the subsurface (Binley 2015). To improve the processing quality, a normalized inversion error filter defined to filter inversion errors outside the range of -2 to $+2\%$ was inserted (Fig. 5C).

Results and discussion

The 3D models of electrical resistivity allowed the generation of maps that presented the distribution of electrical resistivity throughout the study area (Fig. 6). In this way, it was possible to observe the positioning of different ranges of electrical resistivity values along the dumpsite. Purplish tones indicate lower resistivity values that can be correlated with the presence of waste and/or percolate (Zhan et al. 2019). The shades in green represent intermediate values of resistivity and may represent some influence of waste and/or leachate. The zones represented by red tones indicate high values of electrical resistivity, and represent places on the ground apparently without influence of waste and/or percolate, corresponding to the “background” of the area (Fig. 6). These correlations were confirmed by physical–chemical

information from the monitoring wells installed in the study area. The visualization of intervals of smaller, intermediate, and larger values of electrical resistivity along the dumpsite clearly shows the anthropic influence on the physical environment. The highest values of electrical resistivity were observed around the waste disposal site, especially in the region of the municipal road, while the most conductive values found were consistent with the limits of the dumpsite defined by the historical survey and the technical visit in the study area.

When observing the electrical resistivity values at different depth levels, a pattern in the behavior of conductive anomalies was identified, marked in yellow in Fig. 7. At shallower depths, between 2 and 4 m, the conductive anomaly (in purple) is consistent with surface waste disposal over the years. At greater depths, between 10 and 14 m, the presence of the most conductive anomalies (0–80 Ohm m) was not observed in the entire area of the dumpsite. However, it was possible to identify the displacement of the electrical anomaly in the NE–SW direction along the depth. This behavior was expected, since the historical survey of aerial images of the dumpsite

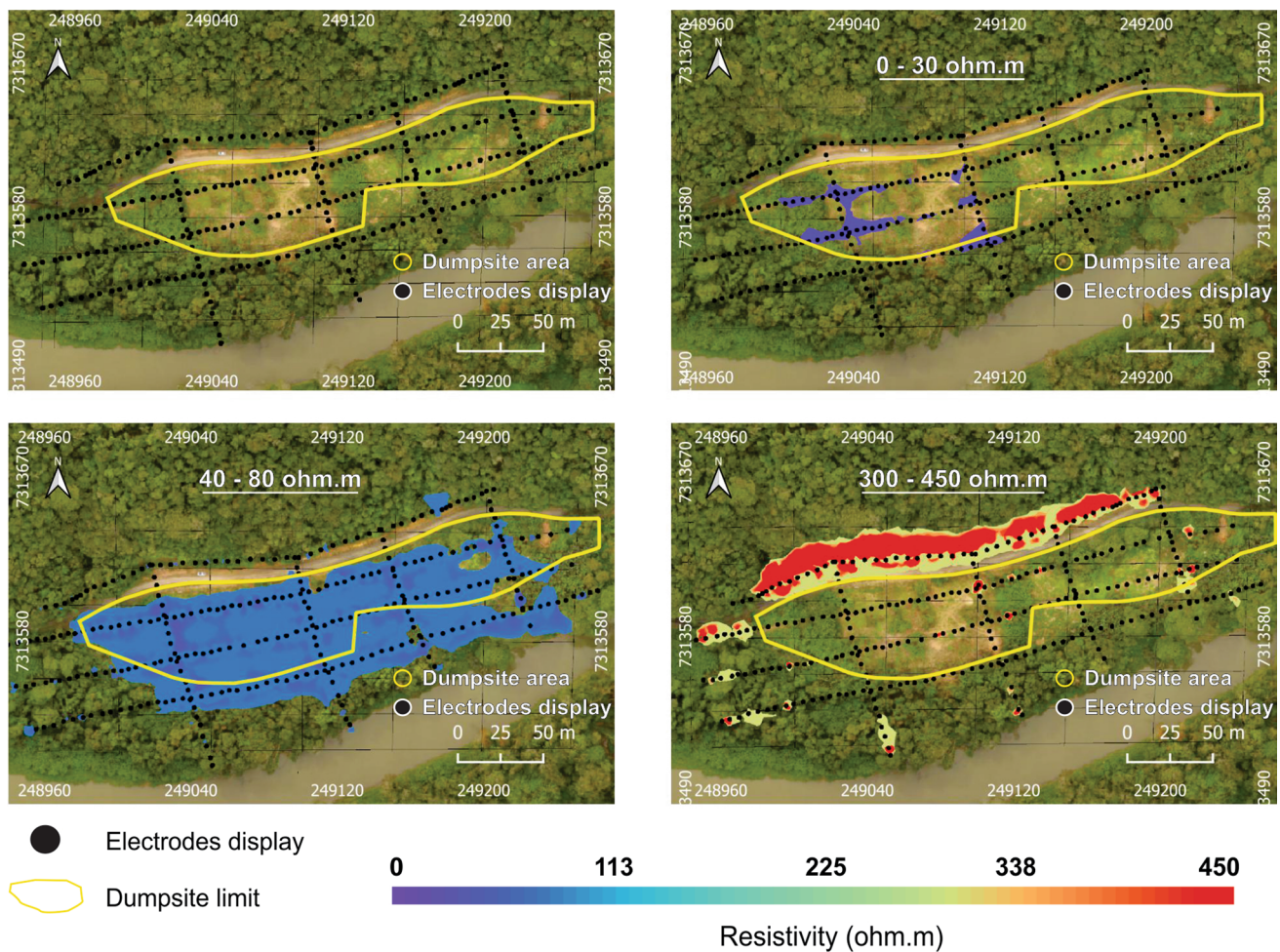


Fig. 6 Distribution of electrical resistivity values in the study area (plan view)

showed that the mass of waste was disposed of mostly in the northwest sector of the area. Although the studies were conducted in different geological contexts, the observed electrical resistivity values in this study are consistent with the values associated with leachate in ERT application studies in dumpsites, such as Zhan et al. (2019), Helene and Moreira (2021) and Guinea et al. (2022). Added to this information, the potentiometric map of the area obtained by the monitoring wells points to a relatively shallow flow of groundwater due to the proximity to the river, and with flow in that direction (Fig. 7).

The results of the physical characterization of the soil in the old dumpsite carried out from samples collected in the capillary fringe indicated the predominance of fine-grained soils (less than 0.002 mm) upstream of the area (MIR1 and MIR2), with silt percentages between 39.7 and 65% (Table 3). Downstream, at all drilling points, except for MIR5 and MIR6, a layer of organic matter was observed in the first 0.10–0.45 m, due to the high deposition of plant material in these areas.

In the MIR3, MIR4, and MIR6 drilling points, silt, and clay granulometry soils were also observed at lower depths and soils consisting of fine sand (grain diameters between 0.0063 and 0.2 mm) from a depth of 4.0 m. In the MIR5 drilling, the presence of material with a higher percentage of clay (51.2%) was identified, with predominantly clayey-silt soils. Therefore, the physical characterization of the soil in the study area showed similar fine granulometry material, especially for silt. In all samples, the values found for this granulometry were greater than 35%. Even the soil samples (MIR3 and MIR4) that had fine sand in their composition also showed the presence of large amounts of fine materials (clay and silt). The MIR4 sample, for example, despite having fine sand in its characterization, has mostly (56%) materials of finer granulometry.

Regarding the physicochemical parameters, the pH ranged from 4.72 to 6.58, which represents acidic to slightly acidic (Table 4). The lowest pH values were observed upstream of the dumpsite. Frequent rainfall throughout the year, such as observed in the region (Capozzoli et al. 2022),

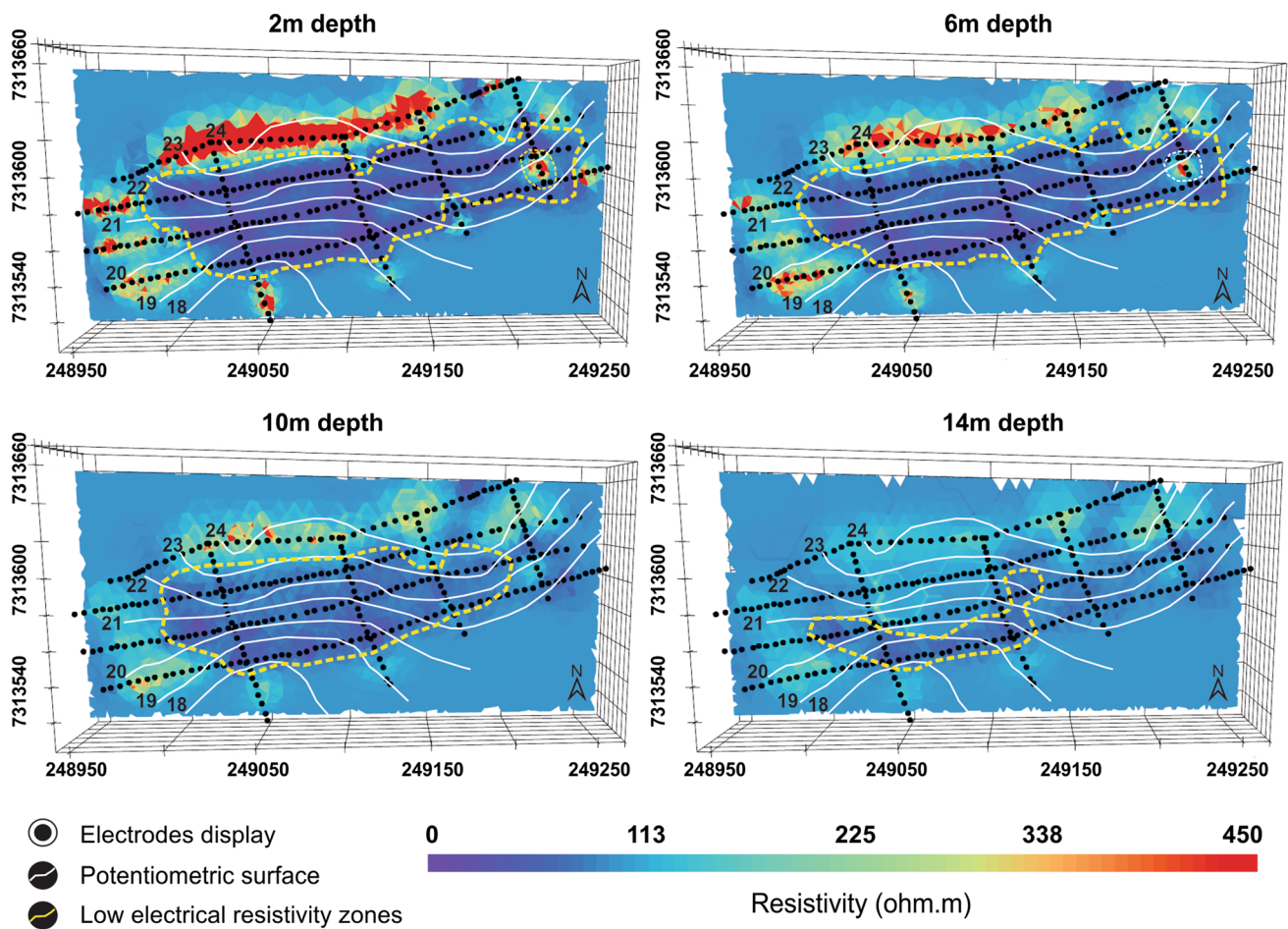


Fig. 7 The 3D electrical resistivity model at different levels (4 m depth variations)

Table 3 Grain size distribution of the soil collected at the capillary fringe

Well ID	Grain size				Textural classification	Collection depth (m)
	Clay (%)	Silt (%)	Sand (%)	Gravel or retained grains (%)		
MIR1	19	65	16	–	Clay silt	7.0–9.0
MIR2	34	39.7	13.1	13.2	Clay silt	5.6–6.3
MIR3	13	36	51	–	Silty sand	4.5
MIR4	20	36	44	–	Silty sand	6.0
MIR5	51.2	41	7.8	–	Silty clay	4.5
MIR6	39	43	18	–	Clay silt	7.5

contributes to the formation of acidic soils, in addition to the proximity to the São Lourenço River (Blake 2005). Moisture contents between 36.9 and 49.4% were observed, except for the MIR5. The high moisture levels are related to the depth of the water level and the high levels of rainfall during the survey period. The moisture content observed in MIR5 (113.3%) is directly related to the organic matter content (17.4%) for this sample since higher contents

result in increased water retention in the soil (Minasny and McBratney 2018).

The description of the soil profiles carried out in the field allowed the generation of three geological sections (one longitudinal and two transversal) to characterize the geology of the former dumpsite. The geological surveys performed at different points in the area identified the presence of waste at depths up to 6 m and proved to be consistent with the

Table 4 Physical–chemical characterization of the samples collected in the capillary fringe

ID	Moisture (%)	Organic matter (%)	Fraction of organic carbon (g/kg)	pH	Electrical conductivity ($\mu\text{S}/\text{cm}$)
MIR1	45.7	1.91	2.7	4.74	28.53
MIR2	38.6	2.65	2.57	4.72	23.6
MIR3	49.4	5.28	17.51	5.99	31.03
MIR4	43.1	3.77	14.01	5.89	37.93
MIR5	113.3	17.4	87.92	5.36	37.33
MIR6	36.9	2.99	2.9	5.11	24.27

ERT sections. The limits of the most conductive anomalies, associated with the presence of waste, were confirmed by excavations and drillings carried out in the field to determine the extension of the waste mass (Fig. 8). Understanding the quantity of waste present in dumpsites is crucial for planning and implementing effective strategies for remediation and recovery of these degraded areas. Determining the waste mass allows for assessing the extent of soil and groundwater contamination, identifying the distribution of pollutant substances, and devising appropriate action plans to mitigate negative environmental impacts. Additionally, precise quantification of the waste assists in allocating the necessary financial and technical resources for the proper cleaning, removal, and appropriate treatment of the discarded materials.

The groundwater monitoring wells installed around the waste mass and close to the geological sections provided physicochemical parameters of the groundwater at different points. The highest electrical conductivity (EC) readings in the monitoring wells were observed downstream of the waste disposal area. High concentrations of salts are naturally expected in arid or semi-arid areas, where evaporation is usually greater than precipitation, a different scenario from the study area, evidencing the presence of anthropic influence (Eludoyin 2020). The EC values measured in the monitoring wells ranged from 76.0 $\mu\text{S}/\text{cm}$ (MIR1) to 306.0 $\mu\text{S}/\text{cm}$ (MIR5). Electrical conductivity is a reading of the quantity of ions dissolved in groundwater. According to the environmental agency of the State of São Paulo (CETESB 2001), even though this is a qualitative measure, values greater than 100 $\mu\text{S}/\text{cm}$ may represent an indication of impacts on groundwater. All monitoring wells, except for MIR1, presented conductivity values greater than 100 $\mu\text{S}/\text{cm}$, which indicates the presence of ions in solution.

The concentrations of different ions and organic compounds were analyzed, interpreted, and compared with the electrical resistivity values obtained at the depths of groundwater sampling. No concentrations of semi-volatile and volatile organic compounds were found in any of the groundwater samples. The identified ions were chloride, nitrogen

(ammoniacal, nitrate, and nitrite), and sulfate. The metals found in the monitoring wells were manganese, aluminum, barium, cobalt, copper, iron, strontium, and zinc. Of these, the first two elements are worth highlighting. Aluminum concentrations were found in all the samples below the limits established by USEPA (2017). However, the presence of this element was detected in most of the monitoring wells. Manganese concentrations in groundwater were identified above USEPA (2017) values in MIR2 (1.87 mg/L), MIR4 (0.515 mg/L), MIR5 (0.799 mg/L), and MIR6 (1.65 mg/L). This chemical element is a natural constituent of Brazilian soils and its presence cannot be associated with waste disposal (Schaefer et al. 2008), since it also occurred in an upstream well (MIR2), in higher concentrations than those observed in the downstream wells.

The comparison between the sum of metal concentrations in groundwater in the monitoring wells, and the electrical resistivity values obtained by the ERT for the same point was consistent for all wells, except for the upstream wells (MIR1 and MIR2). The increase in the concentration of metals in the groundwater resulted in lower values of electrical resistivity, and therefore, the geological material presented a greater flow of electric current in its interior. This behavior was consistent with the other studies that performed correlations of these parameters (Chambers et al. 2006; Chaali et al. 2022).

The relationship between the Σ metals and electrical resistivity was not observed in the upstream wells (Fig. 9). Both points suffered anthropic influence due to grounding for the road construction. MIR1 did not present detectable metal concentrations in the laboratory analysis. MIR2, on the other hand, showed high values of total Fe and Mn. The granulometric analysis of the soil collected in the capillary fringe in this well identified the presence of gravel (13.2%) in the samples. This texture was not identified in any other monitoring well in the study area. As the municipality of Miracatu is inserted in a predominantly crystalline environment, the presence of these elements in the chemical composition of the basement rocks is common (Passarelli et al. 2010).

Although not all metal concentrations found in groundwater were above the limits established by environmental agencies, the relationship between the concentration of metals (Σ metals, in $\text{mg}/\text{L} \times 10$) and electrical anomalies was important for understanding the leachate flow in depth, considering the potentiometric map and information on the chemical quality of the groundwater.

The concentrations of ions observed in the monitoring wells indicated the influence of two ions on groundwater quality, chloride (Cl^-) and sulfate (SO_4^{2-}) since ammoniacal nitrogen and nitrate concentrations were low in all monitoring wells. These ions are formed in organic matter decomposition processes and the low concentrations were

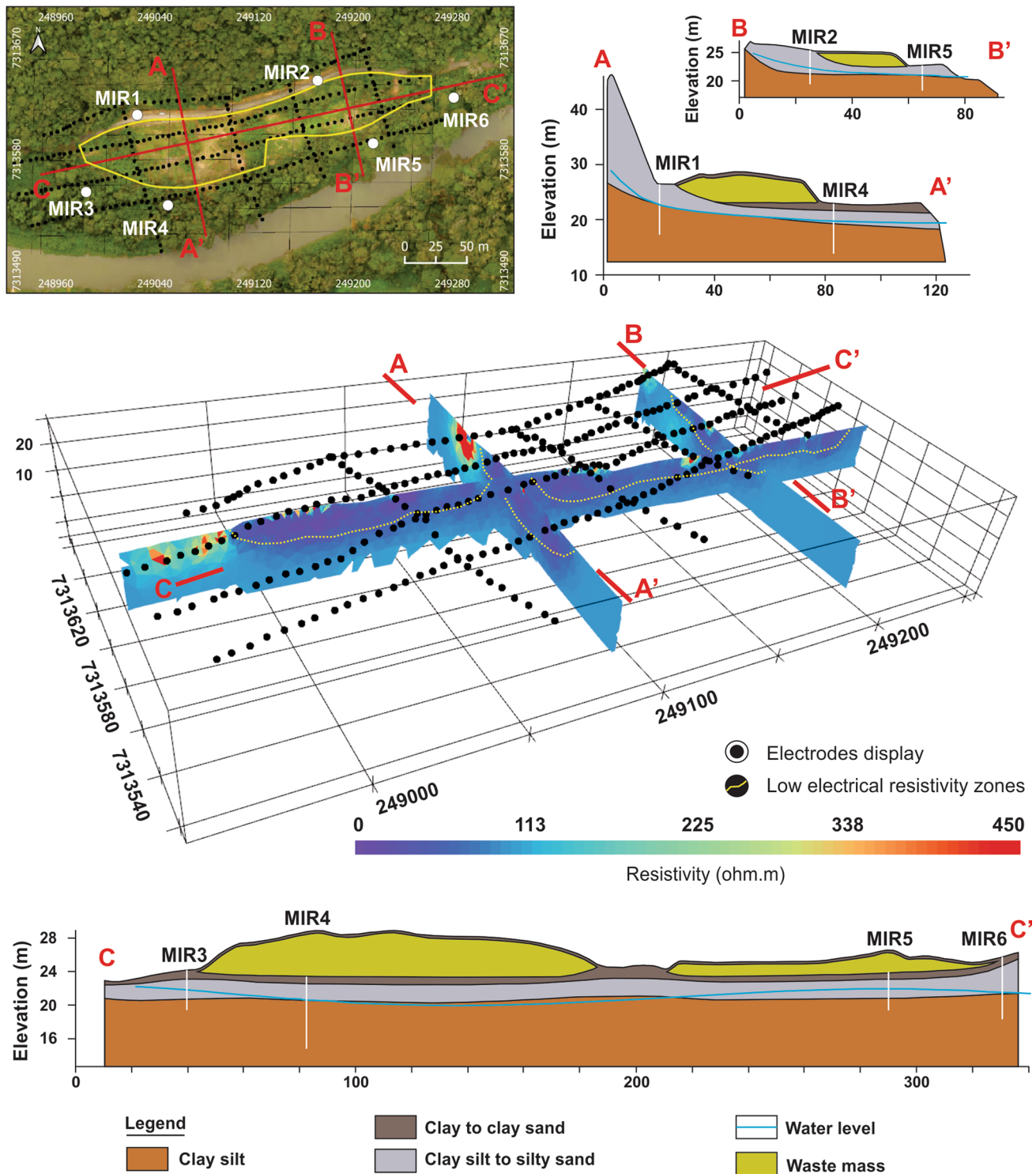


Fig. 8 Geological-geotechnical sections × geoelectrical sections in the landfill area

consistent with the chemical characterization of the soil collected in the capillary fringe of the monitoring wells. As low contents of organic matter and volatile solids were obtained in laboratory tests, it is reasonable to interpret that most of the organic matter has already been decomposed

and leached into deeper layers of the soil. This behavior of the leached material in depth corroborates the distribution of the electrical anomalies, as presented previously in this section (Fig. 10). The relationship between the behavior of the variation in the concentration of chloride, nitrogen

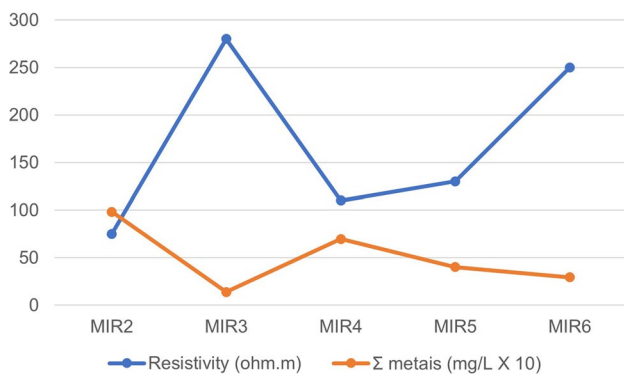


Fig. 9 Relationship between Σ metals and the electrical resistivity of groundwater samples collected in the capillary fringe

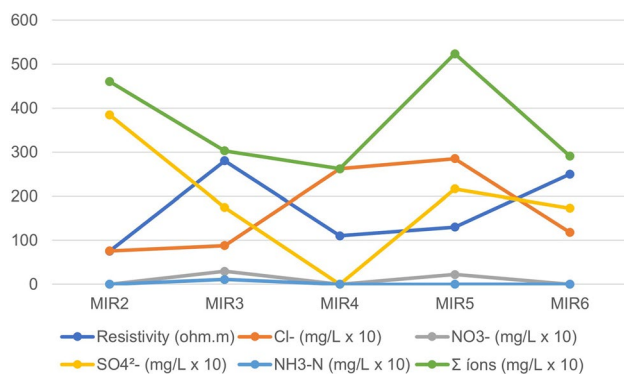


Fig. 10 Graph of the relationship between different concentrations of ions and the electrical resistivity of groundwater samples collected in the capillary fringe

(ammoniacal, nitrate, and nitrite), and sulfate ions, and the electrical resistivity values obtained by ERT is shown in Fig. 10. As well as with the concentration of different metals, the objective was to observe the behavior of different ions in the study area and correlate them with the electrical resistivity values of the medium.

The presence of chloride (Cl^-) was identified in all wells, except for MIR1. Chlorides are one of the main ions present in bodies of water and groundwater, since they are non-reactive solutes. Several studies show that the concentration of chloride in surface water is one of the main factors that cause the increase in salinity (Khatri and Tyagi 2015; Li et al. 2022). Increased groundwater salinity is directly related to increased soil and rock electrical conductivity (Corwin and Lesch 2003; Gomaa 2020; Ojo et al. 2022). The filling of the intragranular pores that structure the soil and the rock fractures by saline waters facilitates the flow of electric current in the physical environment (Lesmes and Friedman 2005; Glover 2015). The concentrations of Cl^- ions in groundwater showed a good relationship with electrical resistivity values. Increased concentrations of this ion resulted in decreases in

electrical resistivity values. In MIR4, for example, the presence of other ions (ammoniacal sulfate and nitrogen, nitrate, and nitrite) was zero or very low in groundwater. However, at this point, the lowest value of electrical resistivity was observed in comparison with the other wells, and also one of the highest values of chloride concentration.

Conclusions

The acquisition lines of apparent electrical resistivity data of the physical environment provided information about the entire waste disposal area and allowed the generation of a very robust three-dimensional finite-element mesh. The 3D inversion of data showed a high correlation between the most electrically conductive anomalies and the waste mass. The behavior of these anomalies, associated with the presence of waste, was confirmed by the physical characterization of the geological materials obtained from the drillings and installation of monitoring wells in the study area.

The geological materials of the capillary fringe of different monitoring wells in the dumpsite were described. Although granulometry is one of the physical parameters that can change the electrical resistivity values of a material, the variations between the granulometry of the soils in this location were not as heterogeneous as it would be expected between an essentially clayey and sandy material. In our work, we found that:

1. Electrical resistivity values of the soils in the capillary fringe obtained by ERT were compared with the concentrations of metals and ions in groundwater at each monitoring well. In the wells placed downstream of the dumpsite, the increase in the concentration of metals in the water resulted in lower electrical resistivity values. The presence of ions, especially Cl^- , is related to the increase in the salinity of groundwater, and showed a close relationship with variations in electrical resistivity values in the downstream wells.
2. Electrical resistivity tomography has proven to be an efficient geophysical investigation technique for determining the mass of solid waste in the inactive dumpsite. The fact that this technique has a good cost–benefit when compared to robust geoenvironmental investigation methods makes its use interesting, especially in scenarios of small cities with limited available investment funds—a common situation in developing countries. The determination of the mass of solid waste in abandoned landfills plays a crucial role in environmental rehabilitation studies.
3. As the *ResIPy* software had not been previously applied in environmental studies of inactive inadequate waste disposal sites, the present study shows that the R fam-

ily of ERT inversion codes for electrical data can be an interesting open-source alternative for data processing in complex scenarios: environments that present considerable anthropic interference, such as dumpsites.

Author contributions LGN and CCG wrote the main manuscript text. AMB performed hydrochemical data analysis. OCBG carried out the geophysical acquisitions. LGN processing of geophysical data. All authors reviewed the manuscript.

Funding No funding was received.

Data availability No applicable.

Declarations

Conflict of interest The authors declare no competing interests.

References

- Abbaspour K, Matta V, Huguenberger P, Johnson CA (2000) A contaminated site investigation: comparison of information gained from geophysical measurements and hydrogeological modeling. *J Contam Hydrol* 40:4. [https://doi.org/10.1016/S0169-7722\(99\)00055-8](https://doi.org/10.1016/S0169-7722(99)00055-8)
- ABNT/NBR 15.495-1: 2007-Poços de monitoramento de águas subterrâneas em aquíferos granulares. Parte 1: Projeto e construção, Associação Brasileira de Normas Técnicas-ABNT, 25 págs
- Abreu AES, Gandolfo OCB, Vilar O (2016) Characterizing a Brazilian sanitary landfill using geophysical seismic techniques. *Waste Manag*. <https://doi.org/10.1016/j.wasman.2016.03.048>
- Atekwana EA, Sauck WA, Werkema DD (2000) Investigations of geoelectrical signatures at a hydrocarbon contaminated site. *J Appl Geophys*. [https://doi.org/10.1016/S0926-9851\(98\)00033-0](https://doi.org/10.1016/S0926-9851(98)00033-0)
- Bharadwaj B, Rai RK, Nepal M (2020) Sustainable financing for municipal solid waste management in Nepal. *PLoS ONE* 15(8):e0231933
- Binley A (2015) Tools and techniques: DC electrical methods. In: Schubert G (ed) *Treatise on geophysics*, vol 11, 2nd edn. Elsevier, pp 233–259. <https://doi.org/10.1016/B978-0-444-53802-4.00192-5>
- Blake L (2005) Acid rain and soil acidification. *Encyclopedia of soils in the environment*. Elsevier, pp 1–11. <https://doi.org/10.1016/B0-12-348530-4/00083-7>
- Blanchy G, Saneiyani S, Boyd J, McLachlan P, Binley A (2020) *ResIPy*, an intuitive open source software for complex geoelectrical inversion/modeling. *Comput Geosci*. <https://doi.org/10.1016/j.cageo.2020.104423>
- Boyd J, Blanchy G, Saneiyani S, McLachlan P, Binley A (2019) 3D geoelectrical problems with *ResIPy*, an open source graphical user interface for geoelectrical data processing. *Fast times*. <https://doi.org/10.13140/RG.2.2.35381.63205>
- Capozzoli CR, Pickbrenner K, Pinto EJ (2022) Atlas Pluviométrico do Brasil: equações Intensidade-Duração Frequência (Desagregação de Precipitações Diárias): estação pluviométrica Pedro Barros; código 02447043 (ANA), município Miracatu, SP-São Paulo:CPRM
- Cardarelli E, Di Filippo G (2009) Electrical resistivity and induced polarization tomography in identifying the plume of chlorinated hydrocarbons in sedimentary formation: a case study in Rho (Milan-Italy). *Waste Manag Res* 27(6):595–602. <https://doi.org/10.1177/0734242X09102524>
- Caterina D, Flores Orozco A, Nguyen F (2017) Long-term ERT monitoring of biogeochemical changes of an aged hydrocarbon contamination. *J Contam Hydrol*. <https://doi.org/10.1016/j.jconhyd.2017.04.003>
- Companhia de Tecnologia de Saneamento Ambiental – CETESB (2001) “Relatório de Estabelecimento de Valores Orientadores para Solos e Águas Subterrâneas no Estado de São Paulo”- CETESB
- Chaali N, Bravo D, Ouazaa S, Jaramillo Barrios C, Beltran J, Seralde D, Benavides-Erazo J (2022) New insights into arsenic and cadmium distribution and origin in paddy soils using electrical resistivity tomography. *J Appl Geophys* 202:104638. <https://doi.org/10.1016/j.jappgeo.2022.104638>
- Chambers JE, Kuras O, Meldrum PI, Ogilvy RD, Hollands J (2006) Electrical resistivity tomography applied to geologic, hydrogeologic, and engineering investigations at a former waste-disposal site. *Geophysics* 71:231–239. <https://doi.org/10.1190/1.2360184>
- Chiles J, Delfiner P (1999) *Geostatistics: modeling spatial uncertainty*. Wiley, New York, p 695. <https://doi.org/10.1002/9780470316993>
- Ciampi P, Esposito C, Cassiani G, Deidda GP, Flores-Orozco A, Rizzetto P, Chiappa A, Bernabei M, Gardon A, Petrangeli Papini M (2022) Contamination presence and dynamics at a polluted site: spatial analysis of integrated data and joint conceptual modeling approach. *J Contam Hydrol*. <https://doi.org/10.1016/j.jconhyd.2022.104026>
- Corwin DL, Lesch SM (2003) Application of soil electrical conductivity to precision agriculture: theory, principles, and guidelines. *Agron J* 95:455–471. <https://doi.org/10.2134/agronj2003.4550>
- Das S, Lee SH, Kumar P, Kim KH, Lee SS, Bhattacharya SS (2019) Solid waste management: scope and the challenge of sustainability. *J Clean Prod*. <https://doi.org/10.1016/j.jclepro.2019.04.323>
- Doyoro YG, Chang PY, Puntu JM, Lin DJ, Huu TV, Rahmalia DA, Shie MS (2022) A review of open software resources in python for electrical resistivity modelling. *Geosci Lett* 9:3. <https://doi.org/10.1186/s40562-022-00214-1>
- Eludoyin AO (2020) Precipitation–soil water chemistry relationship: case study of an intensively managed grassland ecosystem in southwest England. *Appl Water Sci* 10:125. <https://doi.org/10.1007/s13201-020-01209-z>
- Furman A, Ferre TPA, Warrick AW (2003) A sensitivity analysis of electrical resistivity tomography array types using analytical element modeling. *Vadose Zone J* 2:416–423. <https://doi.org/10.2136/vzj2003.4160>
- Gandolfo OCB (2007) Um estudo do imageamento geoeletrico na investigação rasa. Tese (Doutorado)—Universidade de São Paulo-Instituto de Geociências
- Garpelli LN, Gastmans D (2020) Potencial hidromineral dos aquíferos do estado de São Paulo. *Pesquisas Em Geociências* 47(3):e100458. <https://doi.org/10.22456/1807-9806.109987>
- Gimenez Filho A, Albuquerque Filho JL, Dantas ASL, Fernandes LA, Nagata N, Teixeira AL (1987) Geologia da Folha Miracatu, sul-sudeste do estado de São Paulo. In: *Simp Reg Geol*, 6. Rio Claro, vol 1, pp 225–241
- Glover PW (2015) *Geophysical properties of the near surface earth: electrical properties*. Elsevier. <https://doi.org/10.1016/B978-0-444-53802-4.00189-5>
- Gomaa MM (2020) Salinity and water effect on electrical properties of fragile clayey sandstone. *Appl Water Sci* 10:116. <https://doi.org/10.1007/s13201-020-01189-0>
- Guimarães CC, Barbosa AM, Gandolfo OCB (2019) Visual interpretation of satellite and aerial images to identify and study the evolution of inadequate waste disposal sites. *Detritus* 6:85–95. <https://doi.org/10.31025/2611-4135/2019.13821>

- Guinea A, Bicknell J, Cox N, Swan H, Simmons N (2022) Characterization of legacy landfills with electrical resistivity tomography; a comparative study. *J Appl Geophys* 203:104716. <https://doi.org/10.1016/j.jappgeo.2022.104716>
- Guireli Netto L, Barbosa AM, Galli VL, Silva Pereira JP, Gandolfo OCB, Birelli CA (2020) Application of invasive and non-invasive methods of geo-environmental investigation for determination of the contamination behavior by organic compounds. *J Appl Geophys*. <https://doi.org/10.1016/j.jappgeo.2020.104049>
- Guireli Netto L, Malagutti Filho W, Moreira CA, di Donato FT, Helene LPI (2021) Delineation of necroleachate pathways using electrical resistivity tomography (ERT): case study on a cemetery in Brazil. *Environ Chall* 5:100344. <https://doi.org/10.1016/j.envc.2021.100344>
- Helene LPI, Moreira CA (2021) Analysis of leachate generation dynamics in a closed municipal solid waste landfill by means of geophysical data (DC resistivity and self-potential methods). *Pure Appl Geophys* 178:1355–1367. <https://doi.org/10.1007/s00024-021-02700-7>
- Helene LPI, Moreira CA, Bovi RC (2020) Identification of leachate infiltration and its flow pathway in landfill by means of electrical resistivity tomography (ERT). *Environ Monit Assess*. <https://doi.org/10.1007/s10661-020-8206-5>
- International Solid Waste Association–ISWA (2015) Wasted health: the tragic case of dumpsites. ISWA, Vienna
- International Solid Waste Association–ISWA (2016) A roadmap for closing waste dumpsites: the world's most polluted places. ISWA, Vienna
- Issaoui W, Nasr IH, Khaskhoussi S, Inoubli MH (2023) Monitoring of soil contamination from olive mill wastewater (OMW) using physico-chemical, geotechnical analysis and electrical resistivity tomography (ERT) investigation. *Environ Earth Sci* 82:331. <https://doi.org/10.1007/s12665-023-11020-z>
- Jefayinfa SM, Oladunjoye M, Doro K (2023) Imaging the distribution of bitumen contaminants in shallow coastal plain sands in southwestern Nigeria using electrical resistivity. *Environ Earth Sci*. <https://doi.org/10.1007/s12665-022-10718-w>
- Kaya M, Özürlan G, Şengül E (2007) Delineation of soil and groundwater contamination using geophysical methods at a waste disposal site in Çanakkale, Turkey. *Environ Monit Assess* 135:441–446. <https://doi.org/10.1007/s10661-007-9662-x>
- Kaza S, Yao L, Bhada-Tata P, Van Woerden F (2018) What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank Publications
- Khatri N, Tyagi S (2015) Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Front Life Sci* 8:23–39. <https://doi.org/10.1080/21553769.2014.933716>
- Koda E, Osiński P, Podlasek A, Vaverková MD (2020) Geoenvironmental investigation methods used for landfills and contaminated sites management. In: Reddy KR, Agnihotri AK, Yukselen-Aksoy Y, Dubey BK, Bansal A (eds) Sustainable environmental geotechnics. Lecture notes in civil engineering, vol 89. Springer, Cham. https://doi.org/10.1007/978-3-030-51350-4_8
- Krook J, Svensson N, Eklund M (2012) Landfill mining: a critical review of two decades of research. *Waste Manag* 32:513–520. <https://doi.org/10.1016/j.wasman.2011.10.015>
- Lesmes DP, Friedman SP (2005) Relationships between the electrical and hydrogeological properties of rocks and soils. In: Rubin Y, Hubbard SS (eds) Hydrogeophysics water science and technology library, vol 50. Springer. https://doi.org/10.1007/1-4020-3102-5_4
- Li Y, Yang Z, Yang K, Wei J, Li Z, Ma C, Yang X, Wang T, Zeng G, Yu G, Zhigang Y, Zhang C (2022) Removal of chloride from water and wastewater: removal mechanisms and recent trends. *Sci Total Environ* 821:153174. <https://doi.org/10.1016/j.scitotenv.2022.153174>
- Massoud MA, Khoury R, Ghanem R, Ghossainy R, Merhbi F (2022) Development of a pragmatic methodology for the environmental assessment of uncontrolled dumpsites in developing countries. *Environ Earth Sci* 81(296):1–10. <https://doi.org/10.1007/s12665-022-10417-6>
- Minasny B, McBratney AB (2018) Limited effect of organic matter on soil available water capacity. *Eur J Soil Sci* 69(1):39–47. <https://doi.org/10.1111/ejss.12475>
- Ministério do Meio Ambiente–MMA (2020) Plano Nacional de Resíduos Sólidos (Planares). MMA, Brasília, DF. https://www.gov.br/mma/pt-br/assuntos/agendaambientalurbana/lixao-zero/plano_nacional_de_residuos_solidos-1.pdf
- Mohammed Nazifi H, Gulen L, Gürbüz E, Peksen E (2022) Time-lapse electrical resistivity tomography (ERT) monitoring of used engine oil contamination in laboratory setting. *J Appl Geophys* 197:104531. <https://doi.org/10.1016/j.jappgeo.2022.104531>
- Moreira CA, Lapola MM, Carrara A (2016) Comparative analyzes among electrical resistivity tomography arrangements in the characterization of flow structure in free aquifer. *Geofís Int* 55(2):119–129
- Moreira CA, dos Santos EG, Ilha LM, Paes RAS (2019) Recognition of sulfides zones in marble mine through comparative analysis of electrical tomography arrangements. *Pure Appl Geophys* 176:4907–4920. <https://doi.org/10.1007/s00024-019-02243-y>
- Morita A, Pelinson NS, Elis VR, Wendland E (2020) Long-term geophysical monitoring of an abandoned dumpsite area in a Guarani Aquifer recharge zone. *J Contam Hydrol*. <https://doi.org/10.1016/j.jconhyd.2020.103623>
- Morita AKM, Ibelli-Bianco C, Anache JAA, Coutinho JV, Pelinson NS, Nobrega J, Rosalem LMP, Leite CMC, Niviadonski LM, Manastella C, Wendland E (2021) Pollution threat to water and soil quality by dumpsites and non-sanitary landfills in Brazil: a review. *Waste Manag* 131:163–176. <https://doi.org/10.1016/j.wasman.2021.06.004>
- Ojo AO, Olurin OT, Ganiyu SA, Badmus BS, Idowu OA (2022) Electrical imaging characterization of a dumpsite on an abandoned quarry site in Abeokuta, South West, Nigeria. *Sci Afr* 17:e01330. <https://doi.org/10.1016/j.sciaf.2022.e01330>
- Parasnis DS (1997) Principles of applied geophysics, 5th edn. Chapman and Hall, New York, p 429
- Passarelli CR, Basei MAS, Wemmer K, Siga O Jr, Oyhantçabal P (2010) Major shear zones of southern Brazil and Uruguay: escape tectonics in the eastern border of Rio de La plata and Paranapanema cratons during the Western Gondwana amalgamation. *Int J Earth Sci (geol Rundsch)* 100:391–414. <https://doi.org/10.1007/s00531-010-0594-2>
- Ross JLS, Moroz IC (2011) Mapa Geomorfológico Do Estado De São Paulo. *Revista Do Departamento De Geografia* 10:41–58. <https://doi.org/10.7154/RDG.1996.0010.0004>
- Schaefer C, Fabris JD, Ker J (2008) Minerals in the clay fraction of Brazilian Latosols (Oxisols): a review. *Clay Miner* 43:137–154. <https://doi.org/10.1180/claymin.2008.043.1.11>
- Shubo T, Fernandes L, Montenegro SG (2020) An overview of managed aquifer recharge in Brazil. *Water* 12(4):1072. <https://doi.org/10.3390/w12041072>
- SNIS-Sistema Nacional de Informações Sobre Saneamento (2022) Diagnóstico do manejo de resíduos sólidos urbanos – 2021. SNS/MDR, Brasília, DF
- United Nations Environmental Programme–UNEP (2021) Roadmap for the progressive closure of dumpsites in Latin America and the Caribbean. UNEP Coalition for the closure of dumpsites Latin America and Caribbean
- U.S. Environmental Protection Agency (EPA) (2017) Water Quality Standards Handbook: Chapter 3: Water Quality Criteria. EPA-823-B-17-001. EPA Office of Water, Office of Science and Technology, Washington, DC

Zhan LT, Xu H, Jiang XM, Lan JW, Chen YM, Zhang ZY (2019) Use of electrical resistivity tomography for detecting the distribution of leachate and gas in a large-scale MSW landfill cell. *Environ Sci Pollut Res* 26:20325–20343. <https://doi.org/10.1007/s11356-019-05308-6>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.