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CAPACITIVE RESISTIVITY METHOD APPLIED TO THE ENVIRONMENTAL DIAGNOSIS AND MANAGEMENT OF CONTAMINATED AREA OF GAS STATION

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ABSTRACT. This article presents a case study of fuel underground contamination where the geophysical method was applied to support for decision making regarding environmental management activities. The application of geophysical methods that measure electrical resistivity in the study of contaminated areas and their correlations with organic contaminants are discussed, in addition to the presentation of theoretical and practical aspects of the Capacitive Resistivity (CR) method. The importance of this work is based on the evaluation of the potential for identification of free phase of organic contaminant by the capacitive method and the assessment of the effectiveness of the remediation implemented through the geophysical data obtained. The method applied was able to identify the highest electrical resistivities related to fuel in the subsurface and indicated the inefficiency of the current remediation by the inadequate positioning of the extraction wells and the inaccuracies in the monitoring of underground contamination and allowed the proposition of recommendations related to the management of the case based on geophysical information. From the results, it is concluded that the Capacitive Resistivity method can be applied in similar cases of leaks in gas stations to diagnose contamination and to guide the adoption of more appropriate actions of environmental management.

Keywords: organic contaminants; contaminated soils; electrical resistivity

INTRODUCTION

Cases of contamination by gas stations, such as the diagnosis presented here, are relatively frequent and represent 4,523 records in the contaminated area register from the Environmental Agency of the State of São Paulo (CETESB, 2020), which is equivalent to 70% of the total number, much higher, for example, than the industry events with 1,294 occurrences (20%), hence the importance of using all possible methodologies to assess the impacted environment.

In this context, the application of geophysical methods to studies of contaminated soil and groundwater has been increasing because they constitute a fast and non-invasive form of environmental research, where it is essential to understand the response of the geophysical signal in relation to the physical properties of the type of contaminant present in the subsurface and of the geological material. Their use in contaminated areas contributes to a better understanding of the environmental impacts on the subsurface since it allows the indirect evaluation of the underground conditions, both in relation to the existing contamination as well as to the possible pathways of its propagation through the geological environment (Moreira et al., 2017).

According to Aquino (2022), the geophysical method is classified as a screening method in contaminated area management procedures and can be applied in its main stages, from the preliminary investigation to the remediation phase. Based on this, the information obtained from geophysical surveys in contaminated areas is used to register pipelines and underground galleries, map trenches with waste and contamination plumes, guide the location of monitoring and recovery wells, provide area and volume for the contaminated soil removal and remediation, as well as information on soil or rock type, stratigraphy, water level depth, bedrock depth, presence of faults or fractures, underground propagation zones and other geological features of interest.

From an environmental point of view, significant deviations from the normal pattern of geophysical measurements (anomalies) may indicate the existence of subsurface contamination, as their intensities are directly related to the concentrations of contaminants (Gemail et al., 2011); in addition, they are useful for monitoring the propagation of compounds in the geological environment and guide the recovery activities of the impacted site.

The combustible products, target of detection of this work, are organic contaminants less dense than groundwater (light non-aqueous phase liquid - LNAPL) that, according to Ferreira et al. (2004), constitute the following phases when present in underground leaks (Figure 1):

a) *adsorbed* - part of the fuel that is adsorbed on organic matter specifically;
b) *residual* - portion of the hydrocarbon that percolates and is retained in the pores in the form of disconnected globules;
c) *gaseous or vapor* - portion of volatile compounds present in the unsaturated zone of the soil and originating mainly from the free, residual and adsorbed phases;
d) *free or liquid* - floating product in pure state in groundwater (high concentrations and mobility);
e) *dissolved* - fraction dissolved in groundwater whose concentrations are much lower than in the free phase and may be higher than the potability limits.

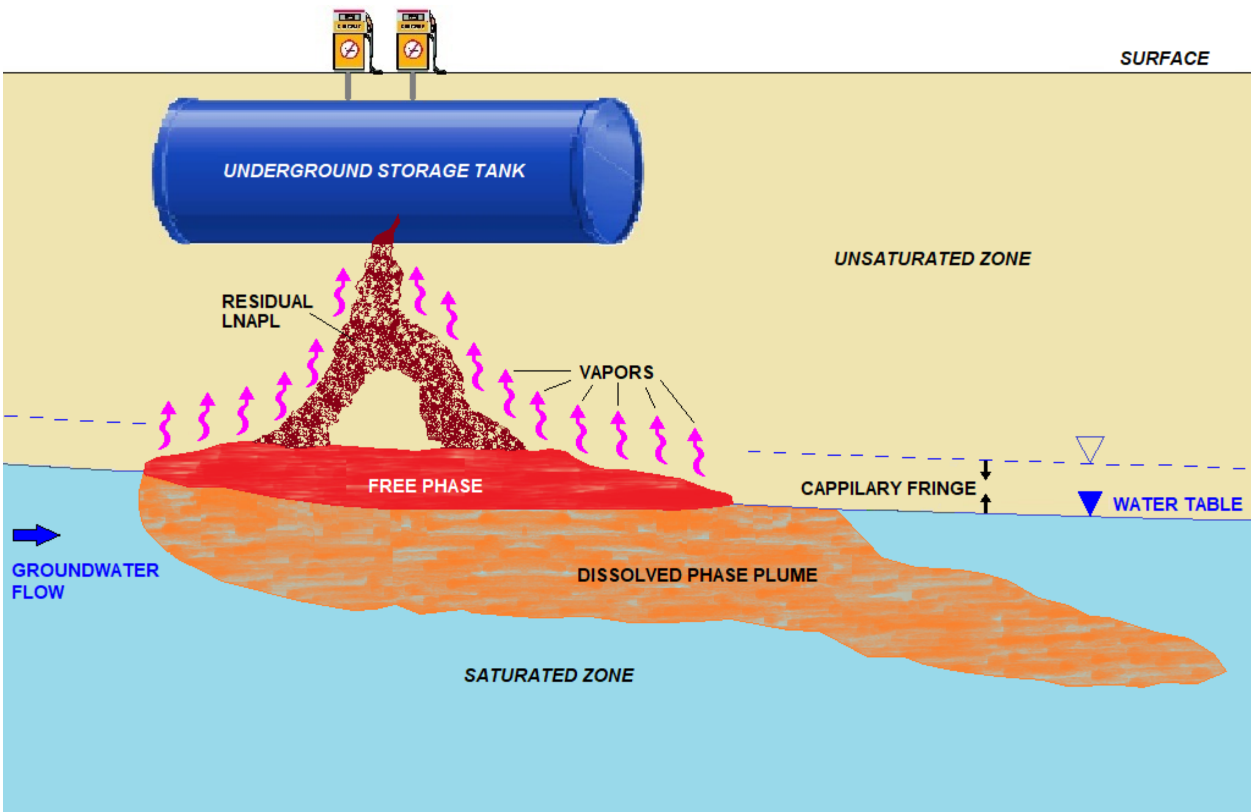

Figure 1: Conceptual model of LNAPL leakage (modified from Ferreira et al., 2004).

This article presents a geophysical investigation at a gas station that was being restored and where the product removal lost its effectiveness. Moreover, there was a suspicion that the free phase dimension was underestimated. These conditions made the use of the Capacitive Resistivity (CR) method the fastest alternative of diagnosis to evaluate the efficiency of the remediation and the need to relocate the monitoring and pumping wells where the extraction was taking place the free, dissolved and vapor phases. As the leak was relatively recent (less than five years), the presence of undegraded fuel free phase still persisted in groundwater at the time of the geophysical survey and was still being detected in existing extraction wells at the site.

The importance of this work consists in evaluating the potential of the capacitive method in the identification of the underground presence of free or residual fuel phase as well as its implementation in the remediation stage to evaluate its efficiency, since the use of geophysical methods occurs in phases of previous investigations (preliminary, confirmatory and detailed) in most cases of suspected or contaminated areas.

DESCRIPTION OF THE STUDY AREA

The investigated area is a gas station located in the municipality of Porto Feliz, State of São Paulo (Figure 2), where there was an underground fuel leak bellow the supply lines two years before the geophysical survey. Therefore, it is considered a recent event, with free phase still present in groundwater. This site is positioned on rocks of the Itararé Group, represented by diamictites and sandstones, and intercalations of siltstones, rhythmites and mudstones presenting variable thicknesses (Versolato, 2019), where the soils are generally shallow, with predominant presence of clay as well as silty material, in the gas station area, according to oral information.

The site is relatively flat with an average elevation of 578 meters and a slight slope of around 3.0%, with a groundwater level between 5.0 and 6.0 meters deep measured in the extraction wells. The direction of the underground flow occurs radially to the west from the gas station towards the lake and to the north and east from the gas station towards the stream, which is in accordance with the local topography (Figure 3).

As for the situation of the impacted area, it was already in the remediation stage at the pumping points A, B, C, D, E, F and G (Figure 4) through multiphase extraction that consists in applying a vacuum in the pumping wells, where the pressure gradient removes simultaneously the free, vapor and dissolved phases of the fuel, which are segregated subsequently.

The application of the Capacitive Resistivity geophysical survey resulted from the need to map the extent of the impacted area and determine the main fuel foci in the groundwater (free phase), as several monitoring wells were lost after repairs to the pavement of the gas station and, as already described, the inefficiency of the fuel recovery system.

Due to the loss of these monitoring wells and their information, the last measurement of the free phase prior to the geophysical survey was restricted to the seven product extraction wells (A, B, C, D, E, F and G) and indicated a variation of 2.0 to 10.0 cm (Figure 4), which may have induced an overestimation of the fuel thickness at these locations, caused by pumping and possible mobilization of the residual phase into these wells, and, at the same time, may have underestimated the real limits of the plume, as these sampled points are concentrated only in the central area of the gas station, where the fuel leak occurred in the underground lines.

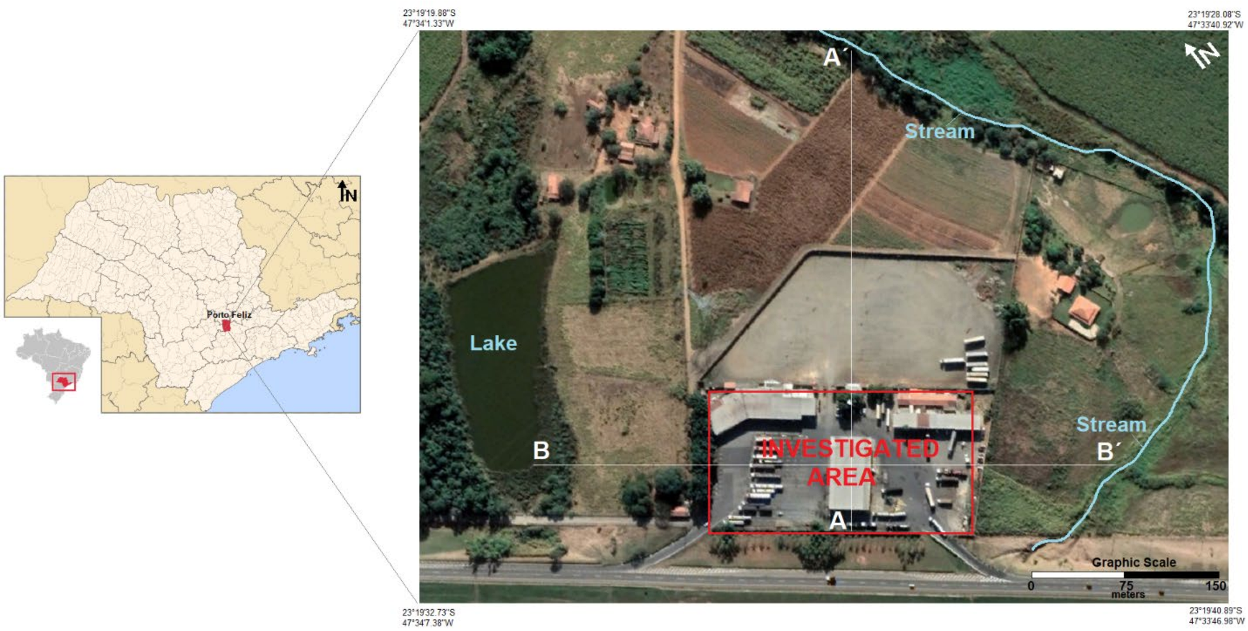

Figure 2: Location of the investigated area (adapted from Google Earth, 2022).

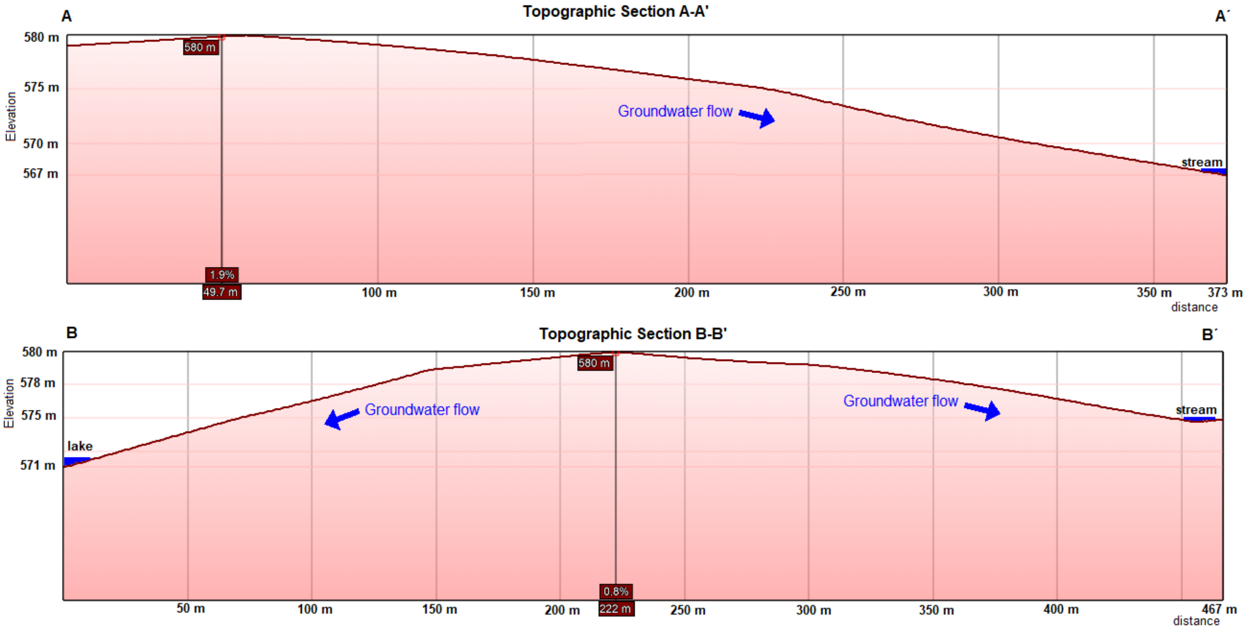

Figure 3: Topographic elevation sections A-A´ and B-B'.

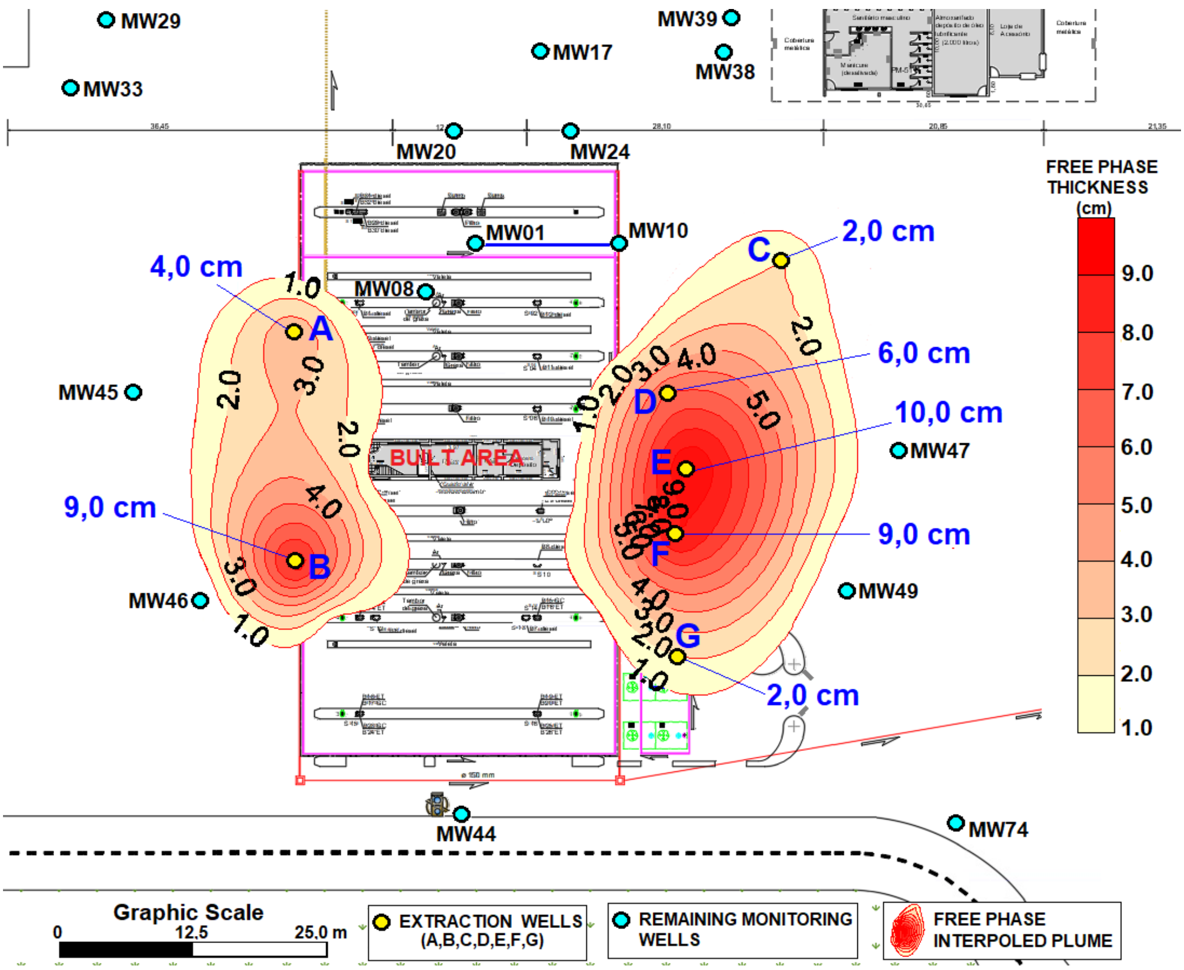

Figure 4: Free phase contour map and measurements in the extraction wells.

METHODOLOGY

Electrical Resistivity of Fuel Contaminants

Gasoline, diesel and their constituent compounds are nonpolar substances and have high electrical resistivities (Inokuchi and Akamatu, 1961; Borner et al., 1993; Loke, 2004), as can be seen in Table 1.

In general, the influence of the presence of fuels on changes in the electrical properties of the environment resulting from chemical interactions with the geological material depend on their concentrations, residence time and local hydrogeological conditions. Thus, their effects on subsurface electrical resistivity measurements can present two distinct behaviors that are identified with the methods that measure electrical resistivity: higher resistivity anomalies such as those observed in the work of Moreira et al. (2017) and Oyinkuro and Wariebi (2017), and also low anomalous values, as seen in the articles by Pellerin and Groom (2003), using Capacitive Resistivity, and Blondel et al. (2014).

Regarding the highest electrical resistivity values detected in the environment by Moreira et al. (2017) and Oyinkuro and Wariebi (2017), this would be the predicted behavior by the fuel in relatively recent events, as it is a nonpolar compound and has high electrical resistivity, as already pointed out. In contrast, the low electrical resistivity values measured in the previously cited articles by Pellerin and Groom (2003) and Blondel et al. (2014) have in common the presence of degraded fuel in older spill events, with fuel residence time for more than a decade in the environment.

As for the greater permanence of fuel in the subsurface, it is essential to point out that the behavior of plumes of organic contaminants in groundwater is determined by the interaction of physical, chemical and biological processes, represented mainly by volatilization, dispersion, sorption, and biodegradation, which contribute to reducing contamination concentrations over time resulting from the phenomenon of natural attenuation, which is specific to local characteristics (Baedecker et al, 1993). Thus, it is verified biodegradation and, therefore, it is not the only nor the main factor of the natural attenuation of underground contamination by fuel.

At the beginning of the contamination by fuel without the influence of natural attenuation processes, the mass of organic contaminant provides higher values of electrical resistivities in the environment due to its high concentrations. Over time and by joint action of natural attenuation processes, the fuel concentrations tend to decrease to the level at which the low electrical resistivities of the environment become prevalent, which is caused by ion mobilization such as Ca^{+2}, Mg^{+2} and HCO^{-3} in the aerobic zone and Sr^{+2}, K^{+1}, Fe^{+2} and Mn^{+2} dissolved in the anaerobic zone, provided by changes in pH, which is studied in detail in the articles by Bennett et al. (1993) and Baedecker et al. (1993), that explain the different effects on geophysical measurements at different times after the fuel spill and what was observed by Blondel et al. (2014).

Thus, it is noticeable that it is not the fuel that becomes less electrically resistive, even when degraded, with loss of mass and decrease in its concentrations, but it is its presence that disturbs the geochemistry of the environment where it is found (Baedecker et al., 1993) and reduces the electrical resistivity of the unsaturated and saturated zone by the mobilization of ions through the changes it causes in the oxidation-reduction regime, often concentrating cations and anions in the groundwater.

It is important to highlight that in the article on the application of geophysical methods by Blondel et al. (2014), as well as in the work of geochemical evaluation of fuels by Bennett et al. (1993) and Baedecker et al. (1993), the evaluations refer to the dissolved phase of the product at low concentration levels that can be, therefore, biodegraded by natural soil microorganisms. On the other hand, their analyzes and conclusions do not address the product-free phase, as mentioned by the authors, whose high concentrations are extremely toxic for this biological community, not allowing its biodegradation. Moreover, they must provide high electrical resistivities to the environment, as verified in the measurements of Moreira et al. (2017) and Oyinkuro and Wariebi (2017).

Capacitive Resistivity Method

For Kuras (2002), the Capacitive Resistivity method has the physical principles and data acquisition similar to the dipole-dipole arrangement (galvanic) of DC Resistivity, considered here measurements through a quadrupole arrangement (Figure 5), with two electric current injection poles (A and B) and two electric potential measurement poles (M and N). However, with a difference in the signal emission source for the subsurface and in the form of voltage reception.

Table 1: Electrical properties of organic compounds (adapted from Inokuchi and Akamatu, 1961; Borner et al., 1993; Loke, 2004).

Organic Compounds	Electrical Resistivity (ohm.m)	Electric Conductivity (siemens/m)	Organic Compounds	Electrical Resistivity (ohm.m)	Electric Conductivity (siemens/m)
Gasoline	$1.0x10^{12}$	$1.0x10^{-14}$	**Diesel**	$4.0x10^{7}$	$2.5x10^{-8}$
Xylene	$6.99x10^{16}$	$1.43x10^{-17}$	**Naphthalene**	$1.0x10^{17}$	$1.0x10^{-17}$
Toluene	$2.0x10^{11}$	$5.0x10^{-12}$	**Anthracene**	$1.3x10^{12}$	$7.69x10^{-13}$
Benzene	$9.09x10^{3}$	$1.1x10^{-4}$	**Pyrene**	$5.0x10^{15}$	$2.0x10^{-16}$
Hexane	$4.17x10^{10}$	$2.4x10^{-11}$	**Chrysene**	$4.0x10^{17}$	$2.5x10^{-18}$
Ethanol	$1.0x10^{6}$	$1.0x10^{-5}$			

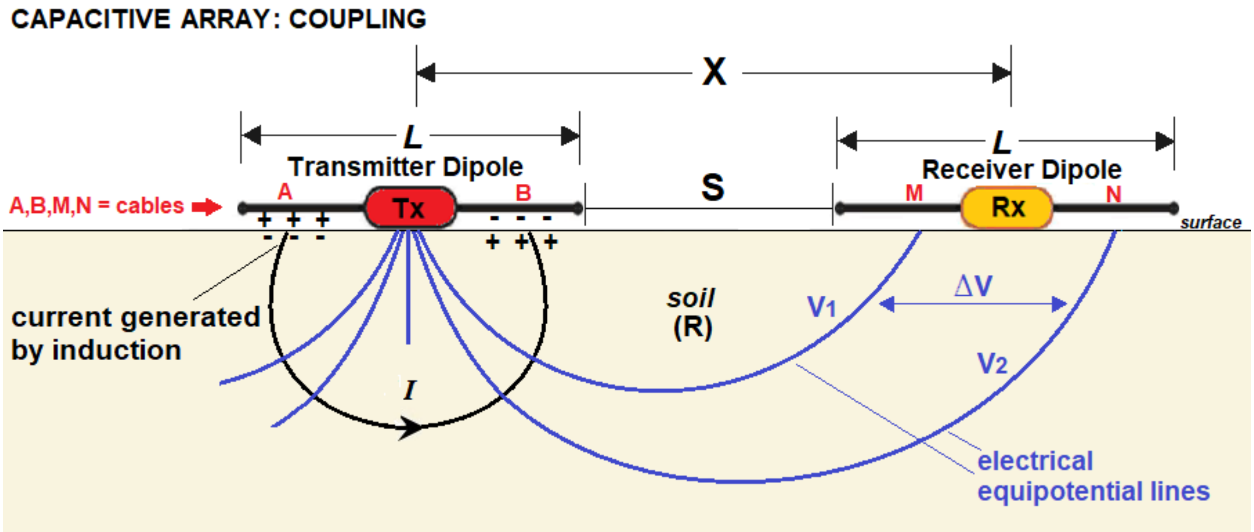

Figure 5: Capacitive dipole-dipole arrangement (adapted from Kuras, 2002).

While the transmission of the electrical current to the subsurface in the DC Resistivity arrangement is given by galvanic contact with electrodes, the capacitive system causes the passage of alternating current (AC) by induction, at a frequency equal to 16.5 kHz, through a coaxial cable coupled to the surface, which acts as a capacitor plate, and the ground, which works as another capacitive plate (Figure 6), whose capacitive cable-earth coupling is characterized by a variable electrical capacitance, depending on the soil resistance conditions (Yamashita et al., 2004).

Thus, during the equipment operation, the transmitter cable electrically charges the ground by induction (Figure 6), which generates electric currents by a variation of charges in a given time ($i=DQ/Dt$) and whose voltage is measured at the synchronized receiver around the frequency of the transmitted signal.

The received voltage level is converted into a digital signal at the receiver and transferred to the equipment's data logger for storage and later conversion into electrical resistivity values in ohm.m units which, according to Kuras (2002), are calculated by Ohm's Law in a similar way to the DC Resistivity method, through the formula:

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

where I is the alternating electrical current in the transmitter; DV is the electrical voltage measured at the receiver; and K is the geometric factor related to the distance between the transmitter and receiver dipoles. In this context, the calculation of the geometric factor of the capacitive dipole-dipole array K is more complex than the dipole-dipole factor of the DC Resistivity and is given by:

$$K = \frac{\pi L}{\ln\left[\left(\frac{b^2}{b^2-1}\right)^{2b}\left(\frac{b^2+2b}{(b+1)^2}\right)^{b+2}\left(\frac{b^2-2b}{(b-1)^2}\right)^{b-2}\right]} \quad (2)$$

where the parameter b is equal to $2X/L$, considering X as the separation between the centers of the capacitive dipoles and L as the individual length of the dipole, as seen in Figure 5.

Unlike the DC Resistivity method, the investigation level of the Capacitive Resistivity is related to the proportionality factor n, according to Groom (2008), which is the ratio of the distance between the length (S), that separates the end of the transmitter and receiver dipoles, and the dimension (L) of the receiver dipole, or of the transmitter, expressed by:

$$n = \frac{S}{L} \quad (3)$$

As it is a geophysical method with the emission of electric current through electromagnetic induction (EMI), another relevant parameter for signal penetration in the capacitive method is the so-called *skin depth* (d), which defines the maximum limit of the distance between the transmitter and the receiver and is associated with the attenuation of the emitted electric field, referring to the depth at which the intensity is reduced to 37% of its original value (Milsom, 2003), calculated according to Timofeev et al. (1994) by:

$$d = 15{,}9\sqrt{\frac{\rho}{f}} \quad (4)$$

where ρ is the electrical resistivity of the medium in ohm.m and f is the frequency of the emitted signal in kHz. When obeying this limit distance of the transmitter and receiver given by the *skin depth*, the studies by Aquino (2022) indicate a direct relationship of 1:1 between the separation of the ends of the dipoles and the depth of the target (S/D), contributing to a better resolution of the data.

Data acquisition and processing

For data acquisition (Figure 7), it was used a capacitive resistivity meter model Ohmmapper TR1, which requires the repetition of the same survey profile more times, with successively greater separations between the transmitter and the receiver to enable sampling of gradually deeper geological portions (Figure 8). In the Ohmmapper´s operating system, it is possible to parameterize the data collection by the sampling frequency by changing the signal trigger time, which allows continuous acquisition or at defined time intervals.

To perform the measurements, the capacitive system was moved along the profile, at sampling rate of 1.0 Hz (one reading per second), with average measurement interval of about 1.14 m and separation lengths between the ends of dipoles of 2.5, 5.0 and 10.0 meters, resulting in distances between the centers of the transmitter and receiver of 7.5, 10.0 and 15.0 meters. The selection of separations of 2.5, 5.0 and 10.0 meters between the transmitter and receiver dipoles is directly related to different depths of interest and to the electrical resistivity sampling of at least one profile at the unsaturated zone, other sampling near the top of the saturated zone, where the fuel free phase could be, and a last profile to collect data further down.

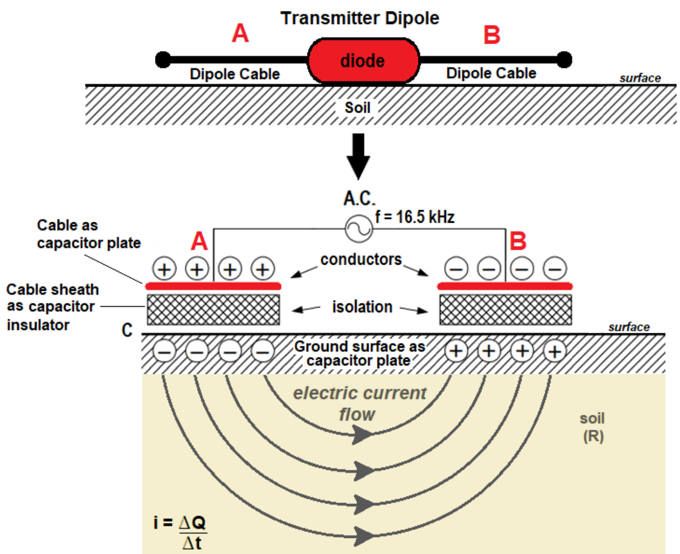

Figure 6: Capacitive ground current injection system (adapted from Yamashita et al., 2004).

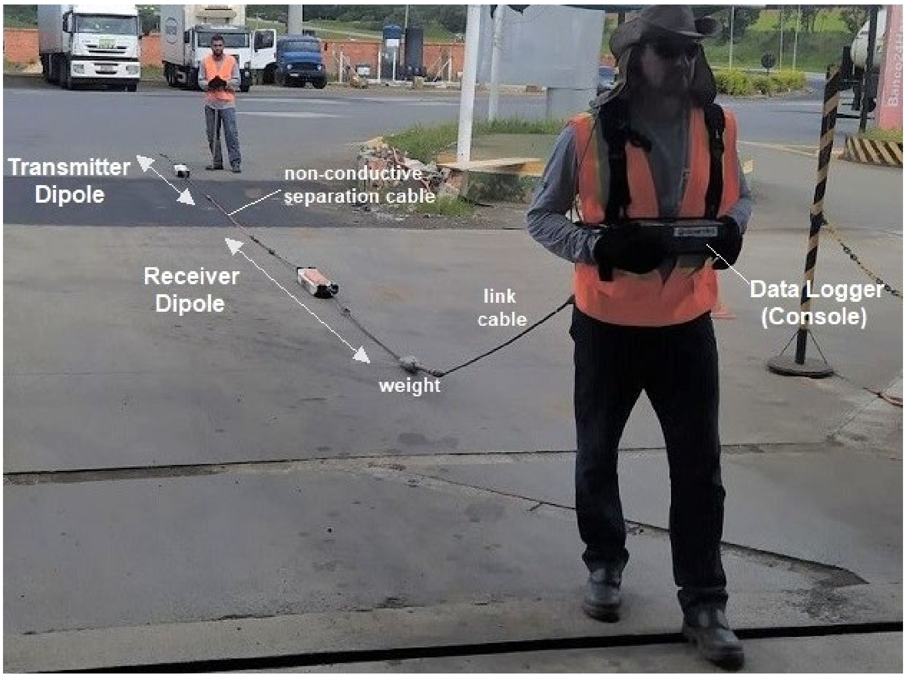

Figure 7: The used Ohmmapper TR1 capacitive resistivity meter.

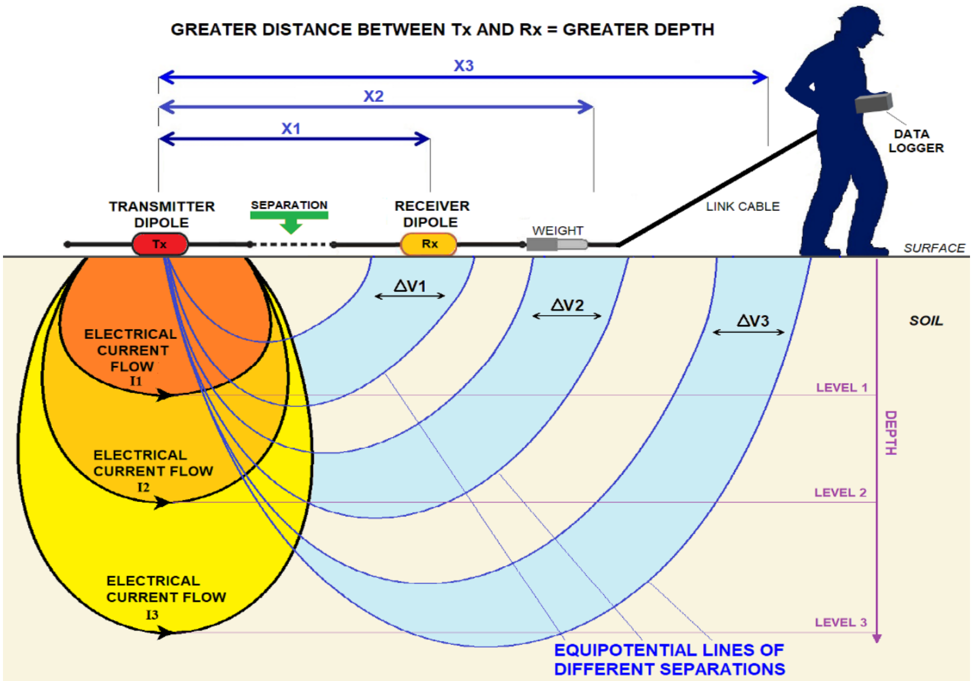

Figure 8: Diagram of dipoles separation and depth increase.

As the Capacitive Resistivity uses the electromagnetic induction of electric current, the measurement point is positioned below the center of the transmitting dipole, which is also common to other electromagnetic methods, such as Ground Penetrating Radar (GPR) and Frequency Domain Electromagnetic (FDEM), and different from the DC Resistivity plotting that gives for the capacitive method more data to be interpolated at the ends of the sections and does not require extended inversion models, considering the same sampling levels.

The field work was carried out through the execution of thirteen parallel lines in the southeast to northwest direction, each one150 m long, equidistant by about 6.0 m and crossing the place of supply and lubrication of vehicles, where, in a diagnosis prior to the geophysical survey, there was a free fuel phase identified at the groundwater pumping points A, B, C, D, E, F and G and it was interpolated the contours of the free phase plume (Figure 9).

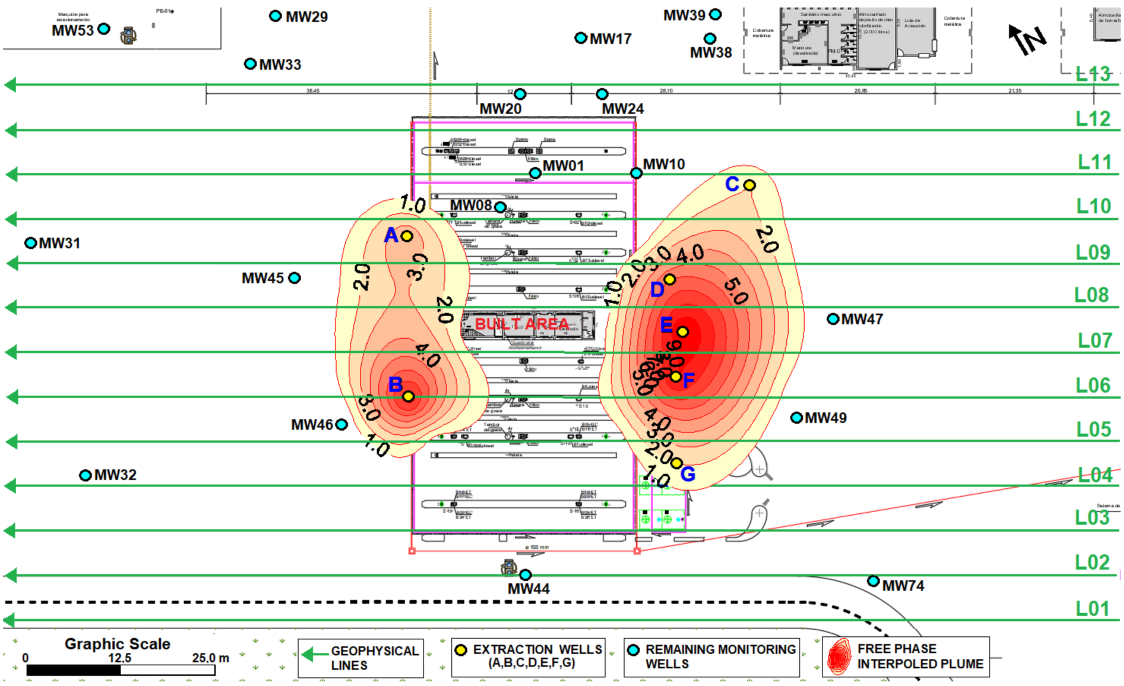

Figure 9: Free phase contour map showing the overlaid geophysical survey lines.

Firstly, the readings of the current injected into the soil, of the electrical potential measured and of the geometric parameters of the executed profile were automatically stored in the Ohmmapper equipment and grouped by the acquisition program Magmap2000 (Geometrics, 2001). For the processing of the data obtained in the field, there was no filtering, because this action could mask the most intense anomalies and restrict the amplitudes of the electrical resistivity, mainly because it is a question of identifying anomalous values related to underground contamination, which also justifies the later choice of individual scales of each section and not a common scale.

In a second step, all the raw data obtained from the same profile at different depths were converted into interpolated apparent resistivity data by the ZondRes2D software, version 5.2 (Kaminskiy, 2010), which later originated the modeled sections through inversion processes where it is possible to visualize the variations of electrical resistivity, both in distance and in depth, considered in the interpretation. In this case, the inversion is the numerical process where the real values of the physical property are determined based on numerical-statistical criteria of best fit between the data measured in the field and the data of the calculated (predictive) model, with the objective of minimizing the mean difference between them, called root mean square (RMS), as described by Loke, 2004.

Finally, a 3D representation was elaborated by the ZondRes2D software from the integration of data from the modeled sections, which made possible to present the electrical resistivities at a specific depth, from which it was possible to estimate the scope of the impacted area and define the regions associated with the greater presence of fuel, according to the anomalies of higher electrical resistivities.

RESULTS AND DISCUSSIONS

As a result of the geophysical survey carried out, the main electrical resistivity sections obtained are presented below (Figures 10 to 16). The choice criterion was the positioning upstream of the line (L02) and the proximity to the existing extraction wells (L04, L06, L07, L09, L10 and L11).

In the electrical sections presented here, it was verified resistivities numerically varying from low values to hundreds of ohm.m units were verified. In this way, it was possible to establish three ranges of electrical resistivity variation: low, intermediate and higher; the first two correlated to certain natural geological materials previewed for the site (clayey and silty soil), and the last, numerically greater, associated to the underground contamination by fuel.

In the comparative analysis, the presented information in section L02 (Figure 10) was adopted as reference, which expresses the natural variations of the electrical resistivities (background), with homogeneous patterns and more horizontal features, correlated only with the presence of clay and silt and free from the effects of fuel contamination. These patterns are very different from the ones observed in the other sections (Figures 11 to 16), where disturbances of the geophysical signal are evident, indicating heterogeneities in the environment, with anomalous regions of higher resistivity, interpreted here as possible free phase in the groundwater or residual phase in the unsaturated zone.

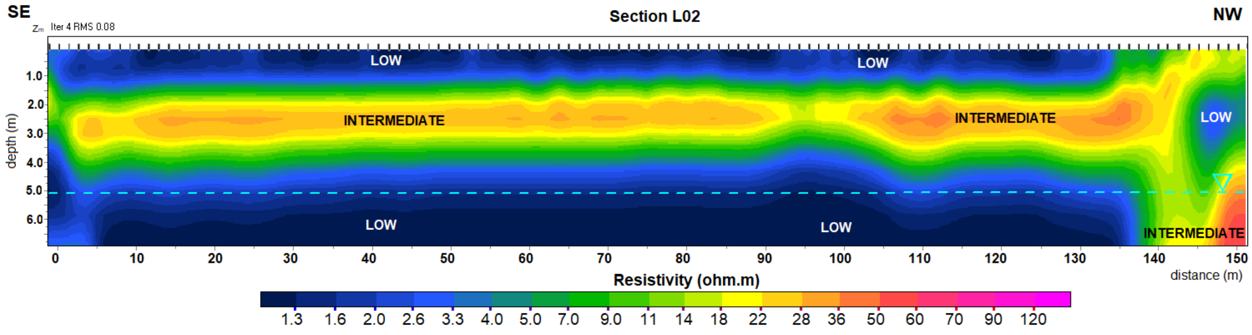

Figure 10: Resistivity section of Line L02 (background).

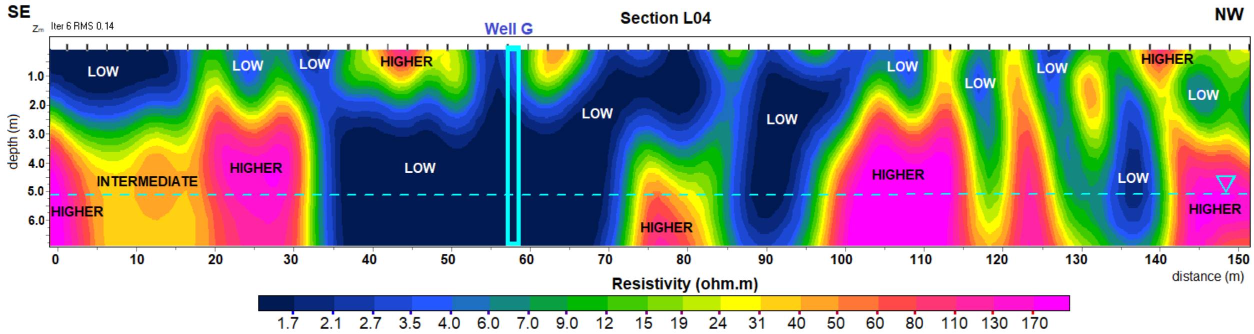

Figure 11: Resistivity section of Line L04.

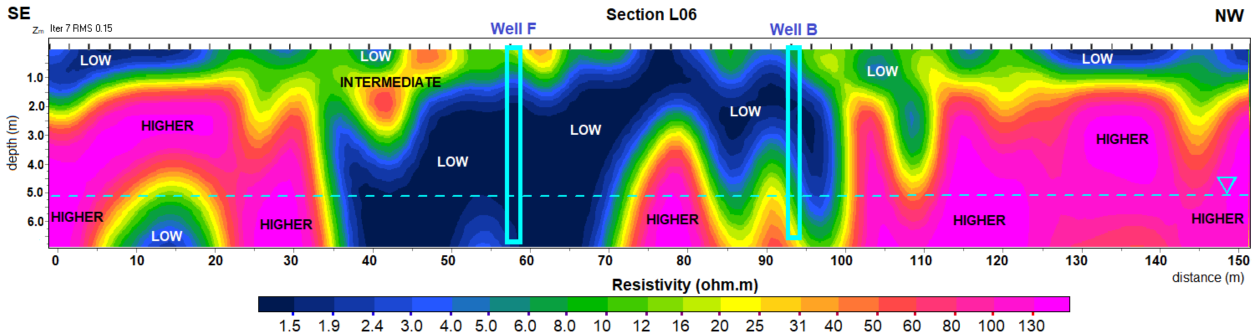

Figure 12: Resistivity section of Line 06.

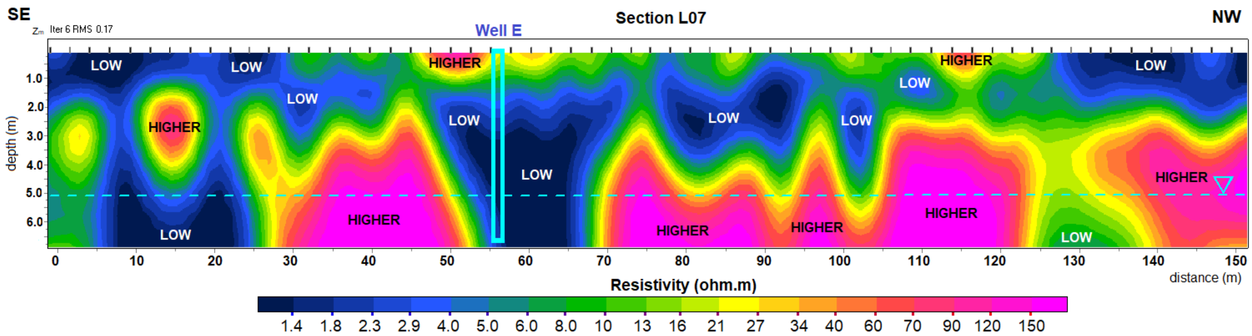

Figure 13: Resistivity section of Line 07.

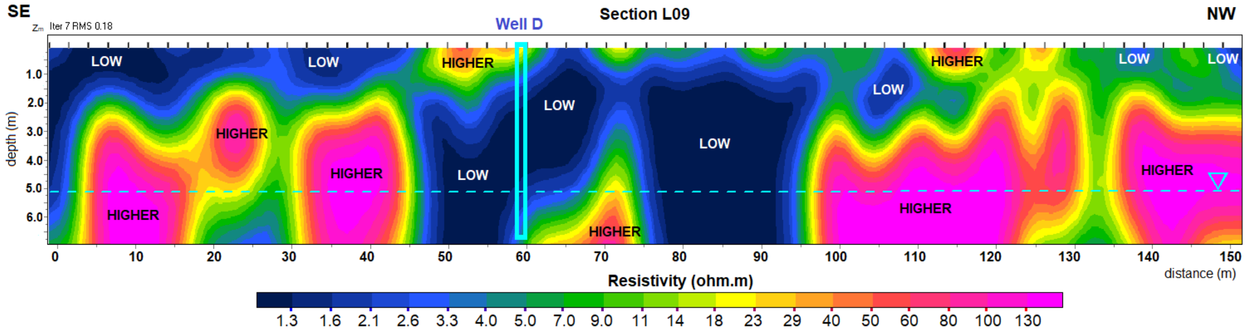

Figure 14: Resistivity section of Line 09.

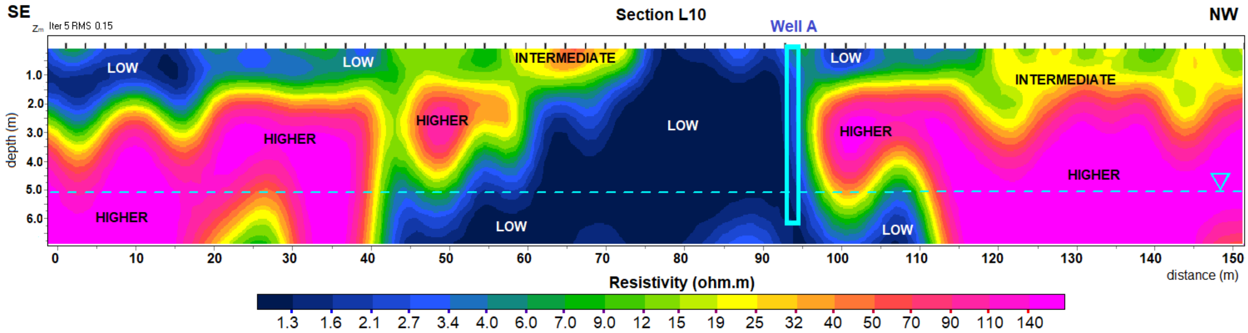

Figure 15: Resistivity section of Line L10.

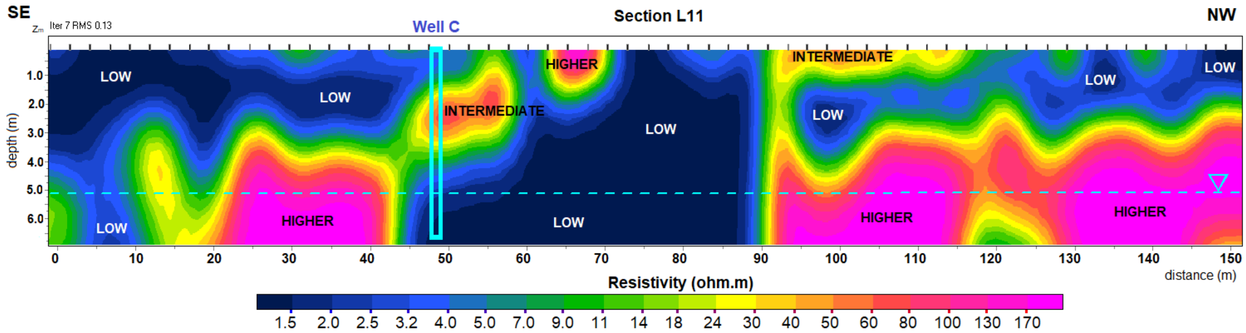

Figure 16: Resistivity section of Line 11.

As for the higher resistivity anomalies defined in sections L04, L06, L07, L09, L10 and L11 as the free or residual fuel phases, they are generally discontinuous, which may reflect the effects of groundwater pumping actions that were taking place at the time of the geophysical survey and that probably have cut the contamination plumes that previously existed.

These discontinuities are more marked in the central portions of the sections, where zones of low electrical resistivity are observed, thus indicating the tendency to return to the values and natural conditions of the underground environment when there is the removal of the product. This is because, in these places, the extraction activities were developed more intensively through the existing pumping wells (A, B, C, D, E, F and G).

It is verified that the positions of all product extraction wells indicated in sections L4, L6, L7, L9, L10 and L11 are located in portions where electrical resistivities are low; therefore, outside the foci of higher resistivity related to probable fuel free phase.

Thus, it is possible to infer that, if the aforementioned extraction wells were effective in removing contamination in the past, they were inadequately located on the date of the geophysical survey in relation to the eventual free phase plume, demanding their relocations to points of higher electrical resistivity in order to promote greater efficiency in the remediation of the still impacted environment.

From the information obtained in the sections, it was possible to establish three electrical resistivity intervals: the lowest two representing lithological materials and the highest one associated with fuel contamination, which are presented in sequence in Table 2.

The electrical resistivity data obtained in the sections were integrated for representation in 3D (Figure 17) and in depth cut maps (Figures 18, 19 and 20), in order to visualize in plan the coverage and the foci of greater presence of free phase of fuel according to the highest resistivity values measured in the investigated area.

Thus, the cut maps of depths of 1.0, 2.5 and 6.0 m are presented below (Figures 18, 19 and 20). The first two represent the unsaturated zone and the last one shows the location of the top of the saturated zone.

The cut maps at depths of 1.0 and 2.5 m (Figures 18 and 19) represent the distribution of electrical resistivities in the shallowest portions and, therefore, in the unsaturated zone. In the first map (Figure 18), the points of greatest resistivity are restricted and are located closer to the central region, where there was a leak in the fuel supply lines. The second map, a little deeper than the previous one, points to a greater scattering of points of greater electrical resistivity, predominantly in the eastern and western portions that, probably, represent the residual phase still remaining in the gas station area.

Both maps of Figures 18 and 19 have very different aspects than the one presented by the 6.0 m depth cut map (Figure 20), whose high electrical resistivity zones are much more evident and continuous and indicate the scan results from the top of the saturated zone.

The map of Figure 20 presents two main anomalous zones of higher electrical resistivities on the flanks of the evaluated area, which are the east and west regions, of about 2,000 and 2,900 m^2 respectively. The coverages of this area represent almost 42% of the dimension investigated and point to probable sources of free phase fuel (plumes), in contrast to a central region with low electrical resistivities where remediation procedures by pumping and extracting product were implemented more intensively at the points A, B, C, D, E, F and G.

In relation to the extension of anomalous zones of higher electrical resistivities to the east and west outside the limits of the gas station in Figure 20, this feature indicates the tendency of migration of eventual plumes of contamination, in accordance with the local topography, towards the lake and existing drainages, as pointed out earlier.

These results also show that most of the monitoring wells remaining at the site are not positioned over anomalous zones of higher electrical resistivity and, therefore, their locations do not meet the needs of monitoring the free phase present and the correct delimitation of their extension.

It is verified that the contours of the free phase plume of the extraction wells, plotted in Figure 20, do not coincide with the result presented in this geophysical survey, which points to a much greater coverage of anomalies of higher resistivities, associated with the organic contamination still present, mainly in the eastern and western regions.

It is possible to notice that the extraction wells (A, B, C, D, E, F and G) are located in points of lower electrical resistivity, where there is a tendency to return to the natural electrical conditions of the environment after the removal of the product, more noticeable in the central region of the gas station, which justifies the loss of efficiency of the remediation recently verified in this area.

Table 2: Electrical resistivity ranges and other section information.

Section	Low resistivities (ohm.m)	Intermediate resistivities (ohm.m)	Higher resistivities (ohm.m)	Extraction wells	Free phase thickness in the extraction wells	Number of iterations	RMS
L02	1.3 to 22.0	22.0 to 70.0	-	-	-	4	0.08
L04	1.7 to 19.0	19.0 to 50.0	> 50.0	G	2.0 cm	6	0.14
L06	1.5 to 20.0	20.0 to 80.0	> 80.0	B and F	both 9.0 cm	7	0.15
L07	1.4 to 21.0	21.0 to 60.0	> 60.0	E	10.0 cm	6	0.17
L09	1.3 to 23.0	23.0 to 50.0	> 50.0	D	6.0 cm	7	0.18
L10	1.3 to 19.0	19.0 to 70.0	> 70.0	A	4.0 cm	5	0.15
L11	1.5 to 18.0	18.0 to 80.0	> 80.0	C	2.0 cm	7	0.13

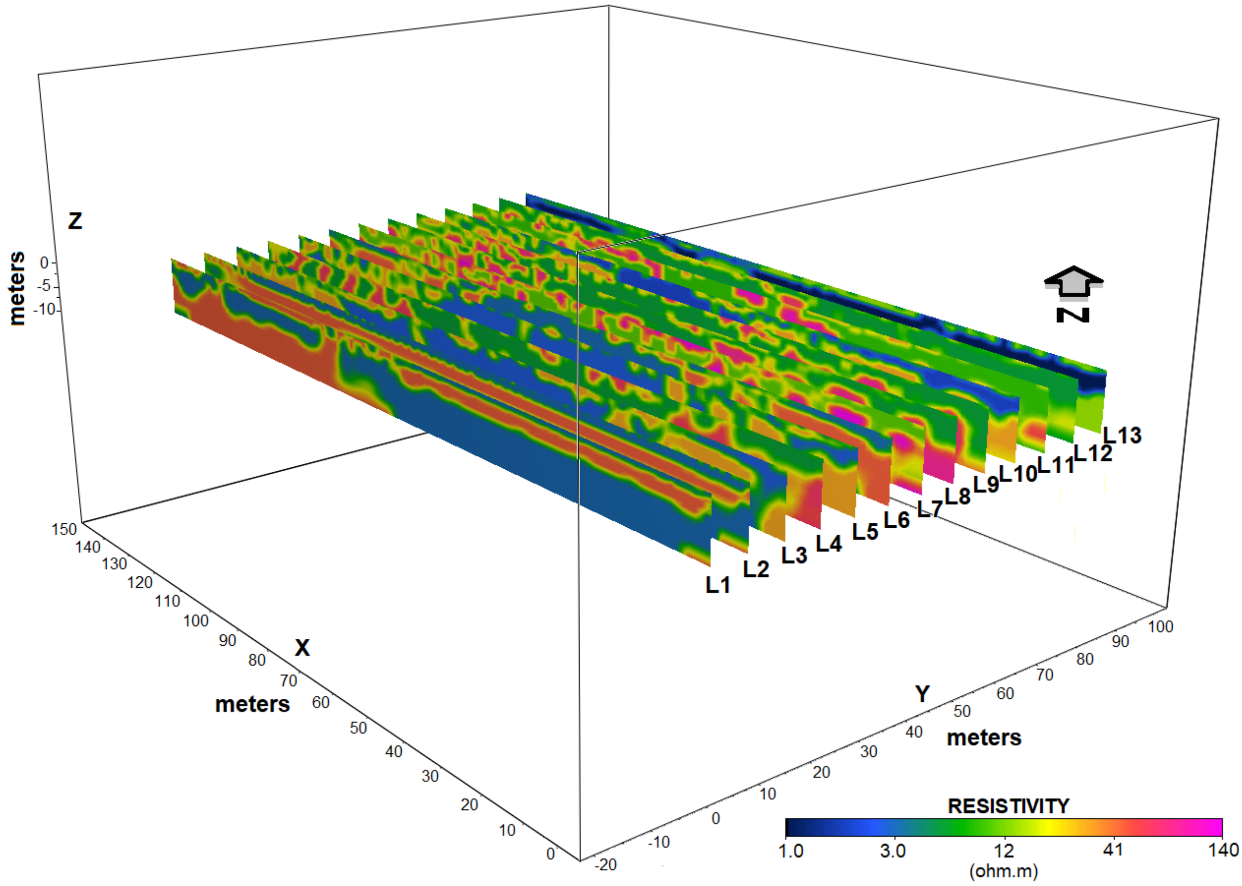

Figure 17: Representation of the resistivity sections in 3D.

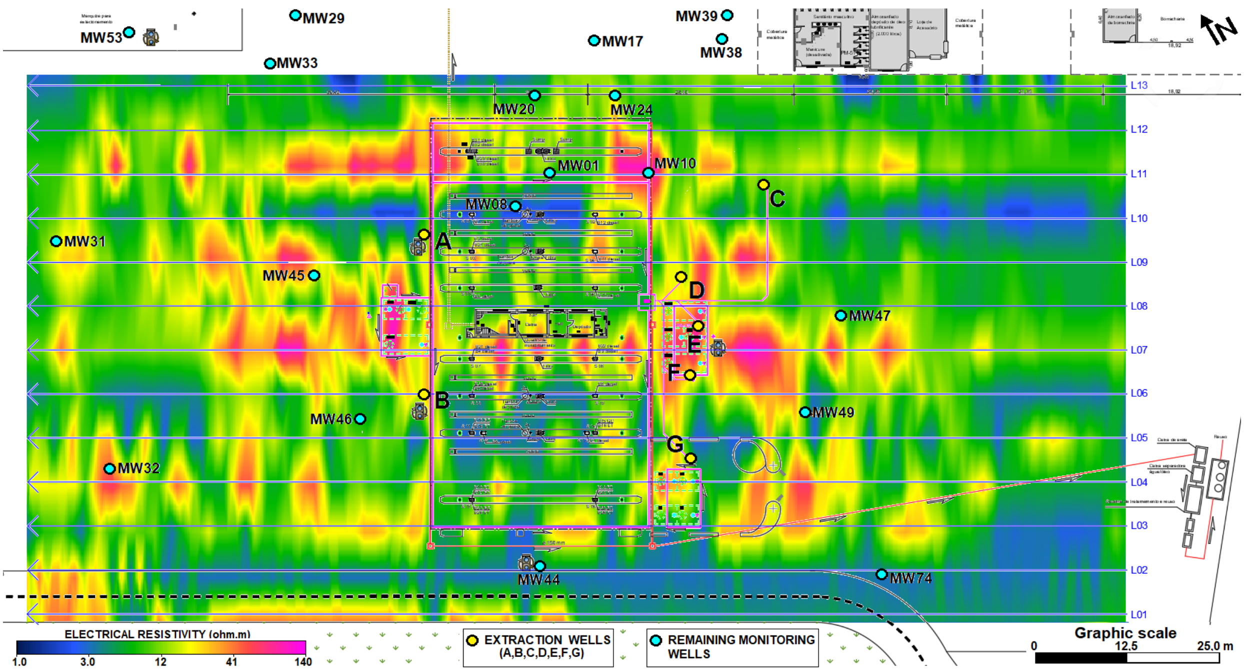

Figure 18: Map of the electrical resistivity at a depth of 1.0 m.

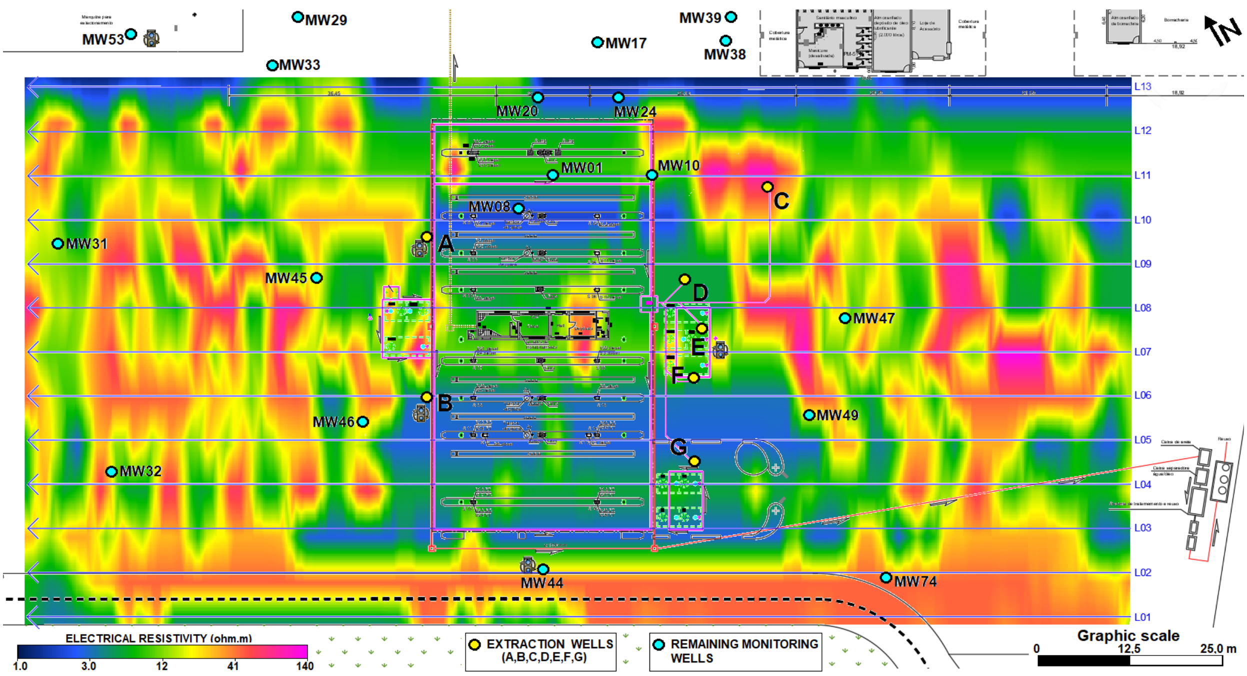

Figure 19: Map of the electrical resistivity at a depth of 2.5 m.

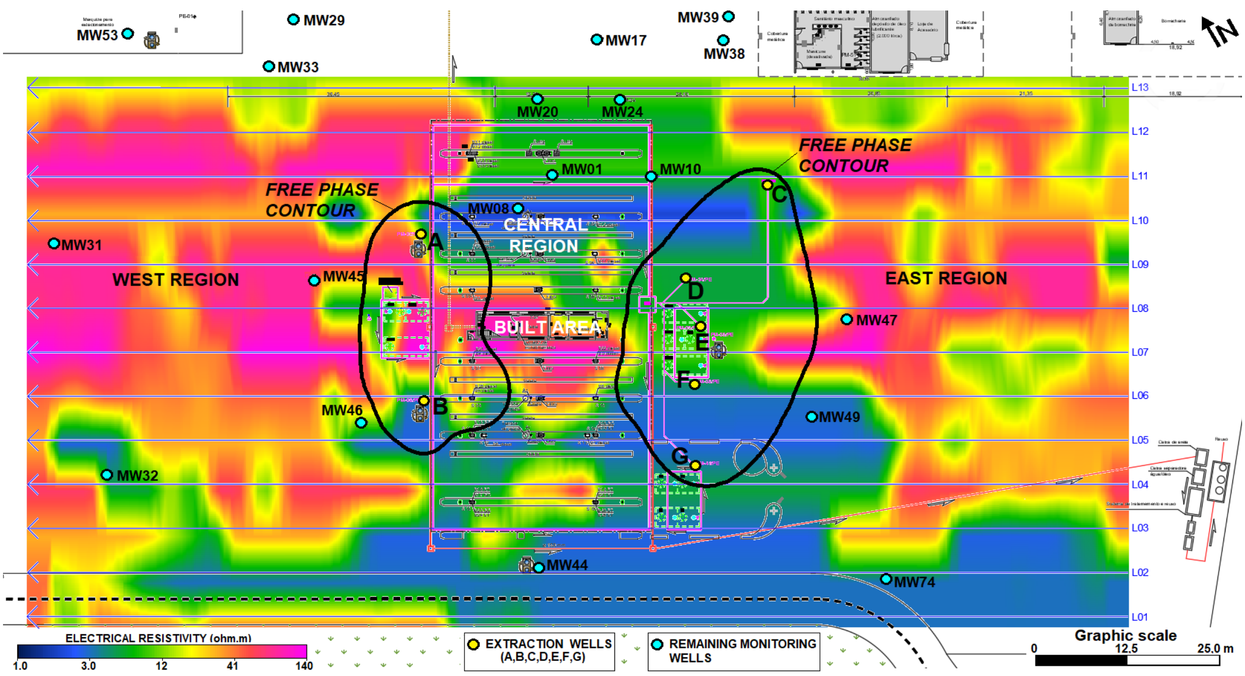

Figure 20: Map of the electrical resistivity at a depth of 6.0 m.

Therefore, it is recommended to change the environmental management actions in relation to the monitoring and pumping of contaminated groundwater such as installing more extraction wells in the anomalous portions of higher resistivity to the east and west and increasing the number of monitoring wells to observe the spread of underground contamination.

CONCLUSIONS

The results of applying the Capacitive Resistivity method confirmed the finding of higher electrical resistivities predicted from a relatively recent leakage event and associated with the underground presence of fuel free phase, which anomalously increases the values of the natural resistivities of the environment, and thus indicates the potential of this method in the identification of contrasts in the physical properties for the diagnosis of the presence of organic and non-degraded contamination.

The information obtained by the geophysical method in question initially indicated that the remediation by multiphase extraction presented satisfactory results, due to the low resistivities verified in the central region of the gas station where the pumping wells are positioned, and, therefore, demonstrate the tendency of the geological environment to return to its natural electrical condition after the removal of the organic contaminant from the groundwater.

On the other hand, on the date the geophysical survey was carried out, these results show that the extraction wells still in operation were no longer adequately located for the removal of the eventual free phase of the product remaining in the area, which explains the loss of efficiency of the remediation works that was observed in that specific region, demanding that their positions be changed according to the foci of greater electrical resistivity observed in this work, or that new pumping wells be installed in the places of more intense geophysical anomalies.

Thus, from the high resolution of the data obtained, the ability to identify anomalous changes in electrical resistivity of the soil related to the presence of fuels and the results expressed in this work, it is possible to conclude that the geophysical method of Capacitive Resistivity can be used in similar events of leaks of underground storage tanks (USTs) from gas stations for diagnosis of contamination, especially when preliminary information is restricted, contributing to an understanding closer to reality and to guide decision-making related to environmental management.

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