Discover Geoscience

Research

Investigation of the contamination behavior in water and soil of an inactive dump from chemical analysis and geophysical method

Leonides Guireli Netto[1,2] · Camila Camolesi Guimarães[1] · Alexandre Muselli Barbosa[2] ·
Otávio Coaracy Brasil Gandolfo[1]

© The Author(s) 2024   OPEN

Abstract

In rapidly growing urban areas of developing countries, inappropriate urbanization practices near water bodies lead to significant environmental degradation, including deforestation, soil impermeabilization, and direct waste discharge into rivers and streams. This not only compromises water quality and ecosystem health but also exacerbates flood risks for nearby communities. Dumpsites, common in these regions due to inadequate waste management infrastructure, pose significant environmental threats, including soil and groundwater contamination. Our study employed a frequency-domain electromagnetic survey on an inactive dumpsite adjacent to one of Brazil's major rivers. This geophysical method provided critical insights for geoenvironmental investigations, facilitating the collection of soil and groundwater samples to understand leachate behavior. We found that the shallower electrical conductivity map aligned with the waste disposal area's boundaries, verified by on-site surveys and excavations. Historical aerial images supported this interpretation and helped explain conductive electrical anomalies in the deeper conductivity map, linked to old irregular housing and waste disposal around the dumpsite. Moreover, the electrical conductivity maps revealed NE-oriented percolation at depth in the study area. Groundwater monitoring wells and soil analyses identified chemical elements exceeding standards set by Brazilian and international environmental agencies in this flow direction. These findings highlight the importance of using investigation techniques with superior spatial resolution compared to traditional environmental monitoring approaches. Electromagnetic methods prove effective in enhancing understanding and management of contamination in dumpsite environments.

1 Introduction

Disorganized urban growth in cities in several developing countries has caused significant environmental impacts by establishing themselves close to important streams and rivers [1]. This process of inappropriate urbanization often results in deforestation, soil impermeabilization, and the dumping of solid waste and sewage directly into water bodies [2]. This not only degrades water quality, threatening public health and aquatic ecosystems, but also intensifies the occurrence of floods, increasing the risks for riverside communities [3, 4]. The urgent need for sustainable urban planning

✉ 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 | ¹Graduation Program in Geosciences and Environmental Science, Geosciences and Exact Sciences Institute, São Paulo State University, Rio Claro, São Paulo State, Brazil. ²Cities, Infrastructure and Environment Department, Institute for Technological Research, São Paulo, Brazil.

Discover

in these locations is evident to mitigate these negative environmental impacts and promote a balance between urban development and the preservation of water resources [5, 6]. In developing countries, dumpsites represent a significant environmental challenge, especially amid the rapid urban growth observed in many cities in these regions and the lack of adequate infrastructure to deal with the corresponding increase in waste generation [6, 7]. With the increase in population and urbanization, solid waste generation has intensified, leading to inadequate and disorderly waste disposal in unregulated areas. This scenario results in severe soil and groundwater contamination problems, threatening human health and the integrity of local ecosystems [8–10].

Traditionally, environmental monitoring in dumpsites has been carried out by collecting soil and groundwater samples for laboratory analysis. However, this method has some significant limitations. Sampling is an invasive, time-consuming, and quite expensive process involving excavation and disturbance of the environment, which can alter the natural conditions of the soil and groundwater [11, 12]. In addition, it is an expensive and time-consuming procedure that requires significant resources in terms of manpower, equipment, and laboratory analysis. Even after the samples have been collected and analyzed, the results may not provide a detailed understanding of the contamination, as they may not adequately represent the spatial and temporal variability of the pollution. It is, therefore, crucial to look for research methodologies that can complement and ideally overcome the limitations of traditional monitoring methods. In recent years, there has been a significant increase in the use of invasive and non-invasive subsurface investigation methods in environmental contamination studies [13]. Indirect methods, such as geophysical methods, make it possible to assess the spatial distribution and extent of physical properties of the environment, which can help to evaluate the presence and behavior of contamination in a more comprehensive and efficient way [14–16].

Geophysical techniques such as electrical resistivity tomography (ERT) have been used extensively in studies of dumpsites [17, 18]. However, there is a significant gap in studies exploring the use of electromagnetic methods in these scenarios. It is important to demonstrate the feasibility of using electromagnetic methods in conjunction with traditional environmental monitoring methodologies, especially in small towns in developing countries. These areas often face significant financial constraints, which makes conventional environmental monitoring, such as collecting soil and groundwater samples for laboratory analysis, a costly and inaccessible option [19]. Using electromagnetic methods in conjunction with other geophysical methods and traditional monitoring techniques can offer a more cost-effective and efficient approach to assessing dumpsite contamination [20–23]. These methods can provide complementary information and help fill the gaps left by conventional methods, allowing for a more comprehensive assessment of the extent and impacts of contamination, especially in dumps that have been unavailable for many years. The study innovated by employing frequency-domain electromagnetic research in an inactive dump near one of Brazil's main rivers, offering an investigation approach with greater spatial resolution than traditional environmental monitoring methodologies. The results made it possible to understand the behavior of leachate in the area, helping to collect soil and groundwater samples for analysis. The geophysical interpretations were based on chemical analyses of the soil and water, as well as a historical photo-aerial survey associated with old documents on the operation of the dump. This multifaceted approach allowed for a deeper understanding of the contamination and behavior of leachate in the area. The information gathered enabled a more precise and detailed investigation, improving knowledge about the environmental risks associated with the dump and contributing to more efficient and safer management of the site.

2 Study site

2.1 Location of study area and temporal survey of use and occupation

The dumpsite is located in the city of Santana de Parnaíba, 35 km from the capital of the state of São Paulo, in southeastern Brazil. The development of the city and the settlement of the communities are related to an important river in the state of São Paulo: the Tiête River. The proximity of the waste disposal site to a highway is also a problem. In Europe, the regulations are very strict, and they don't allow the dumpsite to be close to roads, airports, etc. and visible from people. In South America, environmental regulations also limit the proximity of the dumpsite to these developments, but accelerated and unplanned growth means that the urban sprawl of the city reaches the waste disposal areas [2]. Inadequate urbanization has been a common scenario in many cities in developing countries in Latin America [24, 25]. The city has experienced one of the biggest population growths in the state of São Paulo over the last 30 years. The population of just over 5000 inhabitants in the 1970s reached over 154,105 in 2022. As a result of the remarkable population growth, the production of solid urban waste in the municipality of Santana de Parnaíba has also grown to around 57 tons per day [26].

The dumpsite is approximately 63,000 m² and was originally a valley floor. Household solid waste was deposited on this site until 2011 (Fig. 1). According to surveys of historical aerial images, in 1997 the landfill was already in operation, with major physiographic alterations, and taken over by waste disposal. In 2001, the area occupied by the dumpsite corresponded in plan to approximately 60% of the total area. The remainder was occupied by the recycled material collectors' cooperative (15%) and by the area of land used as a quarry to cover the waste (25%). At the time, the dump received around 1,800 tons of waste per month [26] and there was consolidated irregular occupation around the site. A technical visit carried out that same year revealed the absence of cover for a large part of the waste deposited and of a drainage system for percolated liquids and gases, as well as surface water. The result was the development of localized erosion and the dragging of waste to lower levels. The percolated liquids accumulated next to the landfill massif in the form of a small lake. The aerial image from 2003 shows the landfill in its consolidated form. In 2011, the landfill appears to have ended its activities (Fig. 1).

2.2 Geological and geomorphological context of the study area

The municipality of Santana de Parnaíba has a geological context defined by a sequence of volcanic rocks and meta-sedimentary rocks of the crystalline basement, which extends over approximately 57,000 km² in the eastern part of the state. This basement is mainly composed of igneous and metamorphic rocks, including granites, gneisses, phyllites, schists and quartzites, which are practically impermeable in origin. However, tectonic events that molded the earth's crust, combined with the action of weathering, resulted in the formation of fault and fracture systems, as well as portions of weathered rock. These geological dynamics have allowed groundwater to percolate and be stored, forming a fractured aquifer in the region. The Precambrian aquifer receives natural recharge from rainfall, which infiltrates the layers of weathered rock and fissures and is then stored. The aquifer's low transmissivity and the absence of water flows on a regional scale lead to the formation of independent hydrogeological units with their
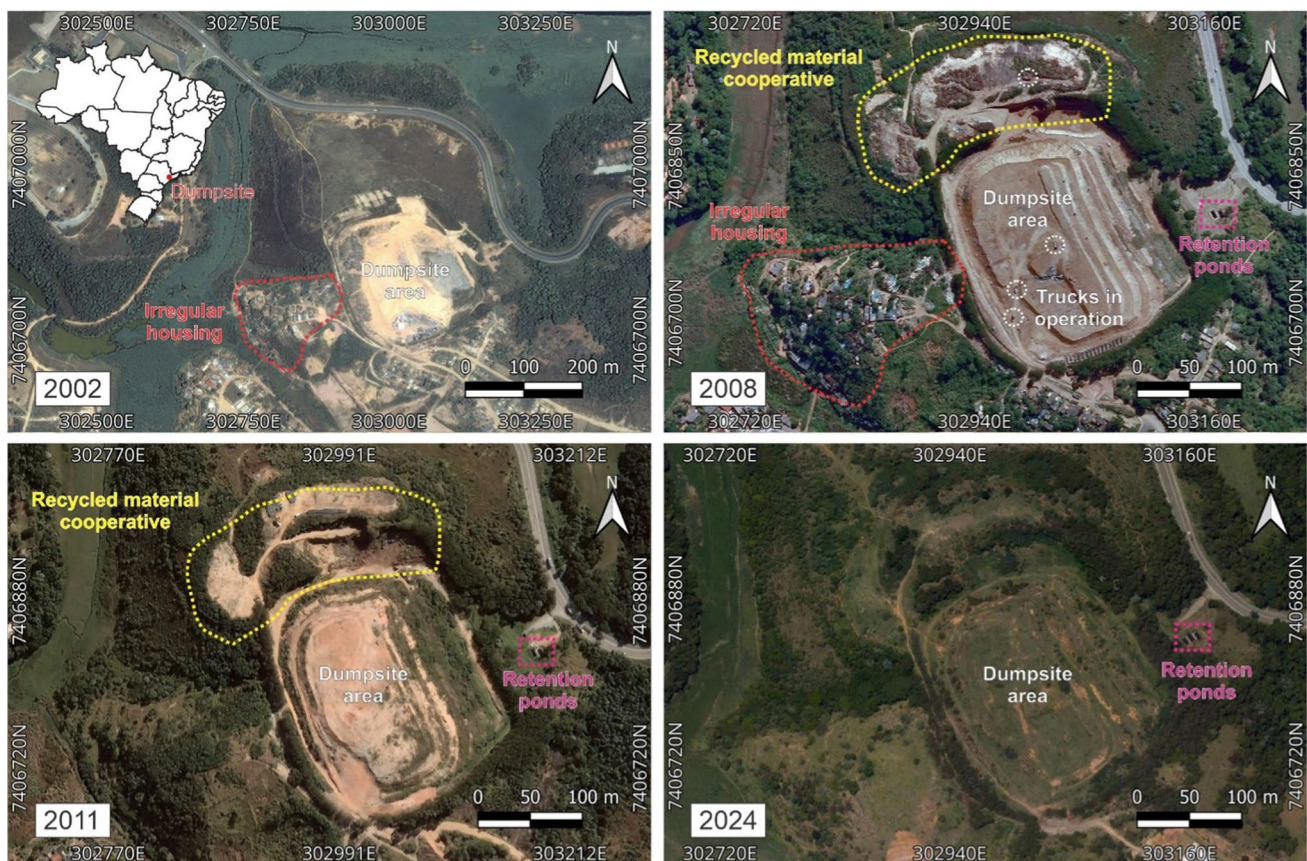

Fig. 1 Historical aerial photos of the last 20 years of use of the dump area. Essential elements were observed in the images, such as the presence and removal of irregular occupations and the area used by the recycling cooperative. The installation of leachate retention ponds after 2002 was also crucial for interpreting the geophysical data

own flow regimes. These characteristics support the basic flow of rivers and streams that drain the nearby valleys, contributing to the management of water resources in the area [27] (Fig. 2).

Geomorphologically, the area of the municipality of Santana de Parnaíba is contained in the unit known as the São Roque Mountains, which represents a portion of the Atlantic Plateau. This portion is characterized by the occurrence of continuous denudation processes, the generation of which is related to the Itaguá and Japí plateau surfaces. The dump area, in turn, is part of the Mar de Morros relief unit. In this unit, there is no geomorphological variation in the landforms, either in the north or the south of the area studied [27]. The climate of the municipality of Santana de Parnaíba is subtropical, with warm, rainy summers and relatively cold winters. The average annual temperature is 20 °C, with a maximum of 23 °C and a minimum of 12 °C. The average annual rainfall is 1300 mm. This type of climate creates ideal conditions for soil development. The hot, rainy summers promote the decomposition of organic matter and the leaching of minerals essential for soil formation. Predominantly in the municipality of Santana de Parnaíba, yellowish-red latosols are found. This type of soil was also found in the dump area [28].

3 Methods

3.1 Electromagnetic method (EM)

Electromagnetic methods are based on measuring the electrical conductivity or related parameters of subsurface materials by inducing electromagnetic fields in the ground generated by alternating currents of artificial or natural origin. Electrical conductivity is expressed in units of Siemens per meter (S/m). In environmental investigation studies, determining
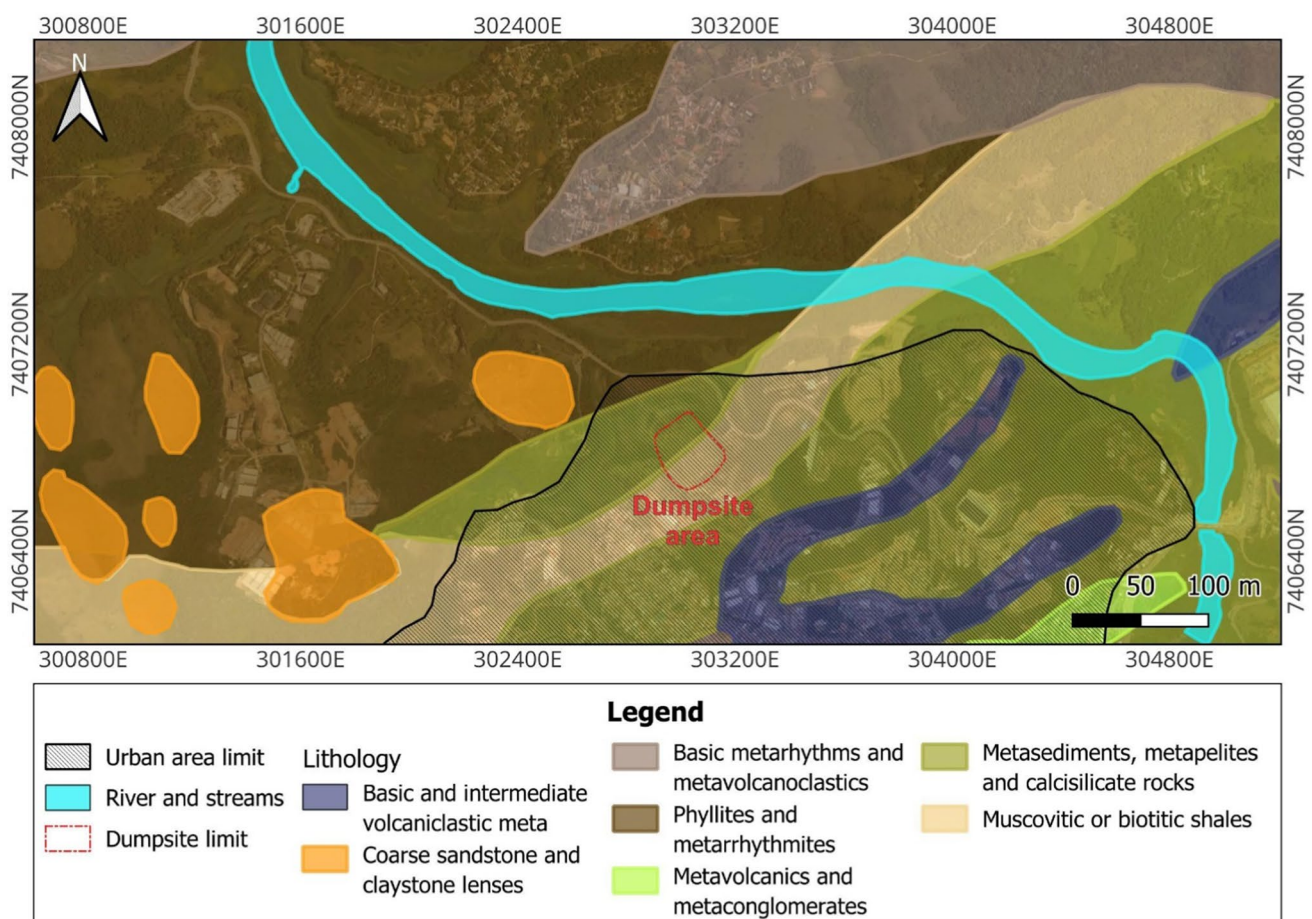

Fig. 2 Geological map of the area surrounding the dumpsite. The proximity to an important river in the state of São Paulo was one of the aggravating factors in the development of the study. Source: modified from [27]

the apparent electrical conductivity of the ground can help to understand the behavior of the contaminant in the physical environment. In landfills and dumps, the presence of leachate alters the electrical conductivity of the environment, making it more conductive compared to the natural conductivity values of the terrain ("background" of the area). This parameter can be an indicator of the presence of subsoil contamination associated with solid waste percolation [7, 8, 29]. [30] Utilized various geophysical methods, including the frequency-domain electromagnetic (FDEM) survey, to assess a heavy-metal contaminated site. The employment of this methodology enabled the mapping of sludge and validation of remediation effectiveness through pre- and post-remediation geophysical assessments. [31] Utilized Time Domain Electromagnetic surveys and drilling investigations to assess contamination in Barka, Oman, identifying migration zones and correlating resistivity with lithology and pinpointing contaminated areas. The study by [32] demonstrated that the FDEM method was crucial for assessing the impact of landfills, providing non-invasive investigation and 3D modeling of soil physical parameters, essential for monitoring waste deposits in a closed landfill in Southern Italy. The results obtained by the geophysical method provided detailed information not obtained through other methods. [33] Introduced multi-frequency electromagnetic surveying for the initial assessment of waste quality at open dumpsites, determining the frequency set of 5000, 11,000, and 15,000 Hz as optimal, providing high correlations and valuable information on waste characteristics.

The principle of the method is based on Ampère's and Faraday's Laws from classical physics. A transmitting bobbin (Tx) is energized with alternating current and placed on the ground (assumed to be uniform) next to a receiving bobbin (Rx). The temporal oscillation of the magnetic field caused by the alternating current in the transmitting bobbin causes an induction of currents in the subsoil. These electrical currents, in turn, generate a secondary magnetic field (Hs) which is recorded together with the primary field (Hp) in the receiving bobbin. The parameters measured by electromagnetic systems are a function of these fields, such as the resultant vector Hr. The secondary magnetic field (Hs) is a complex function of the distance between bobbins (s), the operating frequency (f) and the electrical conductivity of the terrain (Figure 3). Under certain restrictions, technically defined as "operation under low values of the induction number" [34], the relationship between Hs and Hp becomes linearly proportional to the conductivity of the ground, and it is possible to read conductivities directly by measuring this relationship, which is given by Eq. (1):

$$\sigma_{ap} = \frac{4}{2\pi f \mu_0 S^2} \left(\frac{H_S}{H_P} \right) \tag{1}$$

The depths investigated by electromagnetic methods are inversely proportional to the frequencies used. Electrical conductivity measured will be an apparent value (σ_{ap}) which represents the integration of the existing conductivities, from the surface to a given depth of investigation. When acquiring the data, the measurements can be taken according to two orientations of the bobbin's dipole axis: vertical (DV) or horizontal (DH). The depth of investigation is related to the distance between the coils and the arrangement of the dipole axis at the time of measurement. For the dipole in the horizontal position (DH), this depth is approximately 0.75 times the distance between the dipole axes. For the vertical dipole (DV), this depth becomes 1.5 times. It is therefore possible to estimate the vertical variation in conductivity by comparing the values obtained in the two bobbin configurations, one corresponding to shallower portions of the subsurface (DH) and the other reflecting the contribution of materials located at greater depths (DV). The map corresponding to the shallowest investigation (0 m–15 m), resulting from the dipole measurements in the horizontal position (DH), normalized in relation to an established background (15 mS/m), according to equation (Eq. 2):

$$db = 20 \cdot log_{10} \frac{\sigma_{(x,y)}}{\sigma_{bg}} \tag{2}$$

where $\sigma_{(x,y)}$ is the conductivity measurement at the point, and σ_{bg} is the stipulated background value. Figure 3 illustrates data acquisition principle of the Electromagnetic method (EM) in the field.

In order to carry out the geophysical studies, 74 topographic points were set up in the area of the dump and its surroundings, with a distance between them of approximately 40 m, which were then georeferenced using a differential GPS positioning system. The equipment used was a Trimble model Pro XRT with Omnistar differential correction, which enables real-time measurements with sub-meter accuracy. The geophysical survey using the electromagnetic method was carried out with the aim of delimiting the locations of conductive anomalies associated with household waste and its percolate. Electrical conductivity measurements were taken every 20 m (Fig. 3). Model EM-34 equipment manufactured by Geonics Limited (Canada) was used, with spacing between the transmit (Tx) and receive (Rx) coils equal to 20 m, in both horizontal dipole (DH) and vertical dipole (DV) modes. In this way, data was obtained by sampling a volume of the
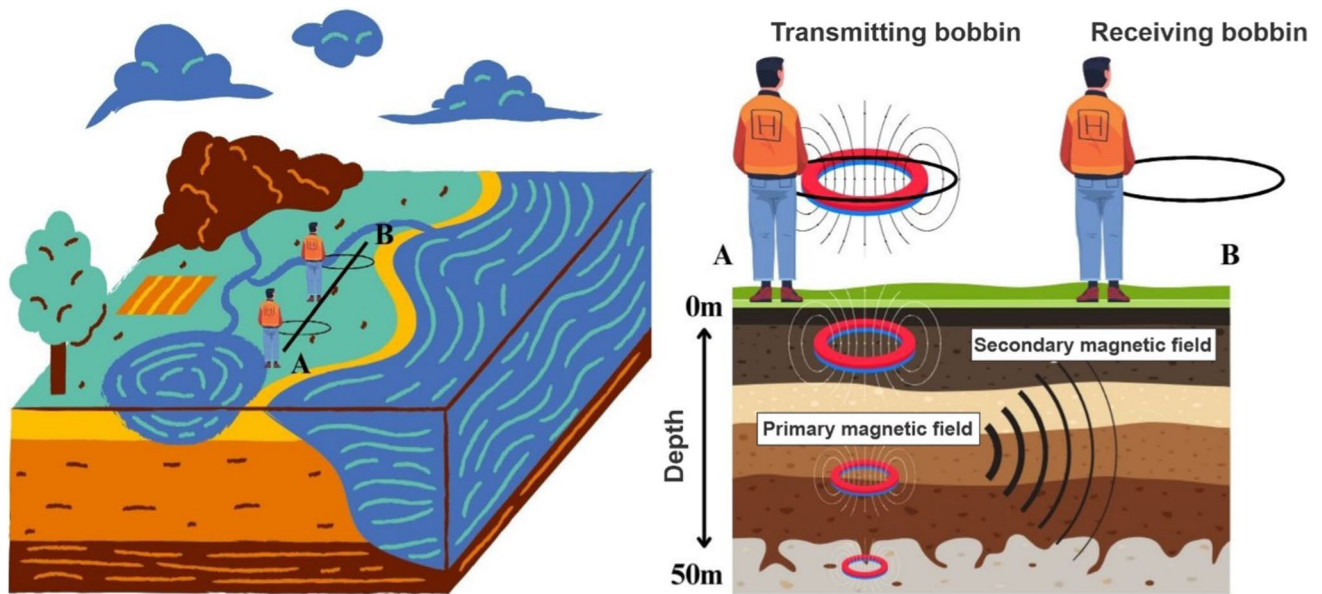
Fig. 3 The secondary magnetic field (Hs) is a complex function of the distance between bobbins(s), the operating frequency (f) and the electrical conductivity of the terrain (Figure 3)

subsurface at two depth levels: one shallower (0–15 m, DH mode) and the other covering greater depths (0–30 m, DV mode).

3.2 Physico-chemical analysis of soil and water

The location of the boreholes for soil sampling and the construction of monitoring wells was determined according to the main potential sources of contamination. As can be seen in Fig. 4, which shows the water and soil sampling points, the distribution of the soil sampling and groundwater sampling is not the same. This scenario is quite common in studies of inactive dumpsites, because some of the groundwater sampling wells were already installed in the area. Probably the criteria for determining the installation points of these wells over the years was established in accordance with the environmental standards proposed by the environmental agency. In this way, the present study used some of these wells and increased the sampling network by installing new wells. Obviously, before using these old wells, it was checked in the field that they satisfied the appropriate environmental standards and that it was feasible to use them. Fourteen boreholes were carried out in the area. For the upstream characterization, two existing wells in the area (Gw1 and Gw2) were used, after proper cleaning and verification of the conditions of use. From the boreholes, representative samples of the soil profile were selected for tactile-visual description in monitoring wells Gw3, Gw4, Gw5 and Gw6. Samples were taken every meter drilled or every change in material. A visual tactile description was carried out on the sampled profile in order to identify characteristics such as texture, color, consistency and odor, as well as external materials present. The results of the characterizations are shown in Fig. 4.

Groundwater sampling was carried out to assess the presence and quantification of anomalous substances from potential sources of contamination. The collection procedures followed those established by the Brazilian technical standards [35]. Water sampling was carried out using the low-flow method, with the aid of a bladder pump and flow cell, a method that makes it possible to obtain groundwater samples with the least agitation and suspension of particulates within the monitoring well. Six groundwater samples were collected, one from each monitoring well. These samples were taken in accordance with standard D6771-02 of the American Society for Testing and Materials. During the groundwater sampling, physical and chemical parameters were monitored using HANNA multi-parameter equipment, monitoring pH, Electrical Conductivity (EC), Oxy-Reduction Potential (ORP), Dissolved Oxygen (DO), Total Dissolved Solids (TDS) and temperature (°C).

The decrease in water level was also monitored using a digital groundwater level meter. Sampling began once these parameters had stabilized. The samples were collected directly into the bottles provided by the laboratory and were immediately placed in refrigerated boxes at a temperature of 4 °C ± 2 °C. During the investigation, permeability tests of
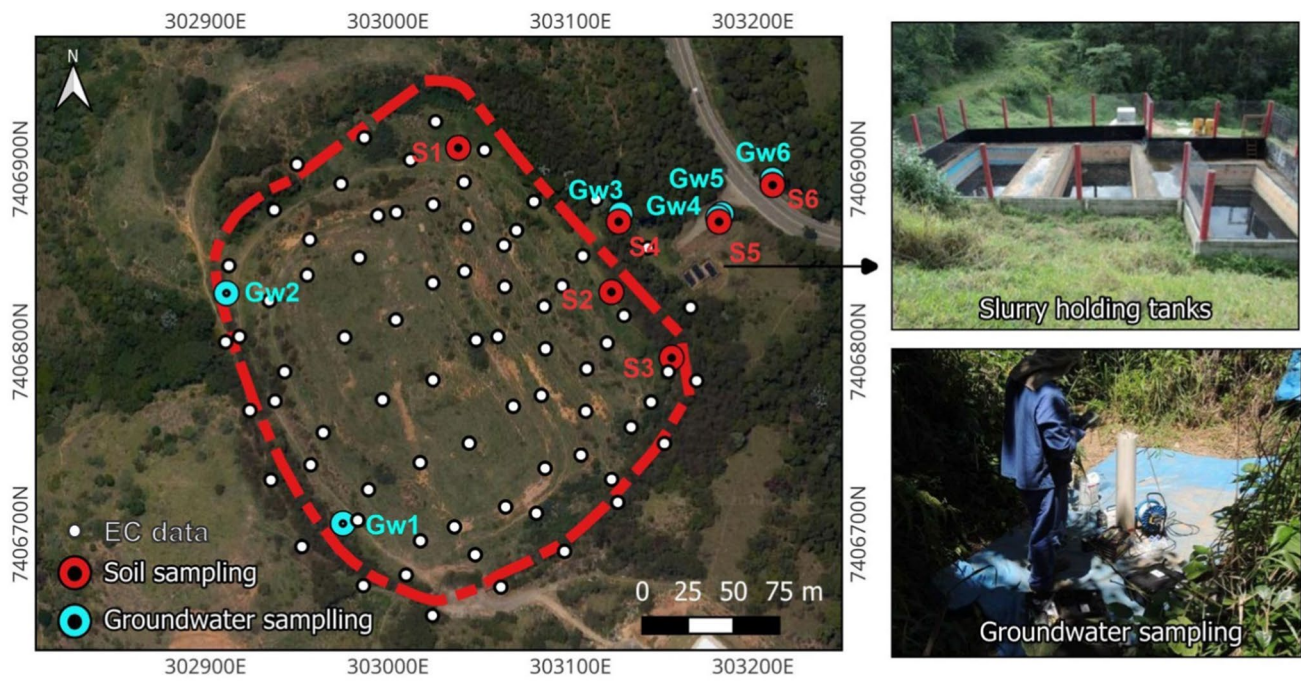
Monitoring wells	Depth (m)	Material description
Gw3	0,00-4,00	Clayey silt, reddish brown, with fragments of schist and quartz. Alteration soil
	4,00-15,00	Clayey silt, dark red, with fragments of schist and quartz. Alteration soil
	15,00-20,00	Sandy silt, dark red, fragments of quartz, alteration soil
Gw5	0,00-1,00	Landfill, remains of building materials
	1,00-6,70	Sandy clay, dark brown, presence of quartz fragments, slightly plastic, slightly sticky. Alteration soil
Gw4	0,00-1,00	Landfill, remains of building materials
	1,00-11,00	Sandy clay, dark brown, presence of quartz fragments, slightly plastic, slightly sticky. Alteration soil
	11,00	Impenetrable
Gw6	0,00-0,20	Garbage
	0,20-1,00	Silty-clay, yellow, non-plastic, non-sticky
	10,00-11,00	Silty-clayey, dark red, non-plastic, non-sticky. Amalgamated soil
	12,00	Impenetrable

Fig. 4 The location of boreholes for soil sampling, the construction of groundwater monitoring wells, and the description of the materials found during the installation of the new monitoring wells (Gw3, Gw4, Gw5, and Gw6) are presented

the Slug Test type were also carried out with a variable load to determine the hydraulic conductivity (K) of the saturated zone in the water monitoring wells. This test involves introducing a billet of known volume into the well, causing the displacement of a volume of water. The water level is then monitored until it reaches 80% of the initial variation (Δh) or 30 min of testing. Based on these results and the construction data of the monitoring wells (diameter and depth), the horizontal hydraulic conductivity of the aquifer was calculated on a local scale. This information made it possible to generate the potentiometric map and understand the hydraulic gradient and groundwater flow velocity in the dump area based on a generalization of Darcy's Law [36] (Eq. 3), where v is the flow velocity, k is the hydraulic conductivity, i is the hydraulic gradient and n_{ef} is the effective porosity.

$$v = \frac{K_i}{n_{ef}} \tag{3}$$

4 Results and discussions

The results obtained from the EM survey were presented in the form of contour maps of the electrical conductivity values measured on the ground. The reddish tones of the map represent high conductivity values, while the light blue tones correspond to low conductivity values, and tend to represent the natural background values of the area under investigation. The maps of the distribution of electrical conductivities in the dump area and its surroundings define the limits of high conductivity anomalies (associated with the presence of waste and/or percolate) and can guide investigation and sampling work. At depths of 0 to 15 m, high electrical conductivity values were identified in the central area of the dumpsite. These values correspond to the area of the mass of waste and the percolated liquids generated from its decomposition. This was confirmed by trenches, geological surveys and visual inspection of the dump area. Average values of electrical conductivity were found around this mass. These values correspond to percolated liquids, since although they are concentrated in the central area at this depth, they may be percolating horizontally outwards from the edge of the mass of waste (Fig. 5). Average conductivity values were also identified at points 49 and 50, corresponding to the area where pruning waste was deposited and burned.

At a depth of 0 to 30 m, high and medium electrical conductivity values were also obtained in the central part of the dump, but in a smaller area than at a depth of 0 to 15 m, showing that the percolated liquids spread more horizontally at this depth (Fig. 6). The figure also shows zones of high and medium electrical conductivity at points 27 and 74; between points 30, 31 and 49; near point 61 and between points 56, 65 and 66, which were not identified at the depth of 0 to 15 m. The electrical anomalies identified at points 27 and 74 and between points 56, 65 and 66 are due to garbage deposits and sewage discharges from previous irregular occupation of these sites, removed around 2007 and observed in the historical aerial image survey (Fig. 1). The electrical anomalies identified between points 30, 31 and 49 come from the former use of the area for waste disposal, information presented in the historical survey of the use of the area and proven by the S1 survey carried out at the site. The electrical anomaly at point 61, which extends to the base of the landfill slopes, is due to the old leachate lagoon, which was later buried with garbage and covered with a layer of soil, as confirmed by the S4 survey carried out at the site.

The geological surveys carried out in the area provided a visual tactile description of the soil at the points where the monitoring wells were installed (Fig. 7). From the geological description of the dumpsite area, it was possible to draw up geological-geotechnical sections with different orientations (A–A' and B–B') along the area. Section AA, in a northwest-northeast direction, was drawn up using data from boreholes S2, S5 and S6. Section BB, in a south-north direction, was drawn up using data from borehole S1. While the geological-geotechnical sections provided a detailed understanding of the characteristics of the soil at specific points in the dumpsite area, the geophysics complemented this information by offering a broader and more in-depth view of the behavior of the contaminants, helping to delimit the areas where the masses of waste were deposited and correlating them with the electrical anomalies detected. The good correlation between the electrical anomalies and the descriptions of the geological-geotechnical sections suggests that the electrical properties of the natural soil and the dumpsite have been altered by the filling of the pores of this material by the leachate from the decomposition of the waste. The development of electrical anomalies at depth, as seen on the map with the distribution of electrical conductivity values between 15 and 30 m, suggests leachate infiltration at depth. The soil present at the landfill was mainly characterized by silty-clayey sand and sandy-clayey silt and showed medium to high permeability to the infiltration of water and percolated liquids. High permeability to air and rainwater infiltration was also observed in laboratory analyses. This can increase biological activity and, consequently, speed up degradation; however, it also increases the production of percolated liquids in the landfill; in a post-rain field measurement, production reached 3600 L/h. Although the dumpsite has a layer of clay soil that can act as a natural impermeable barrier, as seen in the geological-geotechnical sections, the waste disposal area is located on altered rock. In this way, the development of contamination at depth can be aggravating since the fractures present in this rock can act as preferential flow paths for the contaminant and result in the contamination of the aquifer and river located near the area.

The physical–chemical characterizations of the soils and groundwater were compared with the electrical anomalies from the geophysical method (Fig. 8). Although concentrations of nitrogen (ammonia, nitrate and nitrite), total organic
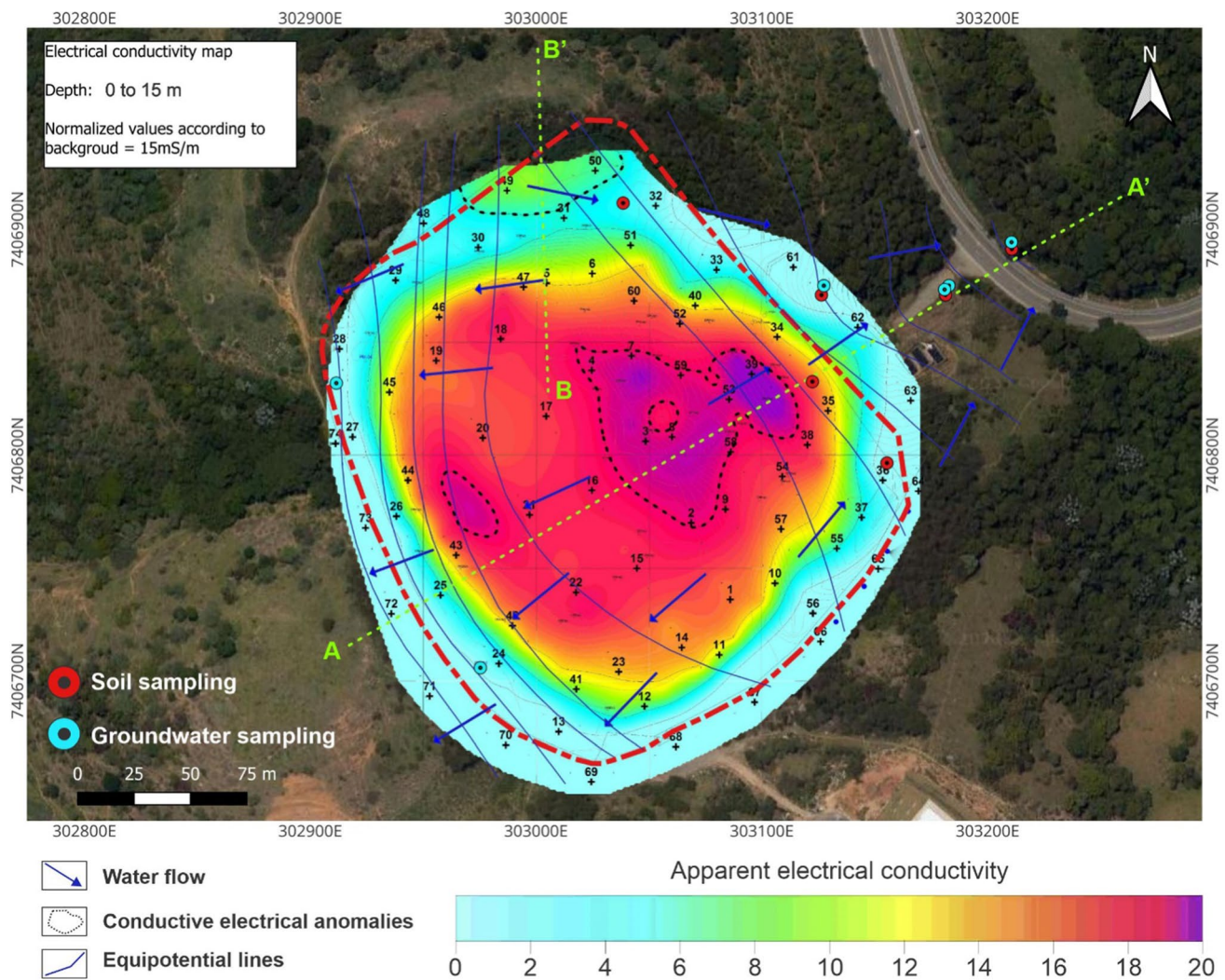
Fig. 5 Electrical conductivity map of the depth from 0 to 15 m with the values normalized in relation to the background = 15 mS/m. The electrical conductivity anomalies were consistent with the dumpsite area

carbon, aluminum, arsenic, barium, lead, chloride, copper, chromium, iron, manganese, nickel, sulfate and zinc were detected in the topsoil samples, they were all below the reference values adopted by the environmental agency of the state of São Paulo. However, values above those established by the USEPA (2015) were observed for the following parameters: aluminum, in samples Gw1 (11,100 mg/kg), S1 (8360 mg/kg), S3 (27,600 mg/kg) and S6 (10,100 mg/kg), with the USEPA guideline value being 7700 mg/kg; arsenic, in samples S1 (694 mg/kg), S3 (438 mg/kg) and S4 (107 mg/kg), the USEPA guideline value being 0.68 mg/kg; and iron, in samples Gw1 (13,600 mg/kg), S1 (12,400 mg/kg), S3 (37,800 mg/kg), S4 (44,700 mg/kg) and S6 (12,500 mg/kg), the USEPA guideline value being 5500 mg/kg, all of which show contamination associated with dump activity [37]. Aluminum, arsenic and iron are common elements in solid waste, especially in discarded materials such as electronic products and industrial chemicals. When waste is deposited in dumps, these elements can leach into the soil and groundwater, resulting in high concentrations, such as those observed in the samples mentioned.

Groundwater was sampled from the four wells installed for the study (Gw3, Gw4, Gw5 and Gw6) and the two old wells (Gw1 and Gw). The readings of the physical–chemical parameters of the groundwater indicated pH values ranging from 5.02 (Gw6) to 5.95 (Gw2), which is considered slightly acidic. The electrical conductivity readings varied greatly in the wells sampled, from 0 µS/cm (Gw2) to 2.447 µS/cm (Gw4). Electrical conductivity is a reading of the amount of ions dissolved in groundwater. According to Brazil's main environmental agency (CETESB 2005), values above 100 µS/cm can represent a qualitative indication of impacts on groundwater. Thus, the readings detected a large quantity of dissolved ions and possible impacts on groundwater quality in wells Gw3 and Gw5. Oxy-reduction potential readings ranged
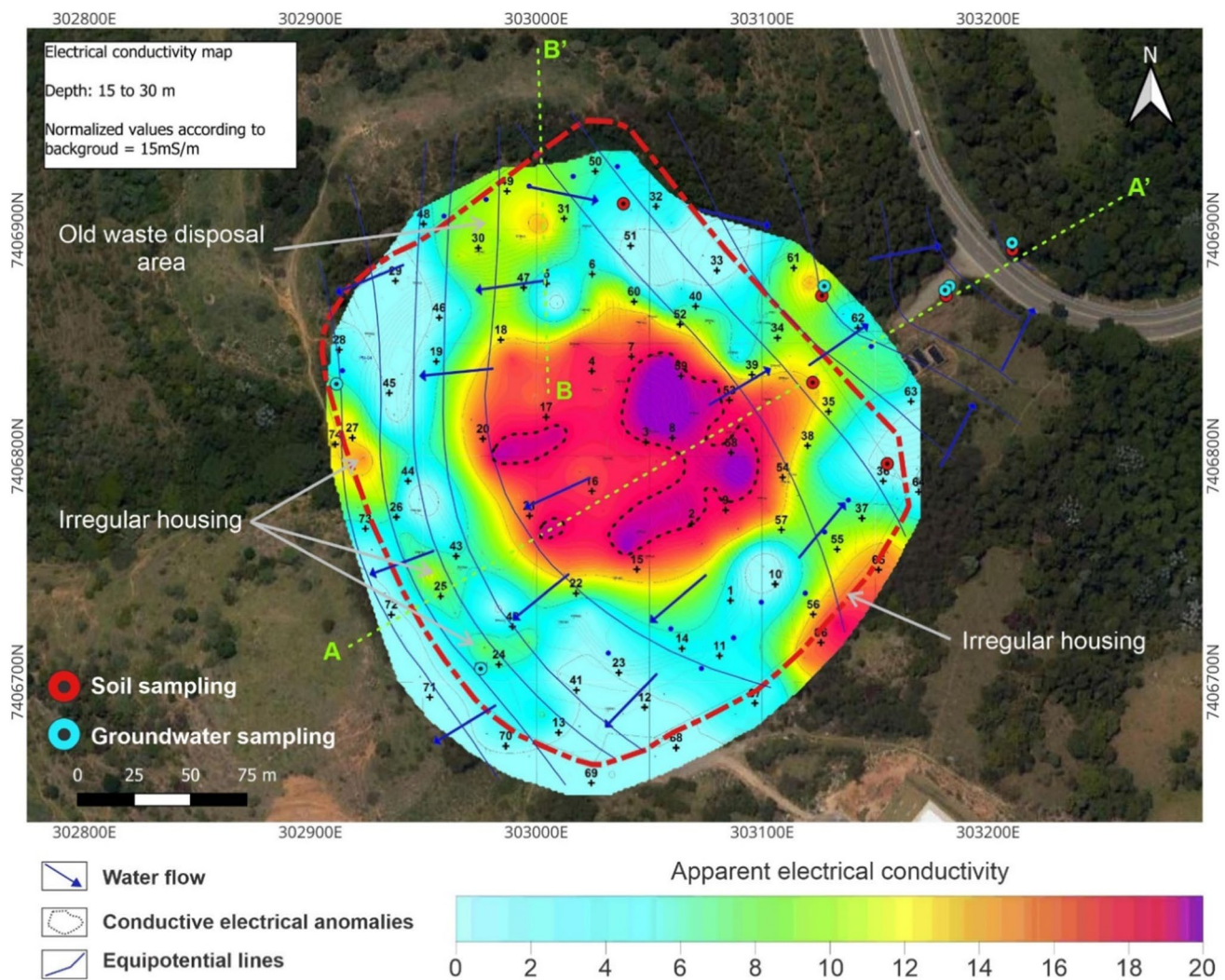
Fig. 6 Electrical conductivity map of the depth from 15 to 30 m with the values normalized in relation to the background = 15 mS/m. The new electrical conductivity anomalies on this map were consistent with the presence of irregular occupations and the former waste disposal area

from 36.7 mV (Gw2) to 174.5 mV (Gw5). At all the points sampled, the oxy-reduction potential showed positive values, indicating an oxidizing environment.

In relation to the chemical characterization of groundwater in the dump area, 249 parameters were analyzed. Concentrations of ammonia nitrogen, total and dissolved organic carbon, total aluminum, chloride, total copper, total manganese, total nickel, sulfate and total zinc were detected, but all lower than the reference values of environmental agencies in Brazil and around the world, such as the Dutch List (DRF, 2009) and the Screening Levels (potability limits) established by the USEPA [32]. However, concentrations of barium, nitrate nitrogen, nitrite, cyanide, iron and chloroform were observed above the applicable guideline values. Sample Gw2 showed concentrations of barium (0.741 mg/L) and nitrate nitrogen (46.4 mg/L) above the values established by Brazil's environmental agency (0.7 mg/L and 10 mg/L, respectively, established by CETESB 2005). Barium concentration (0.906 mg/L) was also detected in sample Gw4 above the value recommended by the same environmental agency. Nitrite concentration was detected in sample Gw6 (18.10 mg/L) and iron in sample Gw3 (2.19 mg/L), both above the guideline value set by the USEPA (0.20 mg/L and 1.40 mg/L, respectively).

In addition, cyanide concentrations were detected in samples Gw4 (420.00 mg/L) and Gw3 (190.00 mg/L) above the guideline value set by the USEPA (0.00015 mg/L). Finally, a concentration of chloroform was detected in sample Gw5 (16.8 µg/L), above the guideline value established by the USEPA (0.22 µg/L). The presence of nitrate nitrogen, nitrite and cyanide in high concentrations can be attributed to the decomposition of organic materials present in the waste from the
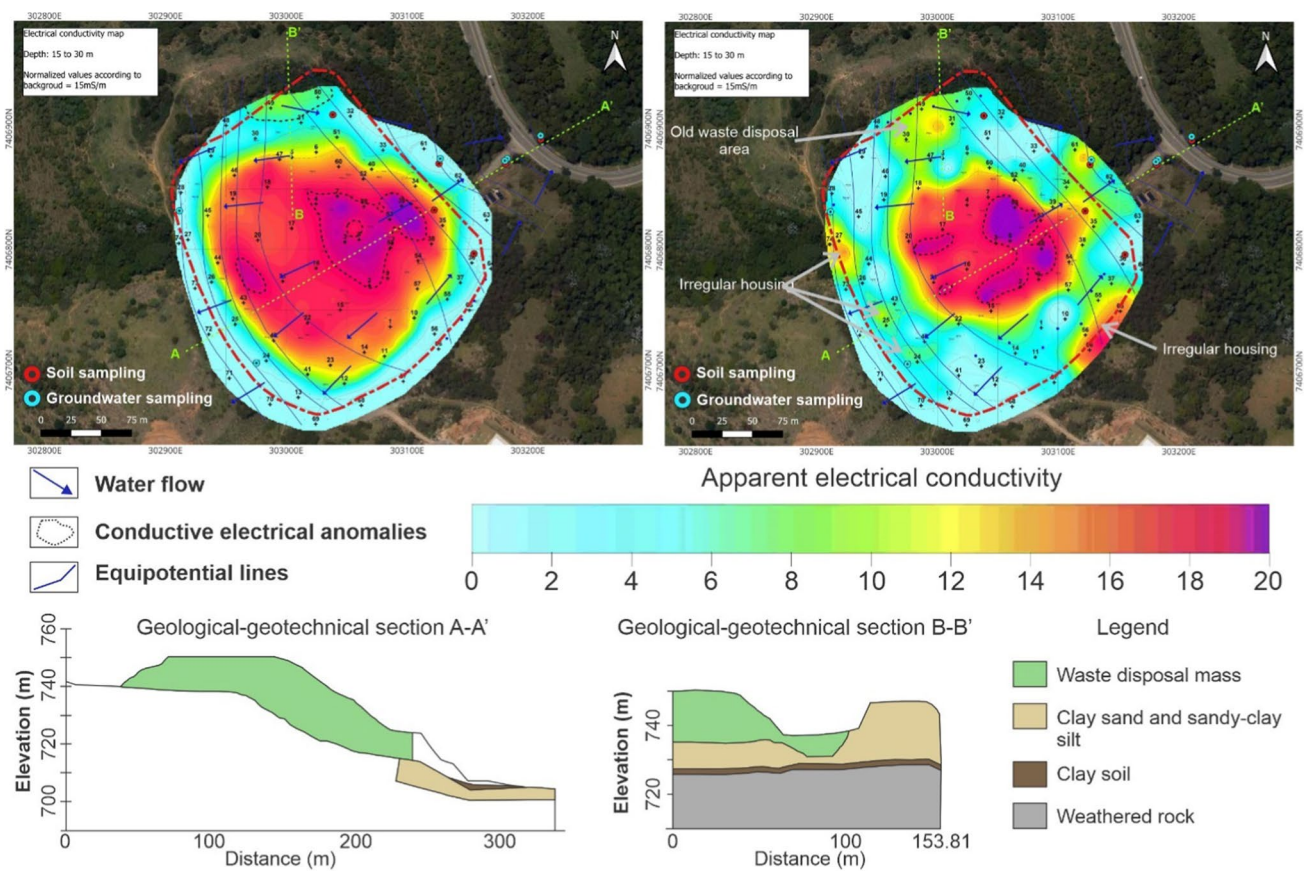
Fig. 7 Electrical conductivity maps of the dumpsite area and the geological-geotechnical sections obtained from the boreholes and excavations carried out in the area. The comparison between the maps and the sections showed the capacity of the non-invasive investigation to determine the waste disposal area

dump, while the presence of barium, iron and chloroform at levels above the reference values may indicate the leaching of these elements from the waste itself. The variations in electrical conductivity obtained by the geophysical method helped determine the waste disposal area and that electrical anomalies were observed at depth, which suggested the infiltration of leachate in the direction of the river (NE direction), which was proven by the presence of contaminants in the wells downstream of the dump area.

Although the use of the geophysical method has significantly contributed to understanding the behavior of the contaminant in the subsurface, this methodology does not completely replace the use of direct investigations, such as geological boreholes and groundwater monitoring wells, which are widely used in studies to monitor and remediate contaminated areas. These traditional techniques remain essential for collecting accurate and reliable data on underground conditions and the extent of contamination. In addition, direct methods provide more detailed information on the composition and structure of the soil, as well as serving as a reference to validate the geophysical results obtained. However, as this study has shown, an integrated approach combining geophysical methods with traditional techniques can provide a more comprehensive and accurate view of the contaminant in the study area, enabling more effective and safer management of contaminated areas. In future studies aimed at improving the methodology applied in this study, we suggest studies in controlled environments, such as operational dumps or landfills, which have a large amount of information about the physical environment available, such as monitoring wells, different soil sampling points and, in the case of landfills, information about the geometry and materials used in the construction of the project. This information certainly helps in the understanding and interpretation of geophysical data and can enable correlations between geotechnical, geoenvironmental and geophysical data.
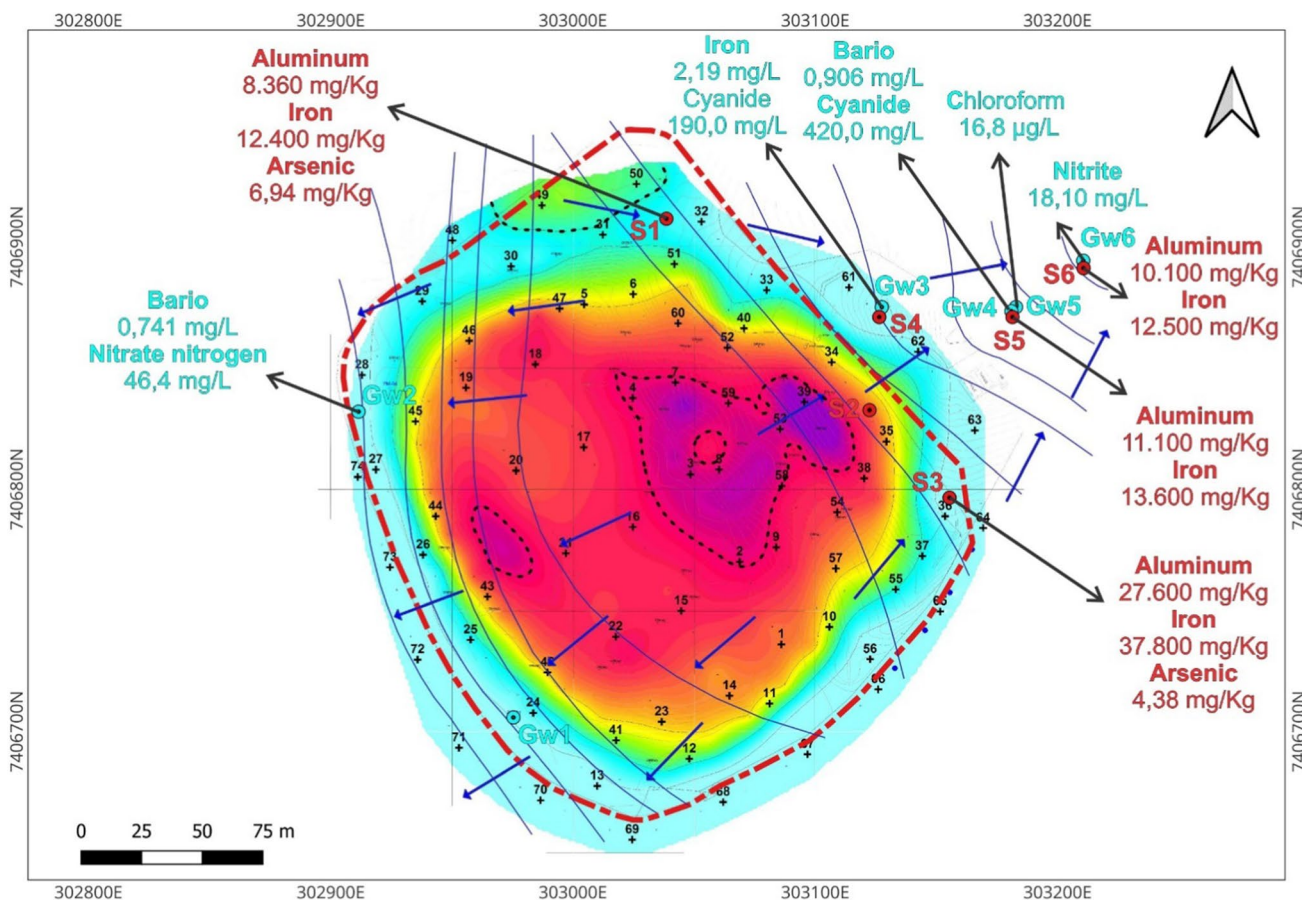
Fig. 8 Map of electrical conductivity from a depth of 0 to 15 m and the results of the chemical analysis of soil and groundwater samples in the dump area. The results of the chemical analysis showed the presence and behavior of contamination in the study area, which was confirmed by the geophysical mapping

5 Conclusions

The vast majority of non-invasive geophysical landfill investigations are carried out using electro-resistivity methods. However, using electromagnetic methods, such as the one proposed in this study, may represent an exciting methodology for investigating inactive dumps with little information on the location and behavior of leachate contamination in the area. In our work, we found that:

1. The shallower electrical conductivity map was consistent with the delimitation of the waste disposal area, proven by the surveys and excavations carried out in the area. The historical aerial images also helped in this interpretation, as well as allowing us to understand the possible reasons for the conductive electrical anomalies present in the deeper electrical conductivity map, since we observed the presence of old irregular houses and waste disposal around the dumpsite area.
2. In addition to providing a more comprehensive lateral view of the study area compared to traditional investigation methods, the electrical conductivity maps suggest NE-oriented percolation at depth in the study area. The groundwater monitoring wells and soil analyses showed the presence of chemical elements above those established by Brazilian and international environmental agencies in this direction of water flow in the area.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. de Lima GN, Fonseca-Salazar M, Campo J. Urban growth and loss of green spaces in the metropolitan areas of São Paulo and Mexico City: effects of land-cover changes on climate and water flow regulation. Urban Ecosyst. 2023;26:1739–52. https://doi.org/10.1007/s11252-023-01394-0.
2. Veldkamp E, Schmidt M, Powers JS, et al. Deforestation and reforestation impacts on soils in the tropics. Nat Rev Earth Environ. 2020. https://doi.org/10.1038/s43017-020-0091-5.
3. Marcotullio PJ, Braimoh AK, Onishi T. The impact of urbanization on soils. In: Braimoh AK, Vlek PL, editors. Land use and soil resources. Dordrecht: Springer; 2008. https://doi.org/10.1007/978-1-4020-6778-5_10.
4. Dragović N, Vulević T. Soil degradation processes, causes, and assessment approaches. In: Leal Filho W, Azul A, Brandli L, Lange Salvia A, Wall T, editors. Life on land. Encyclopedia of the UN sustainable development goals. Cham: Springer; 2020. https://doi.org/10.1007/978-3-319-71065-5_86-1.
5. Keith M, Birch E, Buchoud NJA, et al. A new urban narrative for sustainable development. Nat Sustain. 2023;6:115–7. https://doi.org/10.1038/s41893-022-00979-5.
6. Guimarães CC, Guireli Netto L, Barbosa AM. Monitoring physicochemical parameters in the bioremediation of soil contaminated by petroleum hydrocarbons using poultry manure. Int J Environ Sci Technol. 2024. https://doi.org/10.1007/s13762-024-05567-y.
7. Adeniran MA, Oladunjoye MA, Doro KO. Soil and groundwater contamination by crude oil spillage: a review and implications for remediation projects in Nigeria. Front Environ Sci. 2023;11:1137496. https://doi.org/10.3389/fenvs.2023.1137496~.
8. Guireli Netto L, Guimarães CC, Barbosa AM, Gandolfo OCB. Characterization of an inactive dumpsite using electrical resistivity tomography and hydrochemical data: a case study in Brazil. Environ Earth Sci. 2023;82:529. https://doi.org/10.1007/s12665-023-11233-2.
9. Takeda CM, de Godoy Leme MA, Romeiro DC, et al. Variation of the gravimetric composition of landfilled municipal solid waste over the time in a developing country. Int J Environ Res. 2022;16:83. https://doi.org/10.1007/s41742-022-00463-0.
10. Voukkali I, Papamichael I, Loizia P, et al. Urbanization and solid waste production: prospects and challenges. Environ Sci Pollut Res. 2023. https://doi.org/10.1007/s11356-023-27670-2.
11. Lu M, Zhou C, Wang C, et al. Worldwide scaling of waste generation in urban systems. Nat Cities. 2024;1:126–35. https://doi.org/10.1038/s44284-023-00021-5.
12. Morita AK, Ibelli-Bianco C, Anache JA, et al. Pollution threat to water and soil quality by dumpsites and non-sanitary landfills in Brazil: a review. Waste Manage. 2021;131:163–76. https://doi.org/10.1016/j.wasman.2021.06.004.
13. de Jesus AOC, de Farias AG, Saggioro EM, et al. Contamination assessment of soil and groundwater of a deactivated dumpsite in Brazil. Environ Monit Assess. 2022;194:216. https://doi.org/10.1007/s10661-022-09790-3.
14. Guireli Netto L, Barbosa AM, Galli VL, Silva Pereira JP, Gandolfo OCB, Birelli CA. Application of invasive and non-invasive methods of geo-environmental investigation for determination of the contamination behavior by organic compounds. J Appl Geophys. 2020;178: 104049. https://doi.org/10.1016/j.jappgeo.2020.104049.
15. Bernardo BJ, Candeias C, Rocha FT. Application of geophysics in geo-environmental diagnosis on the surroundings of the Hulene-B waste dump, Maputo. Mozambique J Afr Earth Sci. 2021;185: 104415. https://doi.org/10.1016/j.jafrearsci.2021.104415.
16. Rani P, Cassiani G. Tracking contaminant transport using time-lapse geophysics: a review on applications of electrical methods. Water Sec. 2022. https://doi.org/10.1016/j.wasec.2022.100127.
17. Sanuade OA, Arowoogun KI, Amosun JO. A review on the use of geoelectrical methods for characterization and monitoring of contaminant plumes. Acta Geophys. 2022;70:2099–117. https://doi.org/10.1007/s11600-022-00858-9.
18. Helene LPI, Moreira CA. 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. 2021;178:1355–67. https://doi.org/10.1007/s00024-021-02700-7.
19. de Moraes BYM, Xavier FV, Fachin SJ, Guireli Netto L. Método da tomografia elétrica para investigação subsuperficial de um lixão no município de Jaciara-MT. Geol USP Sér Cient. 2023. https://doi.org/10.11606/issn.2316-9095.v23-206488.

Discover

20. Igboama WN, Hammed OS, Fatoba JO, et al. Review article on impact of groundwater contamination due to dumpsites using geophysical and physiochemical methods. Appl Water Sci. 2022. https://doi.org/10.1007/s13201-022-01653-z.

21. Alao JO, Abdo HG, Ayejoto DA, et al. Evaluation of groundwater contamination and the health risk due to landfills using integrated geophysical methods and physiochemical water analysis. Case Stud Chem Environ Eng. 2023. https://doi.org/10.1016/j.cscee.2023.100523.

22. Adabanija MA. Spatio-temporal monitoring of leachates dispersion beneath a solid wastes dump in basement complex of Southwestern Nigeria. J Appl Geophys. 2023. https://doi.org/10.1016/j.jappgeo.2023.104953.

23. Morita AKM, Pelinson NS, Bastianon D, et al. Using electrical resistivity tomography (ERT) to assess the effectiveness of capping in old unlined landfills. Pure Appl Geophys. 2023. https://doi.org/10.1007/s00024-023-03346-3.

24. Lima GN, Rueda VM. The urban growth of the metropolitan area of Sao Paulo and its impact on the climate. Weather Clim Extrem. 2018;21:17–26. https://doi.org/10.1016/j.wace.2018.05.002.

25. Suhartini N, Jones P. Urbanization and urban governance in developing countries. In: Suhartini N, Jones P, editors. Urban governance and informal settlements. The urban book series. Cham: Springer; 2019. https://doi.org/10.1007/978-3-030-06094-7_2.

26. Fral Consultoria LTDA. Relatório preliminar do plano de ações para adequação da disposição final dos resíduos sólidos urbanos (RSU's) do municipio de Santana de Parnaíba - SP. São Paulo: FRAL Consultoria Ltda; 2001. p. 66p.

27. IPT-Instituto de pesquisas tecnológicas do estado de São Paulo. Mapa Geológico do Estado de São Paulo. São Paulo: IPT; 1981.

28. Oliveira JB, Camargo MN, Rossi M, Calderano Filho B. Mapa Pedológico do Estado de São Paulo: legenda expandida. Campinas: Campinas, Instituto Agronômico/EMBRAPA Solos; 1999. p. 64.

29. Guireli Netto L, Malagutti Filho W, Moreira CA, di Donato FT, Helene LPI. Delineation of necroleachate pathways using electrical resistivity tomography (ERT): case study on a cemetery in Brazil. Environ Chall. 2021;5: 100344. https://doi.org/10.1016/j.envc.2021.100344.

30. Wang TP, Chen CC, Tong LT, et al. Applying FDEM, ERT and GPR at a site with soil contamination: a case study. J Appl Geophys. 2015;121:21–30. https://doi.org/10.1016/j.jappgeo.2015.07.005.

31. Baawain MS, Al-Futaisi AM, Ebrahimi A, Omidvarborna H. Characterizing leachate contamination in a landfill site using Time Domain Electromagnetic (TDEM) imaging. J Appl Geophys. 2018;151:73–81. https://doi.org/10.1016/j.jappgeo.2018.02.002.

32. Deidda GP, De Carlo L, Caputo MC, Cassiani G. Frequency domain electromagnetic induction imaging: an effective method to see inside a capped landfill. Waste Manage. 2022;144:29–40. https://doi.org/10.1016/j.wasman.2022.03.007.

33. Boonsakul P, Sasidhorn B, Wangyao K. Optimization of multi-frequency electromagnetic surveying for investigating waste characteristics in an open dumpsite. J Air Waste Manage Assoc. 2022;72(11):1290–306. https://doi.org/10.1080/10962247.2022.2113181.

34. McNeill JD. Electromagnetic terrain conductivity measurement at low induction number. Geonics Limited Technical Note TN-6. Mississagua: Geonics Ltd; 1980.

35. ABNT - Associação Brasileira DE Normas Técnicas. NBR 15847: Amostragem de água subterrânea em poços de monitoramento—Métodos de purga. 1st ed. Rio de Janeiro: ABNT; 2010.

36. Freeze RA, Cherry JA. Groundwater. Hemel Hempstead: Prentice-Hall International. 1979: xviii + 604 pp.

37. EPA – Environmental Protection Agency. Regional Screening Level Summary Table. EPA: 2015. http://semspub.epa.gov/work/03/2218432.pdf. Accessed Jan 2024.