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HYDROGEOPHYSICAL CHARACTERIZATION OF THE MARIZAL–SÃO SEBASTIÃO AQUIFER SYSTEM IN THE SURROUNDINGS OF THE LIMPEC SANITARY LANDFILL, CAMAÇARI, BAHIA, BRAZIL

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ABSTRACT. A detailed hydrogeophysical survey was conducted using the geoelectrical method in the surroundings of the LIMPEC sanitary landfill, municipality of Camaçari, Bahia, Brazil. Twenty-six vertical electrical soundings (VESs) were done, configured according to the Schlumberger electrode array and spaced up to 400 m between current electrodes. Hydrogeological quali-quantitative information was obtained by integrating geoelectrical results to data from wells and local geology information, namely: *(i)* an apparent resistivity map showed the occurrence of a conductivity anomaly, possibly attributed to the contamination plume, dispersed within the saturated zone, and presenting a SSE convection direction; *(ii)* one-dimensional inversions allowed to interpret the stratigraphic pattern, identify static level depth and the occurrence of possible contamination plumes, and indicate the direction of the groundwater flow, which was also towards SSE; *(iii)* two-dimensional inversions produced inverted geoelectrical profiles, with a mean error below 2%, and confirmed the occurrence of possible contamination plumes disseminated within the unsaturated zone and dispersed within the saturated one. The geoelectrical facies with the highest resistivity values (> 600 ohm.m) were related to the São Sebastião Formation. Facies with intermediate values (100 to 800 ohm.m) regarded the Marizal Formation. In turn, those with the lowest values (< 100 ohm.m) were related to contamination plumes and/or eventual occurrences of silt/clay; *(iv)* the parameters of porosity, hydraulic conductivity, and transmissivity were estimated between 19.2 and 34.2%, 0.11 and 3.37 x10^{-3} cm/s, and 4.7 and 145.6 m²/d, respectively; and *(v)* local free aquifer vulnerability was classified as high, according to the evaluation using the GOD method.

Keywords: geoelectrical method, urban solid waste, hydrodynamic parameters.

RESUMO. Um estudo hidrogeofísico de detalhe, utilizando o método geoelétrico, foi conduzido no entorno do aterro sanitário LIMPEC, município de Camaçari, Bahia, Brasil. Vinte e seis sondagens elétricas verticais (SEVs), sob configuração do arranjo Schlumberger de eletrodos, com espaçamento de até 400 m entre os eletrodos de corrente foram executadas. Informações quali-quantitativas de âmbito hidrogeológico foram alcançadas a partir da integração dos resultados geoelétricos a dados de poços e informações da geologia local, a saber: *(i)* o mapa de resistividade aparente revelou a ocorrência de uma anomalia condutiva, possivelmente atribuída à pluma de contaminação, dispersa na zona saturada, apresentando sentido de convecção na direção SSE; *(ii)* as inversões unidimensionais possibilitaram interpretar o padrão estratigráfico, identificar a profundidade do nível estático, a ocorrência de possíveis plumas de contaminação e apontar o sentido do fluxo hídrico subterrâneo também para SSE; *(iii)* as inversões bidimensionais geraram perfis geoelétricos invertidos, com erro médio inferior a 2%, e confirmaram a ocorrência de possíveis plumas de contaminação disseminadas na zona não saturada e dispersas na zona saturada. Os fácies geoelétricos de maiores valores de resitividade (>600 Ohm.m) estão atribuídos à Formação São Sebastião. Os fácies de valores intermediários (100 a 800 Ohm.m) referem-se à Formação Marizal. Já os de menores valores (<100 Ohm.m), a plumas de contaminação e/ou eventuais ocorrências de silte/argila; *(iv)* os parâmetros porosidade, condutividade hidráulica e transmissividade foram estimados serem entre 19,2 a 34,2%, 0,11 a 3,37 x10^{-3} cm/s e 4,7 a 145,6 m²/d, respectivamente; e *(v)* a vulnerabilidade do aquífero livre local foi classificada como alta, segundo avaliação realizada utilizando o método GOD.

Palavras-chave: método geoelétrico, resíduos sólidos urbanos, parâmetros hidrodinâmicos.

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INTRODUCTION

Brazilian municipalities are responsible for disposing their solid waste correctly in an adequate area, as determined by Federal Law No. 12,306 of 2010 (Brasil, 2010). This piece of legislation instituted the National Policy on Solid Waste, which determines that municipalities must adopt more sustainable models, replacing wastelands and/or controlled landfills, as an environmental protection measure.

Among the various techniques for solid waste disposal, the use of sanitation landfills is one of the safest and most effective. It is also the most adopted technique around the world and presents the best cost-benefit ratio. These structures – sanitation landfills – are generally projected as a work of engineering designed under technical criteria in order to guarantee that the final disposal of waste does not harm public health and the environment (ABNT NBR 8419, 1992).

If on the one hand sanitary landfills can be used to partly solve some of the environmental problems related to inadequate solid waste disposal, on the other they can be potential sources of air, soil, underground, surface water and groundwater pollution, and can contaminate the biota. This therefore demands good studies on management, environmental and geotechnical evaluations and monitoring. In this sense, some geophysical approaches, such as the electrical and electromagnetic methods, for example, can be excellent tools for evaluating and characterizing these areas.

In the literature, there are authors who have shown the effectiveness of the geoelectrical method in studies on geoenvironmental characterization, diagnoses and monitoring in urban solid waste disposal areas: Cardarelli & Bernabini (1997); Meju (2000); Cavalcanti et al. (2001); Elis & Zuquette (2002); Moreira et al. (2011); Bortolin & Malagutti (2012); Porciúncula & Leal (2019). Grellier et al. (2007) and Farhana et al. (2016) showed the applicability of this method in studies on moisture and content of waste mass. Others have estimated hydrodynamic parameters of aquifers: Niwas and Singhal (1981 and 1985); Mazac et al. (1985); Yadav (1995); Soupios et al. (2007); Massoud et al. (2010); Niwas et al. (2011); Ijeh & Onu (2012); Okiongbo & Akpofure (2012); Utom et al. (2012); Arulprakasam et al. (2013); and Anomohanran (2015).

The objective of the present hydrogeophysical study was to conduct a geoenvironmental diagnosis and characterization, evaluate vulnerability, and estimate hydrodynamic parameters of the Marizal–São Sebastião aquifer system in the surroundings of the LIMPEC sanitary landfill, Camaçari, Bahia, Brazil, using the geoelectrical method associated with monitoring well data and surface geology information.

STUDY AREA

The study area is located in the municipality of Camaçari, within the Salvador Metropolitan Area, state of Bahia, Brazil, between UTM coordinates (WGS-84S) 579800 to 581300 (longitude) and 8596700 to 8597700 (latitude). Figure 1 shows a satellite image and overall situation of the study area, indicating the location of the Vertical Electric Soundings (VES), Profiles and wells monitored (WM).

In the geological context, the study area is located in the Recôncavo Sedimentary Basin. This basin is part of a rift system related to the fragmentation of Gondwana (Eocretaceous) and the opening of the Atlantic Ocean (late Jurassic through early Cretaceous). This system consists of an elongated N-S-oriented crustal depression, over an area that encompasses part of the states of Bahia, Sergipe and Pernambuco (Silva et al, 2007).

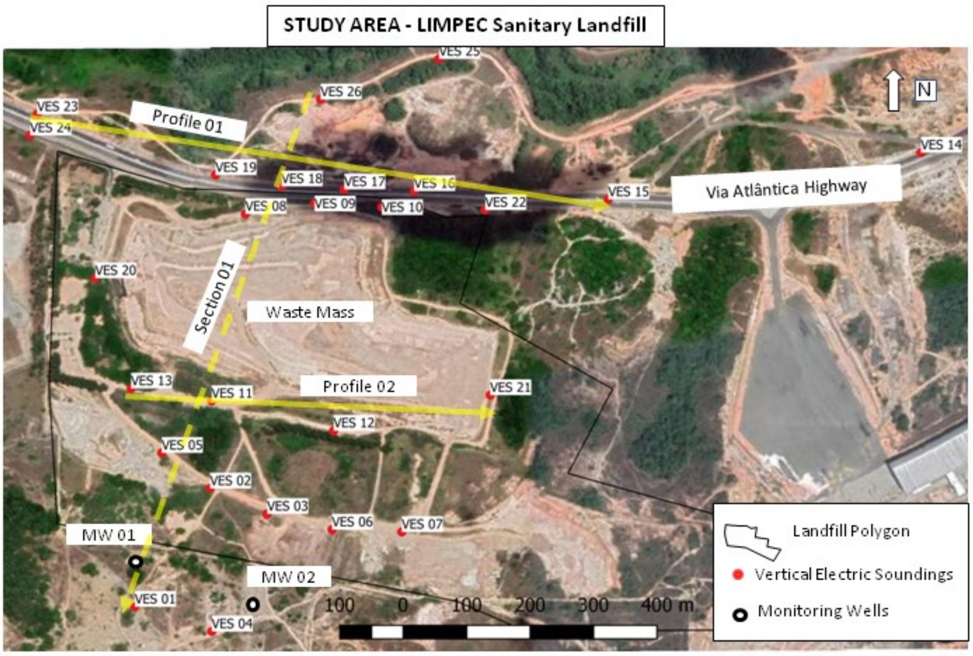


Figure 1 - Study area and location of VESs (modified from Google Earth).

The study area is locally situated upon the Marizal–São Sebastião aquifer system (Lower Cretaceous, Barremian - Aptian) and consists of poorly sorted, reddish-yellow, friable, feldspar-rich quartz sandstones alternated with variegated silty clays (Ghignone, 1979). It is characterized for presenting the largest groundwater reserve in the Recôncavo Basin, the São Sebastião aquifer.

Figure 2 shows examples of aerial images of the study area and occurrences of outcrops in its surroundings: A) bird's-eye-view of the LIMPEC sanitary landfill and the Via Atlântica highway located northwards from it. Sedimentary cover outcrops can be seen in road cuts in the detail; B) example of lateral discontinuity next to VES 14, characterized by the lithological contact between predominantly sandy and silty/clay-rich materials; C) example of cross-bedding occurring near VES 15 found in sandy, medium-grained, poorly-sorted, brown to yellow material – Marizal facies; and D) area southwards from the landfill, showing a slightly wavy relief, pasture vegetation, and occurrence of white to grayish, moderately sorted, and friable sands of the São Sebastião Formation.

THE GEOELECTRICAL METHOD

The geoelectrical method is a geophysical technique that allows the investigation of subsurface regions based on the contrast of electrical resistivity found in various geological and/or geotechnical material. This method consists basically in introducing, through an artificial source and electrodes, an electrical current in the terrain and measuring the difference of electrical potential provided (Koefoed, 1979; Telford et al., 1990; Braga, 2016). After data is treated and processed, subsurface resistivity and geoelectrical behavior can be determined. Results are expressed as contours, maps, profiles and/or sections, which interpretatively provide information of geological, geotechnical, and hydrogeological interest.

A Syscal Pro resistivity imaging system was used in the field. Regarding technique, the VES method was applied, with maximum spacing of 400 m between current electrodes. In total, 26 geoelectrical soundings, using the Schlumberger array, were obtained along the main access routes and roads of the study area, as shown in Figure 1.

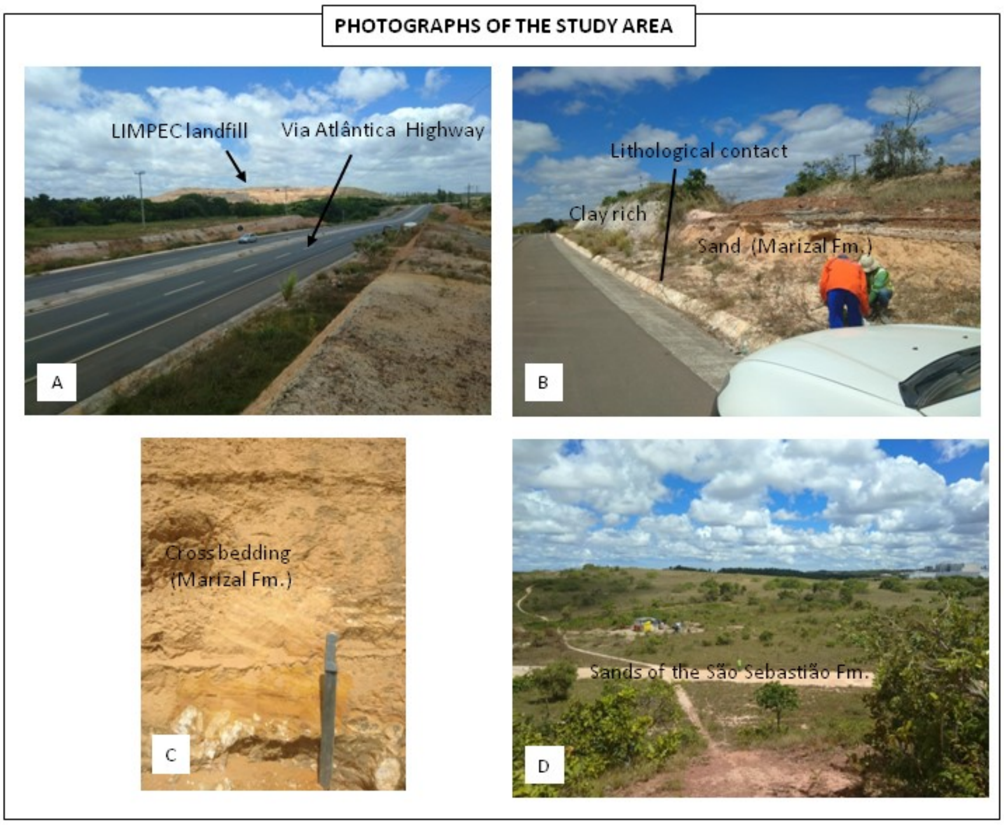


Figure 2 - Photographs of the study area. A) overview of the study area; B) lithological contact; C) cross-bedding (Marizal Formation); and D) sands of the São Sebastião Formation.

Examples of the use of the geoelectrical method in studies on the Marizal–São Sebastião aquifer system are available in the literature. Lima (1999) characterized the hydraulic and qualitative pattern of the Recôncavo aquifer, in the region of Camaçari and Dias D'Avila, Bahia. Porciúncula (2007), in a regional study conducted in the municipality of Alagoinhas/BA, Brazil, classified the Marizal–São Sebastião aquifer system as being free in its upper portion and semi-confined from 100 m and deeper, approximately. Pereira and Lima (2007), Porciúncula and Lima (2012) and Amarante et al. (2015) studied the geoelectrical behavior of disperse contamination plumes within the aquifer. Porciúncula & Leal (2019), in a geoelectrical detailed study, classified this aquifer as semi-confined, presenting alternated sandy and clay-rich layers close to the eastern border of the basin, in the region of the municipality of Simões Filho/BA, Brazil.

RESULTS

Apparent resistivity map

Maps of apparent electrical resistivity for various depths were constructed through interpolation. Qualitative information on local subsurface geoelectrical behavior was obtained through these maps.

Figure 3 shows an example of an apparent resistivity map (into the aquifer) for an approximate depth of 30 m, considering a depth theory about AB/4. An ellipsoidal conductive anomaly can be observed in the surroundings of VESs 08 and 11. The anomaly is slightly elongated towards SSE, indicating the possible direction of local groundwater flow. This feature, represented in blue, persists at other depths and may be related to possible occurrences of contamination plumes. In turn, these plumes could have been caused by subsurface leachate leaking or due to the ineffectiveness of

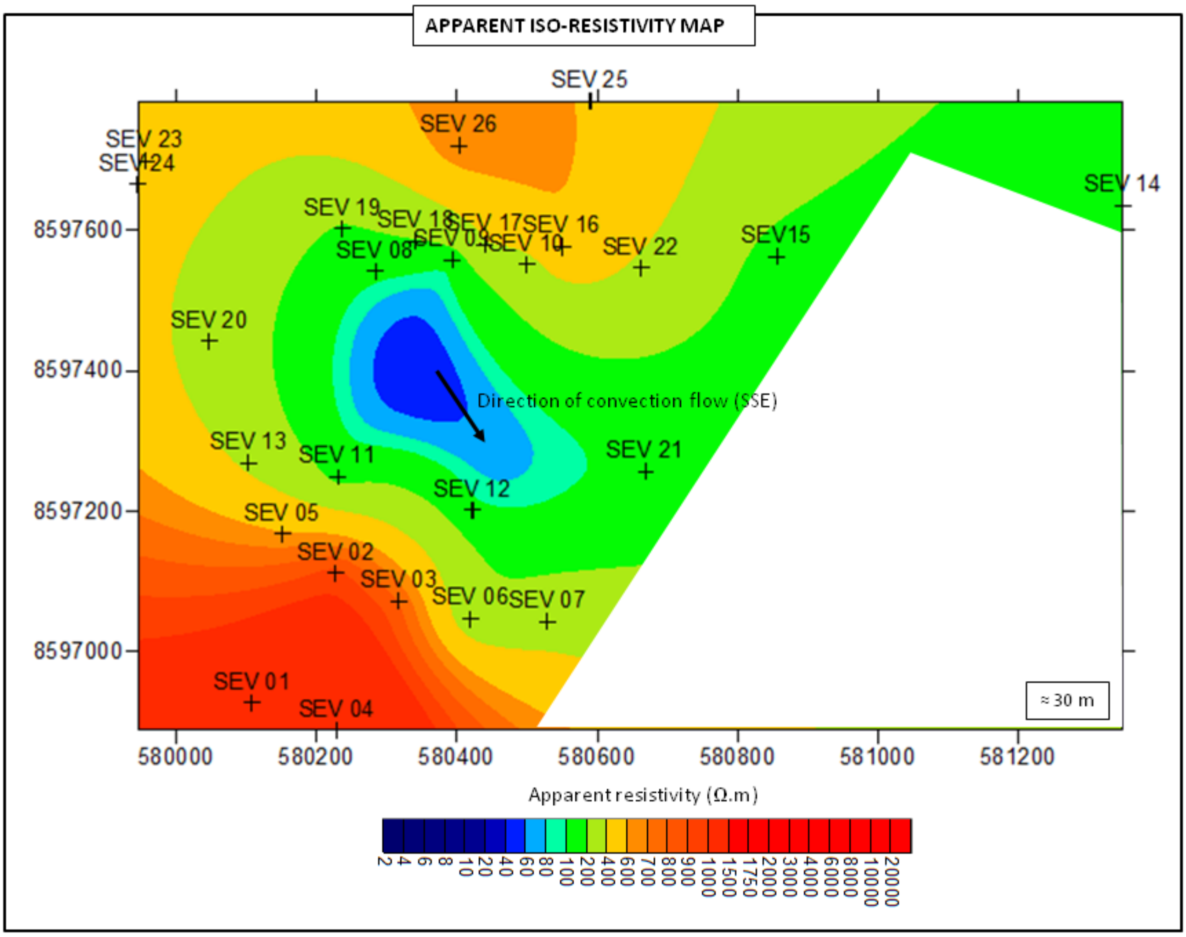


Figure 3 - Apparent iso-resistivity contour map.

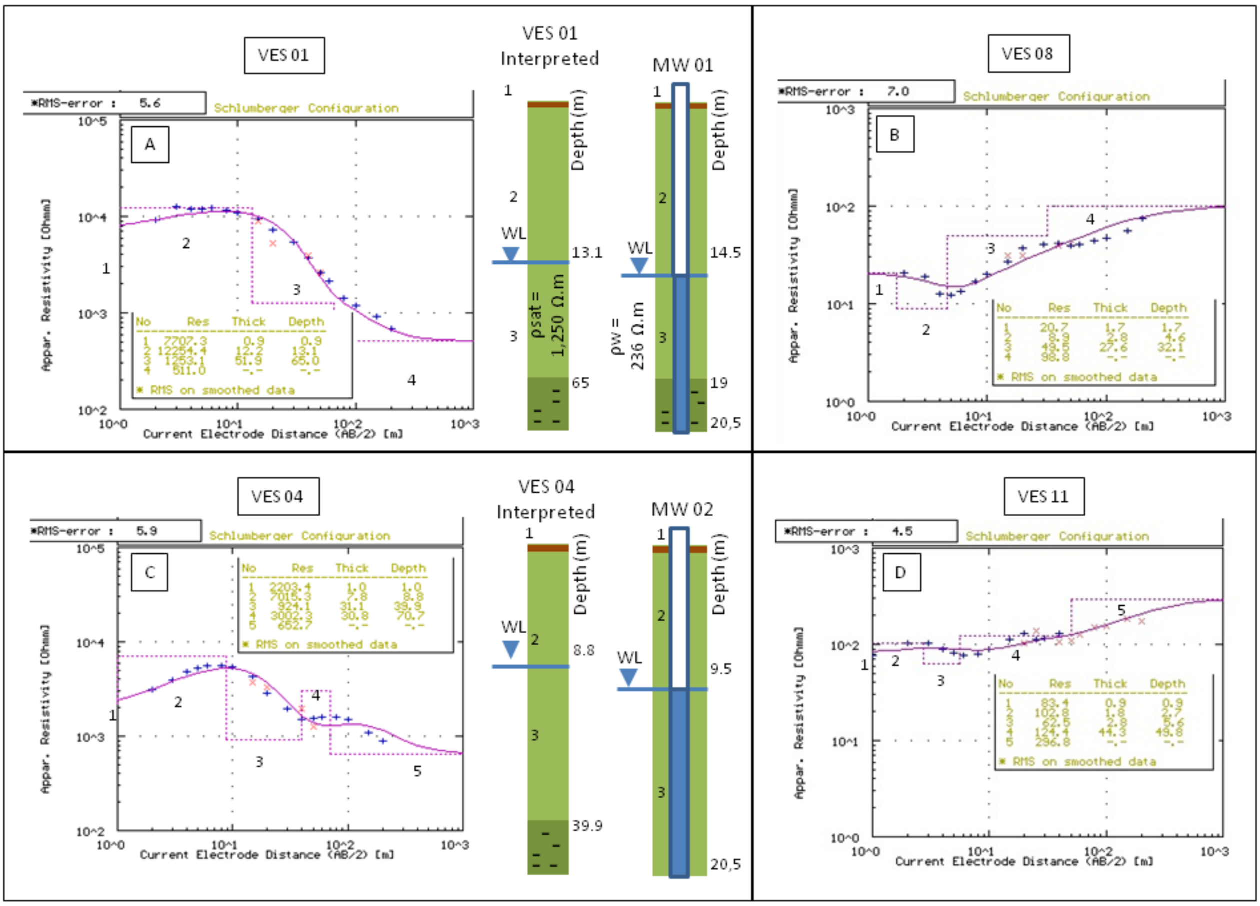
retention cells and/or operational errors and/or possible leakage from groundwater pipes that carry leachate, by gravity, to the CETREL water treatment station located approximately 3 km east-northeastwards from the LIMPEC sanitary landfill.

One-dimensional inversions

All 26 VESs obtained underwent one-dimensional inversion, presenting an error ranging between 2.0 and 7.0%, with a mean value of 3.7%. These soundings reached survey depths of approximately 100 m.

Figure 4 shows examples of inverted VESs (VESs 01, 04, 08, and 11). Two monitoring well profiles (MW 01 and MW 02) were correlated with VESs 01 and 04, respectively. Hydrostratigraphic correspondence could be observed between MWs and their respective VESs, especially when identifying the phreatic level, which was interpreted as being located approximately at 10 m of depth. This correspondence between geoelectrical results and well data should be considered when validating the hydrogeophysical model interpreted in the area.

In addition, VESs 08 and 11, located near the conductive geoelectrical anomaly (identified in the apparent iso-resistivity map), more precisely upstream and downstream from this feature, respectively, presented a low range of electrical resistivity values, varying between tens to hundreds of ohm.m. On the other hand, VESs 01 and 04, located upstream and more distant from the anomaly, presented relatively higher values, ranging between hundreds and thousands of ohm.m. Moreover, the existence of a possible contamination plume in the surroundings of VESs 08 and 11, which caused a reduction in local electrical resistivity values, could be inferred by



No	Res	Thick	Depth
1	7707.3	0.9	0.9
2	12254.4	12.2	13.1
3	1253.1	51.9	65.0
4	511.0	-.-	-.-

No	Res	Thick	Depth
1	20.7	1.7	1.7
2	8.9	2.8	4.6
3	49.5	27.6	32.1
4	98.8	-.-	-.-

No	Res	Thick	Depth
1	2203.4	1.0	1.0
2	7015.3	7.8	8.8
3	924.1	31.1	39.9
4	3002.3	30.8	70.7
5	652.7	-.-	-.-

No	Res	Thick	Depth
1	83.4	0.9	0.9
2	102.8	1.8	2.7
3	62.5	2.8	5.6
4	124.4	44.3	49.8
5	296.8	-.-	-.-

Figure 4 - One-dimensional inversion of VES 06.

comparing these VESs. This interpretation reiterates the previously obtained results in the qualitative evaluation of the apparent resistivity map in the earlier section.

Two-dimensional inversions

Two-dimensional inversions were conducted by integrating aligned VESs, which provided qualitative and quantitative information about the subsurface region. Figure 5 presents two examples of two-dimensional inversion profiles (profiles 01 and 02), which showed an error below 2%.

Profile 01 is located northwards from the landfill, along the side of the Via Atlântica highway. It was built by integrating VESs 23, 19, 18, 17, 16, 22, and 15. This profile confirms the occurrence of a conductive anomaly close to VESs 18 and 19, between the 270 and 330-m positioning interval of the profile. The conductive anomaly to its right is possibly related to the occurrence of a layer/lens of clay/silt, identified from chargeability data results (induced polarization – IP) of VES 15. This anomaly was noted due to an increase in the contour at a depth of approximately 10 m, as clearly observed in the figure. Chargeability data, which were gathered along with electrical resistivity data, were not among the objectives of the present study and, therefore, have not been discussed herein.

Profile 02, located southwards from the landfill and built using VESs 13, 11, 12, and 21, also presented possible disseminated plumes, centered near VESs 11 and 12, between the 150 to 200-m and 300 to 350-m positioning intervals, respectively.

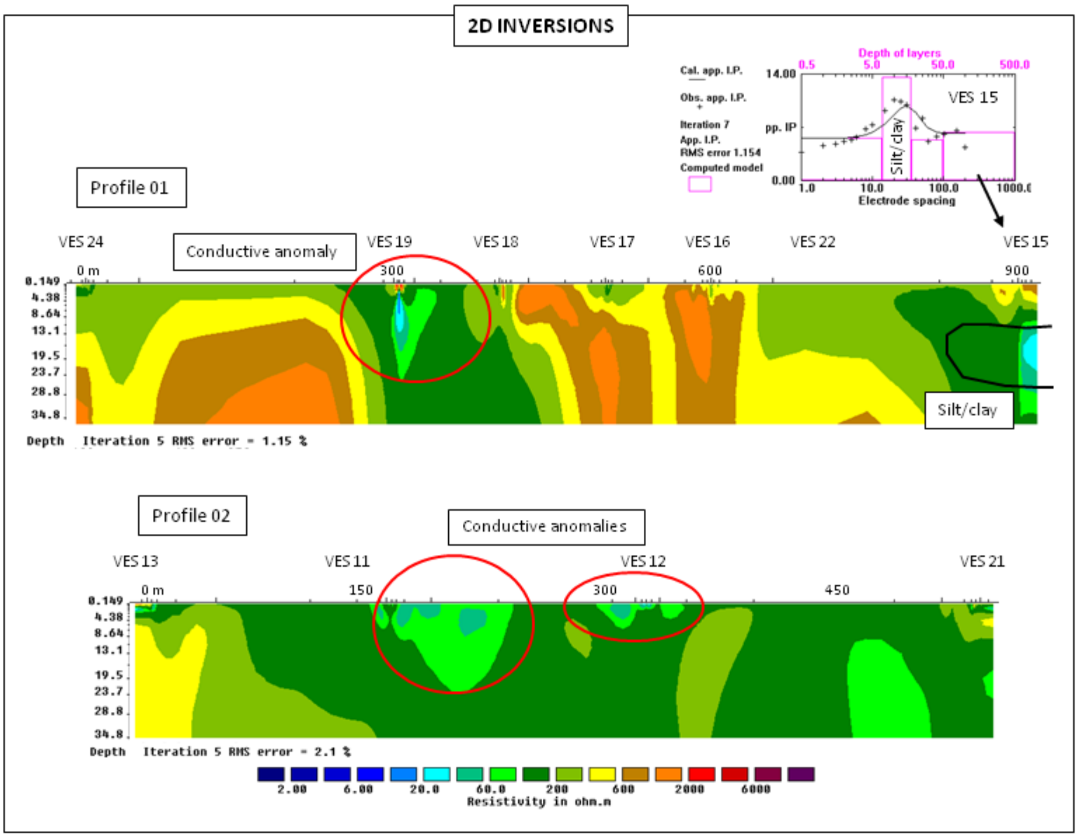


Figure 5 - Profiles 01 and 02 with two-dimensional inversion.

In general, the geoelectrical facies with the highest resistivity values (> 400 ohm.m) were attributed to the São Sebastião Formation. Facies with intermediate values (100 to 600 ohm.m), to the Marizal Formation. In turn, those with the lowest values (< 100 ohm.m) were attributed to contamination plumes and/or eventual occurrences of silt/clay.

Hydrodynamic parameters

The results of VESs offered information about thickness and resistivity of aquifers. This information can be used to calculate the transversal resistance ($R = \rho h$) and longitudinal conductance ($C = \sigma h$), known as Dar-Zarrouk parameters, that can be used to estimate the aquifer parameters, for example hydraulic conductivity and transmissivity (Niwas & Singhal, 1981 and 1985).

In the upper free portion of the local aquifer, the parameters of porosity, hydraulic conductivity and transmissivity could be estimated using VES 01, groundwater conductivity measurements of MW 01, and empirical relationship results.

Archie (1942) established an empirical relationship between the formation factor (F) and porosity (∅):

$$F = a\emptyset^{-m} = \frac{\rho_{sat}}{\rho_w} \qquad (1)$$

Winsauer et al. (1952), based on several experiments using sandstones, determined with a better error adjustment the value 0.62 for the formation constant (a). Several authors consider the cementation exponent value between 1.3 (more friable) and 2.5 (more cemented). Considering that the first few meters of the São Sebastião Formation in the local subsurface consist of a more friable material, the interval between 1.3 and 2.0 was chosen as the cementation exponent.

With this information and using Archie's law, the porosity ($\emptyset$) of the aquifer could be estimated as ranging approximately between 19.2 and 34.2%, with a median value of 26.7%. Lima (1993) attributed the interval between 24.6 and 32.7%, and a mean value of 27.5% for the porosity of the Massacará Group (Tucano Basin), a correspondent of the São Sebastião Formation (Recôncavo Basin).

Hydraulic conductivity (k) can be calculated using the Kozeny-Carman equation (Kozeny, 1953; Domenico & Schwarz, 1990):

$$k = \frac{\delta g}{\mu}\left(\frac{p^2}{180}\right)\left(\frac{\phi^3}{(1-\phi)^2}\right) \qquad (2)$$

Considering water density $\delta = 1000\, kg/m^3$, gravity $g = 10\, m/s^2$, water dynamic viscosity $\mu = 0.0014\, kg/ms$, porosity $\phi = 19.2$ and 34.2%, and adopting the range of mean values of grain diameter of the Massacará Group, varying between $p = 0.05$ and $0.28\, mm$, provided by Lima (1993), the hydraulic conductivity was estimated between 0.11 and 3.37 x10^{-3} cm/s, with a median value of 1.74 x10^{-3} cm/s, approximately. The same author considered mean permeability value as approximately 1.8 x10^{-3} cm/s for the first 500 m. This value is very close to the median value found in the present study and is within the estimated order of magnitude. Transmissivity (T=kh) presented results ranging between 4.7 and 145.6 m²/d, with a median value of 75.2 m²/d, approximately.

Aquifer vulnerability

Local aquifer vulnerability was evaluated using the GOD method (Foster & Hirata, 1988), which considers the degree of confinement of aquifers, characteristics of the unsaturated (vadose) zone or confining layer, and either depth of phreatic level or depth of the confining layer bottom. Based on the results obtained in the present study, the local aquifer was classified as unconfined (free), the unsaturated zone was sandy, and the phreatic level was located at a depth of approximately 10 m. The local aquifer in the study area was classified as presenting high vulnerability to contamination.

Hydrogeophysical model

A hydrostratigraphic section that was representative for the region was constructed using the integrations between 1D inversions of VESs 26, 18, 08, 11, 05, and 01 and the remaining information obtained in this study (Fig. 6). The hydrogeophysical schematic model consists of two aquifer units within the upper 100 m: (i) a free one, represented by the surface cover, a layer of the Marizal Formation, and by the upper portion of the São Sebastião Formation; and (ii) a semi-confined one, represented by the lower portion of the São Sebastião Formation, subjacent to the clay/silt layer/lens found at depths of 50 to 65 m, approximately. The static level occurs, on average, at a depth of 10 m and groundwater flows towards SSE. In the unsaturated zone, possible contamination plumes occur disseminated in the surroundings of the waste mass. In the saturated zone, a possible contamination plume of at least 300 m in length and 40 m in depth was found below the landfill area. Porosity and hydraulic conductivity for the free aquifer component were estimated at 26.7% and 1.74 x10^{-3} cm/s, respectively. Transmissivity, considering the thickness of the free aquifer (50 m) was approximately 75.2 m²/d. This zone presented high vulnerability to contamination.

CONCLUSIONS

Results of the hydrogeophysical study, using the resistivity method with Schlumberger array, yielded information on the configuration, quality and potentiality of the Marizal–São Sebastião aquifer system, in the surroundings of the LIMPEC sanitary landfill, municipality of Camaçari, state of Bahia, namely: *(i)* apparent iso-resistivity map for the depth of approximately 40 m, which allowed the identification of a possible contamination plume with low-electrical resistivity and elliptical form, elongated towards SSE, the same direction of local

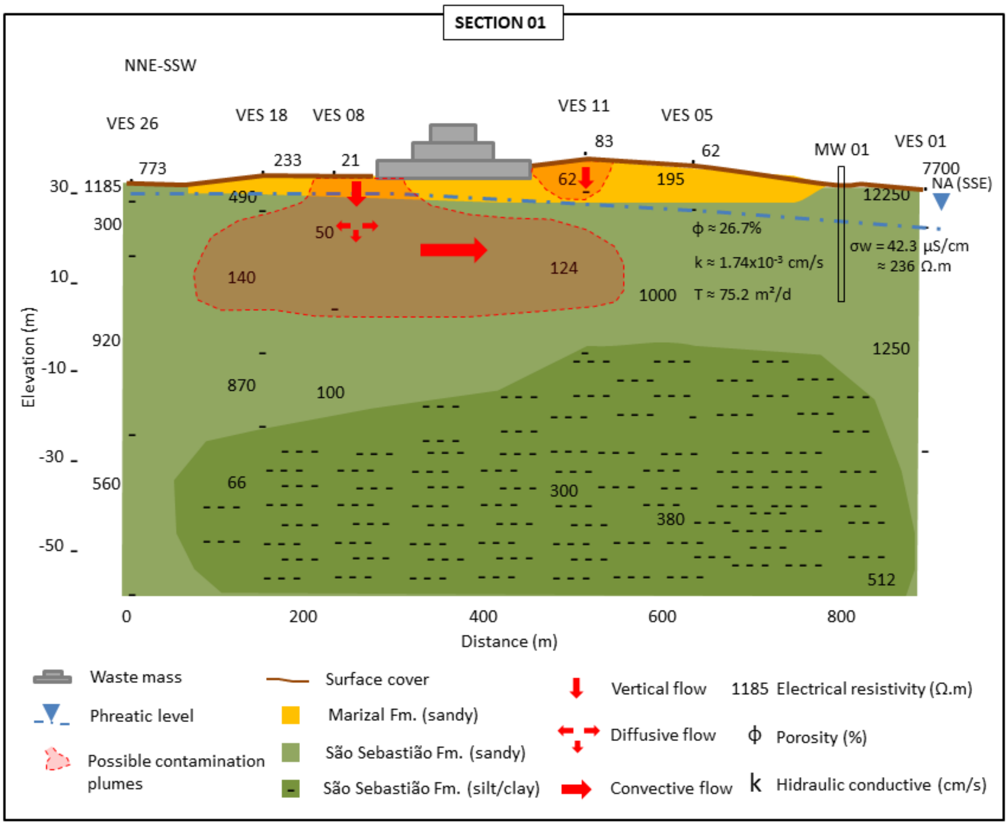


Figure 6 - Hydrostratigraphic section.

underground water flow; *(ii)* one-dimensional inversions contributed to obtain the depth of the static level, layer stratigraphy, and the direction of the underground water flow; *(iii)* contamination plumes and their subsurface behavior and distribution were identified using two-dimensional inversions; *(iv)* the parameters of porosity, hydraulic conductivity, and transmissivity were estimated using empirical relationships; and *(v)* aquifer vulnerability was classified as high, according to the evaluation using the GOD method. In general, the present study contributes to the increase in knowledge on the configuration and state of the Marizal–São Sebastião aquifer system. It exemplifies a potential application of hydrogeophysics to estimate hydrodynamic parameters, conduct geoenvironmental characterizations and evaluations of areas that receive urban solid waste, which can help to elaborate decision-making strategies related to local land and groundwater resource management.

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