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França Aquino, Wagner; Tonello, Paulo Sérgio; Rebelo Resende, Pedro

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EXPERIMENTATION AND INDIRECT METHODS APPLIED TO INVESTIGATE THE CONTAMINATED AREAS

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Wagner França Aquino[1]; Paulo Sérgio Tonello[2]; Pedro Rebelo Resende[3]

ABSTRACT: This article presents definitions and geophysical methodologies based on the experimental method, as well as its characteristics, variables and potentialities, applied in the investigation of the underground contamination by several contaminants. The methodological concepts and applications on the Environmental Geophysics are approached for investigation of contaminated areas and potential sources of contamination based on the bibliography of the last 20 years, in addition to national and international norms. The importance of this article is due to the need to update technical texts, since the Manual of Contaminated Areas of CETESB, the main thematic reference, completes almost two decades of publication, being unavailable for consultations. Protocols are presented for the application of geophysical methods considering which contaminants features and limitations for each purpose. Besides that, theoretical aspects of the experimental methodology based on the different geophysical methods applied to environmental studies are presented, as well as examples that are constituted in cases where the methodology was successfully employed and contributed to the diagnosis of contamination underground and represent investigative parameters. Experimental methods applied to environmental geophysics are adequate for sustainability, because they involve innovative, non-invasive and unaltered technologies in the investigated environment, being often the only alternative of initial diagnosis in the suspected contaminated area.

KEYWORDS: environmental geophysics; geophysical methods; contaminated areas.

RESUMO: O presente artigo tem por objetivo principal apresentar as diferentes metodologias geofísicas, suas definições, características e potencialidades, exemplificando quais seriam os mais adequados métodos para cada tipo de situação envolvida na investigação da contaminação subterrânea. No desenvolvimento do texto, é abordada a temática de áreas contaminadas e suas fontes de contaminação, os termos conceituais da metodologia geofísica, o histórico no Brasil dos estudos ambientais para investigação da qualidade do solo e água subterrânea, o enquadramento da Geofísica Ambiental no Gerenciamento de Áreas Contaminadas e apontamentos quanto às normas de referência nacionais e internacionais sobre a aplicação dos métodos geofísicos em estudos de contaminação subterrânea. Além disso, são apresentados os aspectos teóricos em que se fundamentam os métodos geofísicos aplicados aos estudos ambientais, bem como exemplos de aplicação e que se constituem em casos onde a metodologia foi empregada com sucesso e contribuiu de forma relevante para o diagnóstico ambiental dos locais investigados. A relevância deste tipo de divulgação, além do aspecto de apresentação dos métodos geofísicos e de sua importância para diferentes profissionais da área ambiental, também traduz a necessidade de atualização dos textos técnicos sobre o tema, haja vista que o Manual de Áreas Contaminadas da CETESB, que é a referência principal que congrega os métodos aqui descritos, já completa quase duas décadas de sua publicação e, atualmente, não está disponível para consultas. Ao final deste artigo técnico, são apresentadas tabelas orientativas quanto à aplicação dos métodos geofísicos para a detecção de contaminação por diversos tipos de contaminantes, e referente à influência do material geológico local e relativa às características, potencialidades e limitações dos métodos geofísicos aqui abordados.

PALAVRAS-CHAVE: geofísica ambiental; métodos geofísicos; áreas contaminadas.

RESUMEN: Este artículo presenta definiciones y metodologías geofísicas basadas en el método experimental, así como sus características, variables y potencialidades, aplicadas en la práctica de investigación de la contaminación subterránea por varios contaminantes. Se abordan los conceptos metodológicos y las aplicaciones sobre el geofísico ambiental para investigar las áreas contaminadas y las posibles fuentes de contaminación basadas en la bibliografía de los últimos 20 años, además de las normas nacionales y internacionales. La importancia del presente surge de la necesidad de actualizar los textos técnicos, ya que el manual de áreas contaminadas de CETESB, la principal referencia temática, completa casi dos décadas de publicación. Se presentan protocolos para la aplicación de métodos geofísicos teniendo en cuenta qué contaminantes, características y limitaciones para cada propósito además de los aspectos teóricos de la metodología experimental basados en los diferentes métodos geofísicos aplicados a los estudios medioambientales, así como ejemplos que constituyen casos en los que la metodología fue empleada con éxito y contribuyó al diagnóstico de contaminación subterránea. Los métodos experimentales aplicados a la geofísica ambiental son adecuados para la sostenibilidad, ya que implican tecnologías innovadoras, no invasivas e inalteradas en el entorno investigado, siendo a menudo la única alternativa del diagnóstico inicial en un área sospecha de contaminación.

PALABRAS-CLAVE: geofísica ambiental; métodos geofísicos; áreas contaminadas.

1 Wagner França Aquino, Doutorando pela Universidade Estadual Paulista – UNESP, Programa de Pós-graduação em Ciências Ambientais - Instituto de Ciência e Tecnologia de Sorocaba - UNESP. E-mail: wagnergpr@gmail.com

2 Paulo Sérgio Tonello, Doutor pela Universidade Estadual Paulista – UNESP, Programa de Pós-graduação em Ciências Ambientais - Instituto de Ciência e Tecnologia de Sorocaba – UNESP,. E-mail: paulo.tonello@unesp.br

3 Pedro Rebelo Resende, Doutor pela Faculdade de Engenharia da Universidade do Porto – FEUP. Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (INEGI) – FEUP. E-mail: presende@inegi.up.pt

1. INTRODUCTION

According to the World Health Organization (WHO), the growing trend of the problem, related to solid waste, has been emerging as a serious contemporary environmental problem. Inadequate management of urban solid waste directly generates other important impacts, both environmental and health of the population (WHO, 2007). The inadequate final destination of solid domestic, industrial or even health-care waste has been one of the main environmental problems that has been faced in recent years, and there is no waste management plan, together with the lack of specific more stringent legislation in the recent past, have led to the use of harmful actions on the environment, specifically with regard to soil and groundwater quality, as pointed out by Kist, Rosa, Moraes and Machado (2018).

According to Gouveia (2012), much of the waste produced still does not have an adequate sanitary destination, despite progress in the last twenty years, waste is still deposited in open air, the so-called dumps, present in more than half of the municipalities Brazilians. The percentage of municipalities that use controlled landfills, where the waste is only covered by land, remained practically unchanged between 2000 and 2008, and there was an increase in the destination for landfills, which use specific technology in order to minimize environmental impacts and damages or risks to human health. Solid waste can compromise soil, water and air quality because they are sources of volatile organic compounds, pesticides, solvents and heavy metals, among others (Giusti, 2009).

In addition, decomposition of the organic matter present in the domestic waste results in the formation of a dark liquid, the leachate, which can contaminate the soil and surface or groundwater by contamination of the groundwater (Gouveia, 2012).

In addition to these environmentally damaging procedures, clandestine waste disposal occurs without the knowledge of the public agencies responsible for environmental control and inspection. This situation is also exacerbated by the environmental impact established after the decommissioning of some industrial plants and, in addition to the risks to the near population, demand high resources to be spent on their rehabilitation (Salinas, 2015).

In this context, it is also important to indicate the negative environmental effects that leakages in gas stations have caused (Lima et al., 2017), and that residues in the agricultural activity can generate to the plantation areas (Souza et al., 2018), as well as the subterranean contamination by leachate from decomposition of bodies and materials buried in cemeteries (Silva, 2018).

Especially in the urban areas of large metropolitan areas, where there is a growing need for soil reuse for different purposes, the environmental impacts caused by underground contamination have generated so-called Contaminated Areas, which according to the Environmental Company of the State of São Paulo (CETESB) reached 6,110 in the year 2018, in the State, and are defined by State Decree n. 59.263, dated June 5, 2013, as: "*area, land, local, installation, edification or improvement containing quantities or concentrations of material under conditions which cause or are likely to cause harm to human health, to the environment or another good to protect* ". The management of Contaminated Areas is also provided for in the aforementioned Decree and regulates Law n. 13,577 published on July 8, 2009, which deals with the protection of soil quality against harmful contamination changes, definition of responsibilities, identification and registration of contaminated areas and rehabilitation of these areas to make safe your current and future uses.

Cortes, Alves, Ruiz and Teixeira (2011) reported that the absence of planning in waste management can have important consequences not only for the environment but also for business continuity, being of great importance the identification, evaluation and management of environmental passives. In view of the need for environmental preservation, the development of public policies and the improvement of legal demands are becoming more and more frequent. Thus, the degradation of soil and groundwater quality, both by industrial contamination and by irregular waste discards, becomes a public health issue with social impact, and its consequences must be investigated in order to evaluate the extent and impacts on the environment.

In this context, the application of geophysical methods based on the experimental methodology for the evaluation of soil and groundwater contamination has been developing in a significant way in recent years, both by the demand from industries or environmental consulting companies, as well as by the requirements of research institutions and environmental control, since the increasing adoption of non-invasive technologies, is justified by the efficiency and speed that these methods present to diagnose the presence of contaminants in subsurface. It is emphasized here that, often, periodic geophysical surveys are the only way to establish the monitoring of the spread of the present contamination, mainly in abandoned industrial areas and that need a systematic environmental control, and where the figure of the polluting agent, responsible for diagnosis and remediation, is difficult to determine (Aquino, 2000).

For this purpose, the present study proposes the following research question: what are the models of experimental research and non-invasive geophysical methods applied to the diagnosis of contaminated areas? Therefore, this article discusses how experimental research can be applied in practice in geophysical surveys, as a strategy used in the presumptive diagnosis of the presence of contaminants in suspected or proven contaminated areas and to present practical examples of technologies applied for the diagnosis in areas suspected of contamination, or in defining the extent of subterranean contamination in contaminated sites.

2. EXPERIMENTAL RESEARCH AND GEOPHYSICAL METHODS APPLIED TO ENVIRONMENTAL INVESTIGATIONS

According to Martins and Theóphilo (2009) the experiment is a research strategy of positivist orientation and that seeks the construction of knowledge through verification and guarantee of scientifically proven results, that is, knowledge acquired under conditions of control, legitimized by experimentation and verified by the levels of significance of the measurements. The experiments can control the variables whose effects are to be studied, even the strange variables, since they can be controlled if they are kept constant. Therefore, the experiments are studies that best fit the purpose of identifying causal relations between variables, being intensively used in natural science investigations such as sociology, psychology, physics, chemistry, biology, medicine, etc., as a process of observation made in a planned situation, in such a way to meet what was proposed.

Experimental research is planned with manipulation and controlled testing to understand causal processes (Blakstad, 2014). Generally, one or more variables are manipulated to determine their effect on a dependent variable. The experimental method is a systematic and scientific approach to research in which the researcher manipulates one or more variables, and controls and measures any change in the other variables (Wilson & Shuttleworth, 2014). Experimental research is often used where (Shuttleworth, 2014; Wilson, 2014):

- ✓ There is a temporal priority in a causal relation (cause precedes the effect);
- ✓ There is consistency in a causal relationship (a cause will always lead to the same effect);
- ✓ The magnitude of the correlation is high.

As for its definition, the geophysical methods are indirect methodologies of underground research, based on the acquisition of instrumental data on the surface, and are thus characterized as non-invasive or non-destructive methods (Reynolds, 2011), allowing to evaluate the local geological conditions through the contrasts of the different physical properties of the subsurface materials, for example, as conductivity or electrical resistivity, dielectric permittivity, magnetism, density, etc., and which may originate from lithological heterogeneities and other natural changes or not. When discussing the application of Geophysics, an important question refers to the different terminologies related to the definition of method, technique and arrangement. Thus, adapting the classification proposed by Braga (2006), it is considered here:

- Method: applied geophysical methodology as a function of the measured physical parameter (eg Ground Penetrating Radar, Inductive Electromagnetic Method, Electrical Resistivity Method, etc.);
- Technique: type of field research for the application of the geophysical method, with horizontal and / or vertical measurement of the terrain (eg horizontal profiling, geophysical sounding, well profiling);
- Arrangement: arrangement of the emitters and receivers of the geophysical signal in the development of the field technique (eg common off set, dipole-dipole, vertical magnetic dipole, etc.).

Conceptually, Environmental Geophysics is associated to the area of application of Geophysics to evaluate the harmful effects caused to the geological environment by the action of certain agents in subsurface, and Greenhouse (1991) and Steeples (1991) define it as the application of geophysical methods for investigations of shallow biophysical-chemical phenomena that have implications for the environmental management of a site. From this premise, geophysical methods can be used in two large fields of application in environmental problem studies: first, the diagnosis of the effects caused to the physical environment in degradation events, such as erosion and silting processes, among others, and a second objective particularly focused on the investigation of environmental impacts caused by underground contamination, subject of this article. The speed, precision, versatility and relatively low cost also allow applications of geophysical techniques in the remediation and monitoring stages of contaminated areas (Moreira, Aquino, & Dourado, 2007).

In Brazil, the application of Environmental Geophysics to studies of underground contamination began in the second half of the 1980s through academic cooperation between the University of Waterloo (Canada) and the Center for Underground Water Research (CEPAS) of the University of São Paulo (USP). At this time, Ellert, Greenhouse, Williams, Mendes and Hassuda (1986) and Mendes (1987) used the Electromagnetic Inductive Method associated with the electrical resistivity measures of the terrain, to evaluate the impacts caused to groundwater by different sources of contamination, such as landfills, cemeteries, and places with inadequate waste disposal.

Simultaneously to these initial studies, José and Ellert (1989) performed Inductive Electromagnetic surveys to identify the contamination coming from landfill of domestic waste, with correction of measured data of electrical conductivity as a function of the variation of the depth of the water level.

From these pioneer surveys, others were followed, in order to determine the presence of contamination by different sources, such as the research carried out by Costa and Ferlin (1993) using the Electromagnetic Inductive and Electrical Resistivity Method in tannery waste disposal area, and by Lima and Sato (1993) applying electrical resistivity measures to evaluate the contamination of aquifers in petrochemical complex, which have also been succeeded by several works, thus consolidating the applications of Environmental Geophysics.

2.1 ENVIRONMENTAL GEOPHYSICS IN CONTAMINATED AREAS

The application of geophysical methods in the investigation of Contaminated Areas consists of the local condition evaluation, in relation both to the existing contamination, as well as the possible dynamic processes of the contaminant migration through the geological environment, contributing to a better knowledge of the environmental impacts caused.

In general, the results of the geophysical investigation in the diagnosis of underground contamination show graphs with the variation of the measurements (profiles), vertical sections of the subsoil (sections) and intensity maps of the readings (plants), allowing to elaborate virtual models and to individualize the presence of underground tanks, buried drums, soil contamination and plumes in groundwater, trenches with waste and other environmental features of interest.

In the Manual of Contaminated Areas of CETESB (2001), the geophysical methodology is presented in an exclusive chapter, being classified as screening methods, that is preliminary methods of scanning, which, when applied to the environmental diagnosis of underground contamination, has as basic objective the identification of the contaminants presence in subsurface, besides the definition of the geological and hydrogeological features of the regions investigated.

Due to the increasingly frequent use of Environmental Geophysics in the investigation of underground contamination, the ABNT Standard n. 15.935 (2011) was elaborated and published, which reports on the selection and environmental application of geophysical methods on the surface and wells, very generally, for the geological characterization and hydrogeological analysis of the physical environment, detection and/or delimitation of contaminants, detection of residues and buried objects, detection of trenches and delimitation of landfills and dumps.

Beyond this Brazilian standard, should be cited as a reference the content presented in standard D 6429-99 of the American Society for Testing and Materials (ASTM) of the United States, reissued and approved in 2006, and has several other standards inserted in its text, with the objective of providing a detailed guide to the selection and use of surface geophysical methods applied in geological, geotechnical, hydrological and environmental investigations, and the Guide of the Environmental Protection Agency (1993) describing the geophysical techniques for aerial and surface surveys, besides wells surveys, applied to the contaminated areas.

Compared to traditional methods of subsurface research, such as drilling for example, one of the main advantages of applying the geophysical methodology is the speed in the evaluation of large areas with relatively lower cost. In addition, geophysical surveys allow the execution of continuous profiles, making it possible to identify with greater accuracy the lateral variations resulting from the lithological changes or originated by the presence of underground contamination (Greenhouse, 1996).

The characteristics of the geological environment, besides the nature of the contamination, can determine the contaminants behavior in subsurface. In this context, the interpretation of the geophysical data can contribute to obtain information on the type of soil or rock, stratigraphy, depth of water level, depth of the rock basement, presence of faults or fractures, existence of important aquifers, underground propagation and other geological features of interest (CETESB, 2001).

In the assessment of the presence of subsurface contamination, the use of geophysical methods is focused specifically on the location of trenches containing waste, investigation of contamination in soil and groundwater, detection of tanks or drums buried, and determination of leaks from tanks or pipelines (Aquino, 2000).

According to Greenhouse (1991), the application of two or more distinct geophysical methods increases the precision of the interpretations, minimizing the ambiguities in the interpretation of the results, and the nature of the contaminants and the local geology, in this order, are the decisive factors in the selection of the geophysical techniques to be used.

In relation to geophysical measurements, the significant deviations from the normal standard of values constitute the anomalies and, from the environmental point of view, may indicate the presence of contaminants in subsurface. The interpretation of the geophysical anomalies is of fundamental importance in the investigation of Contaminated Areas, since their intensities have a direct relation with the concentrations of the contamination, besides being useful in the orientation of the subsequent works to monitor the propagation of contaminants and recovery of affected regions (Gretsky, Barbour, & Asimenios, 1990).

Information obtained from geophysical surveys is useful for the location of monitoring wells, but can also provide area and volume estimates for the removal and remediation of contaminated soils. In addition, they may be applied at the phase of investigation of a contaminated region to reduce the risk of drilling of buried drums containing waste, or of underground ducts and galleries. Thus, the geophysical surveys can be carried out in the different stages of activities established for the Management of Contaminated Areas (CETESB, 2001) and can be described as follows:

- Preliminary Investigation: the geophysical methodology can be used to detect pipes or underground galleries in the suspected area (interferences mapping);
- Confirmatory Investigation: geophysical methods are used as screening methods to locate the most appropriate sampling points by determining anomalies that represent zones with the highest concentrations of contaminants (hot spots);
- Detailed Investigation and Investigation for Remediation: geophysical methods can be used to map and monitor the propagation of contamination;
- Remediation Phase of Contaminated Area: these methods can be applied in the evaluation of the efficiency of the recovery works by confirming the reductions in contaminant concentrations.

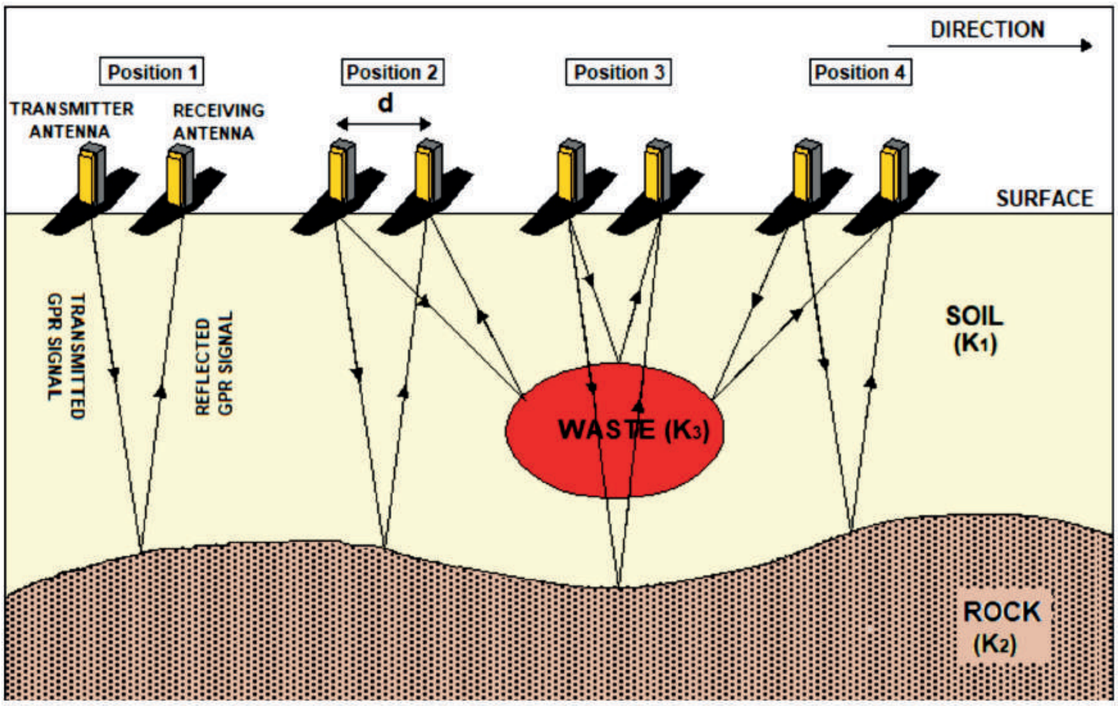
3. METHODOLOGY

3.1 EXPERIMENTAL METHODS FOR STUDIES OF UNDERGROUND CONTAMINATION

There are a variety of geophysical methods that can be used in environmental studies, but the main and most appropriate methods applied to soil and groundwater contamination research are the GPR (or Geo-radar), Inductive Electromagnetic (EM) and Electrical Resistivity (ER), which are electrical methods and are classified as active, because they artificially generate signals transmitted to the subsurface where they are modified according to the characteristics of the environment they cross, as well as the Magnetic Method (Magnetometry), which, unlike the previous ones, is a passive method to measure changes in Earth's natural magnetic field (Reynolds, 2011).

The advantage of these four previously mentioned methods in relation to other geophysical methods, is basically the ability to detect the

Figure 1. Emission and reflection of the GPR signal in subsurface



Source: Adapted from Davis & Annan (1989)

presence of underground contamination, and not only to identify the geological features of the areas under study (CETESB, 2001).

3.1.1. GROUND PENETRATING RADAR

The Ground Penetrating Radar (GPR), also called Geo-radar, is a geophysical method based on the emission, refraction and reflection of subsurface electromagnetic waves (Aquino, 2000).

The operation of this method occurs when pulses of high frequency radio waves (between 10 and 2500 MHz) are radiated to subsurface through an antenna coupled to the ground (Figure 1). Subsequently, when the signal transmitted in depth reaches bodies or strata with different dielectric permittivity (e) part of the wave reflects on these objects or interfaces, while another part propagates until the next discontinuity. The reflected electromagnetic wave is captured by a receiving antenna, the signal being amplified, digitized and stored for further processing (Davis & Annan, 1989).

It is verified, therefore, that the main factor that affects the behavior of the GPR wave in the soil is the dielectric permittivity of the medium, which is expressed by the dielectric coefficient *"K"* (dimensionless). As for the values found in the materials present in the subsurface, water presents a high value of its dielectric coefficient (*K* @ 81), when compared to those observed for the mineral grains (*K* @ 3 to 5) and that constitute the matrix of a rock, as well as to the air (*K* = 1) which can fill the pores of the rock.

Table 1 shows the values of the dielectric coefficients of some potentially contaminating substances in soil and groundwater, many of which are frequently identified in the diagnostics of contaminated areas, with emphasis on fuel hydrocarbons and organic chlorinated compounds and which, in the majority of them, have relatively low dielectric coefficients, on average between 1.8 and 3.4, increasing the values of these coefficients when the compounds pass into the group of acids, ketones and alcohols (Annan et al., 1991); API, 1993; Daniels et al., 1995).

The frequency of the signal emitted by the GPR contributes directly to a greater or lesser penetration, as well as resolution of the method (Davis & Annan, 1989). Thus, larger wavelengths (400 to 1,000MHz) allow greater resolution (greater detail) in detriment of a lower penetration, and, in the inverse form, greater depths can be achieved by signal emission at lower frequencies (25 to 100 MHz).

According to the results provided by the GPR method, the final product of field acquisition is a continuous section (distance traveled x depth), formed by a series of signals obtained at each sampling point (traces), representing a high resolution image (Davis & Annan, 1989). Through these sections it is possible to identify representative

Table 1. Dielectric coefficients of potentially contaminating substances in soil and groundwater

SUBSTANCE	K	SUBSTANCE	K	SUBSTANCE	K
Kerosene	1,8	Toluene	2,4	Methylene chloride	9,1
Hexane	1,9	Xylene	2,4	Phenols	9,9-15
Cyclohexane	2,0	Naphthalene	2,5	1- Butanol	18,0
Aviation gasoline	2,1	Polycarbonate	2,8	Methyl Ethyl Ketone	18,0
Teflon	2,1	Polystyrene	3,0	1- Propanol	20,0
Hydrocarbons	2,2	PVC	3,0	Ammonia	21,0
PCB	2,2	Trichlorethylene	3,4	Ethanol	24,0
Polypropylene	2,2	Chlorobenzene	5,6	Methanol	33,0
Carbon tetrachloride	2,2	Acetic acid	6,1	Acetone	37,0
Benzene	2,3	Tetrahydrofuran	7,5	Sulfuric acid	84,0

Source: Adapted from Annan *et al.* (1991); API (1993); Daniels *et al.* (1995).

configurations of geological, hydro-geological and environmental features in subsurface, and other structures present.

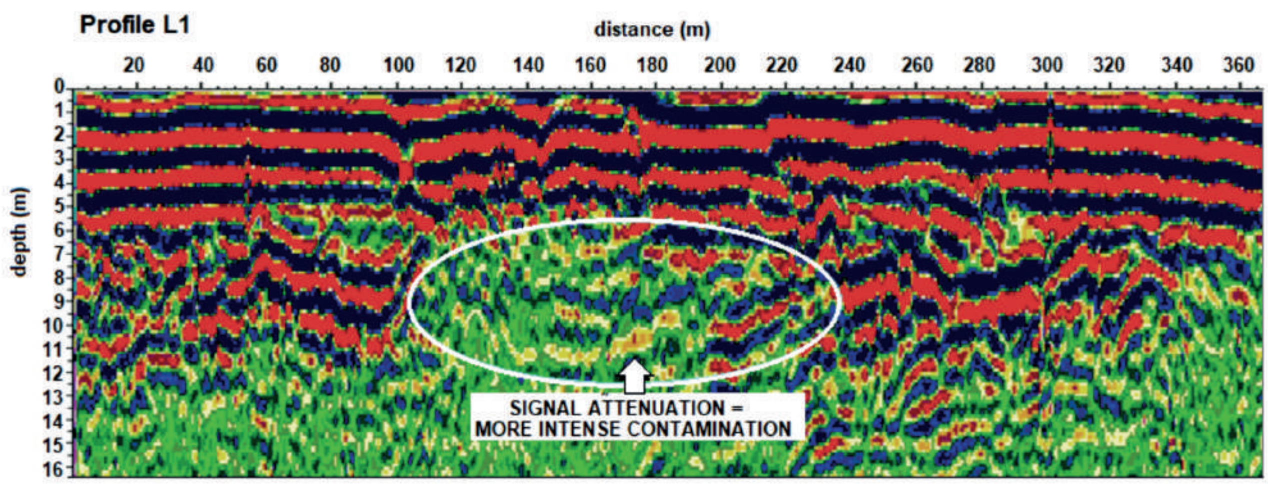
Among the geophysical methods discussed here, it is the one that presents a greater diversity of applications, not only for environmental surveys, but also to geotechnical studies, engineering, mining, forensic science, and others, because the GPR equipments can operate in several frequencies, thus diversifying their uses.

As for the applications of this method in studies of environmental passives from contaminated areas, it can mention the location of trenches with residues, detection of underground tanks of any type of material and metal/plastic drums buried, mapping of ducts and underground galleries, in addition to leakage identification in pipes and landfill, besides the investigation of organic and inorganic contamination (CETESB, 2001).

Currently, there are two types of GPR equipment available on the market: shallow structure detectors, or locators in real-time, with shielded antennas and higher operating frequencies for identification in situ of pipelines, underground boxes, tanks, buried drums and trenches shallow; and conventional equipment, with smaller frequency antennas, shielded or not, commonly used for geological, geotechnical and environmental studies at greater depths and with further processing of data.

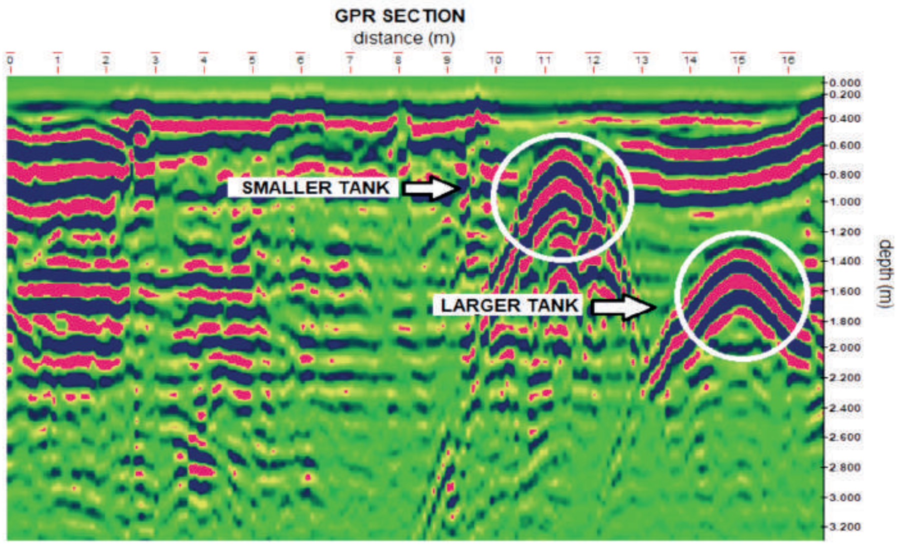
According to Aquino (2000), in GPR surveys in areas contaminated with inorganic compounds disseminated in the soil, the phenomenon of the attenuation of the electromagnetic wave is detected

Figure 2. GPR section of site contaminated by industrial waste



Source: Aquino (2000)

Figure 3. Section of GPR with location of underground tanks



Source: Geométodos Levantamentos Geofísicos Ltda (2018)

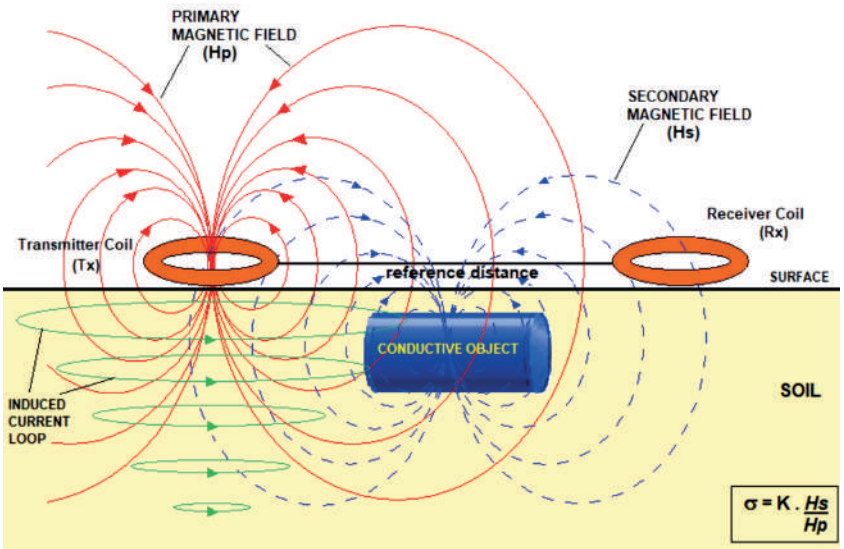
in the sections obtained as a zone of absence or decrease of the signal intensity, called "shadow zone" and, consequently, can be correlated to the presence of higher concentrations of contaminants in subsurface (Figure 2).

One of the most frequent demands in surveys using the GPR method in investigating contaminated areas is the detection of buried drums containing waste or the location of underground fuel tanks. These bodies, when cross-sectioned by a surface GPR profile, generate in the obtained section geometric configurations called diffraction hyperboles, which is an underground event in response to a buried object with limited borders when hit by the electromagnetic signal (Davis & Annan, 1989). In this way, it is possible to determine accurately the position and depth of these targets by observing the apex (inflection point) of each diffraction hyperbola generated in the GPR section, as can be seen in the example of Figure 3.

3.1.2. INDUCTIVE ELECTROMAGNETIC METHOD (EM)

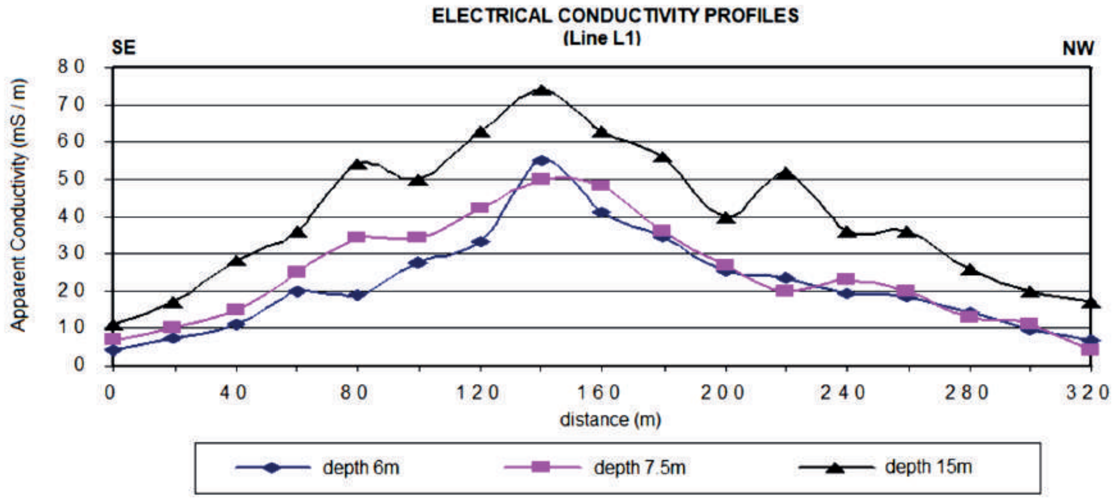
The application of the Electromagnetic Inductive (EM) method in environmental studies bases in the possibility of realizing readings of electrical conductivity of the terrain at various depths. The main advantages of this geophysical technique are the ease of data acquisition, readings at various depths, versatility of field equipment and the possibility of screening large areas in a short time. These advantages translate into rapidity and low cost (McNeill, 1980; Environmental Protection Agency [EPA], 1993; Goldstein, Benson, & Alumbaugh, 1990).

Figure 4. Principle of the Inductive Electromagnetic Method



Source: Adapted from Mcneill (1980)

Figure 5. Electrical Conductivity Profiles of different depths



Source: Aquino (2000)

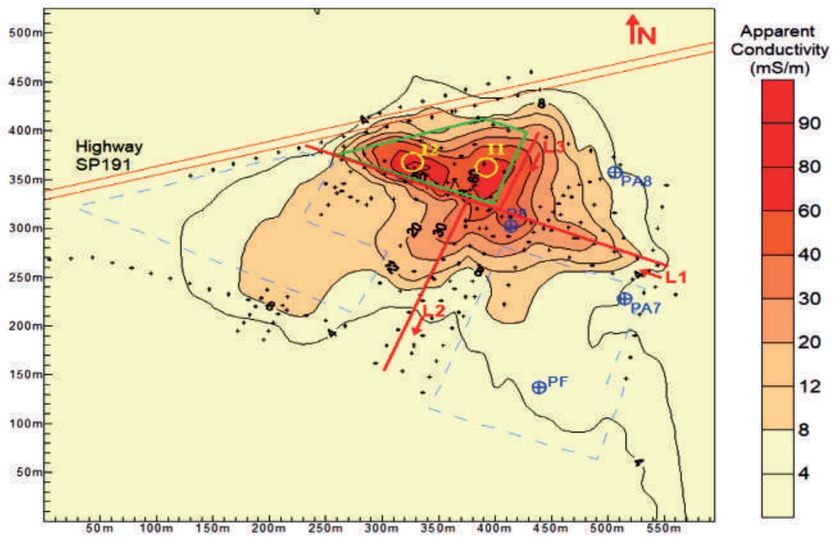
The Inductive Electromagnetic (EM) method relies on the induction of a primary electromagnetic field (Hp) to subsurface through a transmitting coil, and in the generation of a secondary electromagnetic field (Hs) in depth, which is detected on above ground receiving coil (Figure 4). In this method, the physical property measured is the electrical conductivity of the medium and that is proportional to the relation between the primary field emitted and the secondary field captured, being read in milliSiemens per meter in the equipments called conductivity meters (McNeill, 1980).

Thus, through the use of the Inductive Electromagnetic method it is possible to investigate the presence of inorganic or metallic contaminants, often from solid wastes or industrial effluents, since these compounds in contact with soil or groundwater produce an increase in concentration of free ions, thus increasing the electrical conductivity of the medium, allowing its detections (Greenhouse, 1996).

Therefore, the main applications of the Inductive Electromagnetic method in surveys of contaminated areas are the location of trenches with inorganic or metallic residues, buried metal drums and tanks, detection of underground metallic ducts and plume mapping of inorganic contamination in places of inappropriate waste disposal, such as poorly operated landfills or dumps (CETESB, 2001).

In addition to these applications, diffuse contamination in agricultural areas, due to inadequate waste or effluent disposal as reported by Souza et al. (2018), can be efficiently mapped by the Inductive Electromagnetic method and which is very fast in surveying large areas.

Figure 6. Map of Apparent Electric Conductivity Anomalies



Source: Aquino (2000)

Normally, in the acquisition of data with this method, successive measurements at constant distance intervals are performed along established profiles for recording possible lateral differences in electrical conductivity because increases in measured values may indicate the presence of contaminants in the soil (Aquino, 2000). In the other way, where there are buried metallic objects, eg tanks or drums, are required, continuous measurements can be performed for tracking and locating those targets.

As example, in the graphs of Figure 5, the behavior of the electrical conductivity at different levels of investigation of 6.0, 7.5 and 15.0 m depth in a proven contaminated area is observed, with maximum electrical conductivity value in the central part of the profile when it crosses the main focus of the plume of contamination by infiltration of industrial waste (Aquino, 2000).

Also occurring the need to visualize the hot spots of inorganic or metallic contamination on local plant, the limits of the disseminated contamination plumes and to estimate the tendency of contaminants propagation (underground flow) are elaborated electrical conductivities maps, whose larger values, according to Aquino (2000), may be associated with the location of areas with the highest concentration of contaminants in subsurface, as seen in Figure 6.

3.1.3. ELECTRICAL RESISTIVITY METHOD (ER)

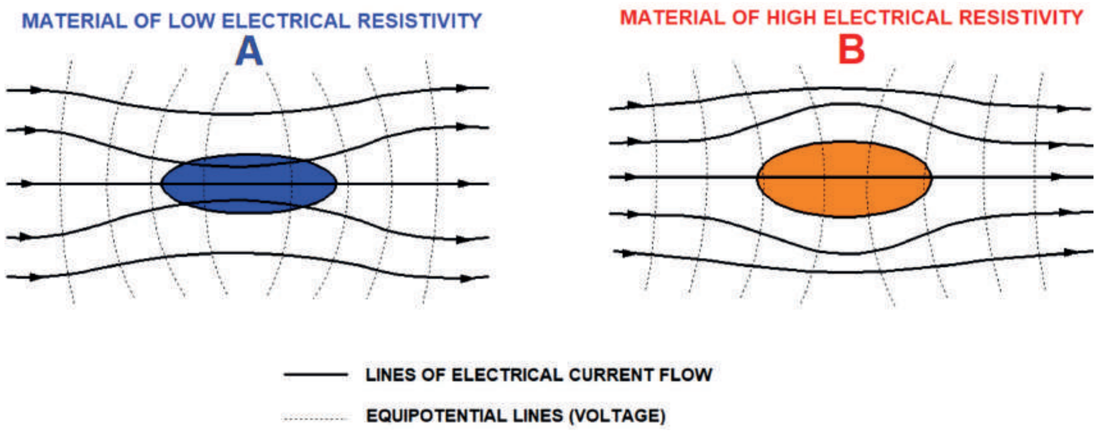
The Electrical Resistivity Method seeks to indirectly evaluate the behavior of electrical resistivity

Table 2. Electrical resistivity and conductivity of geological materials and chemical compounds

MATERIAL	ELECTRICAL RESISTIVITY (OHM.M)	ELECTRICAL CONDUCTIVITY (SIEMENS/M)
IGNEOUS AND METAMORPHIC ROCKS		
Granite	$5{,}0x10^{3}$ - 10^{6}	10^{-6} – $2{,}0x10^{-4}$
Basalt	10^{3} - 10^{6}	10^{-6} - 10^{-3}
Slate	$6{,}0x10^{2}$ – $4{,}0x10^{7}$	$2{,}5x10^{-8}$ – $1{,}7x10^{-3}$
Marble	10^{2} – $2{,}5x10^{8}$	$4{,}0x10^{-9}$ - 10^{-2}
Quartzite	10^{2} – $2{,}0x10^{8}$	$5{,}0x10^{-9}$ - 10^{-2}
SEDIMENTARY ROCKS		
Sandstone	8 – $4{,}0x10^{3}$	$2{,}5x10^{-4}$ – 0,125
Shale	20 – $2{,}0x10^{3}$	$5{,}0x10^{-4}$ – 0,05
Limestone	50 – $4{,}0x10^{2}$	$2{,}5x10^{-3}$ – 0,02
SOILS AND WATERS		
Clay	1 - 100	0,01 - 1
Alluvium	10 - 800	$1{,}25x10^{-3}$ – 0,1
Groundwater (fresh)	10 - 100	0,01 – 0,1
Sea water	0,2	5,0
CHEMICALS		
Iron	$9{,}074x10^{-8}$	1,102x107
Potassium Chloride (0,01 M)	0,708	1,413
Sodium Chloride (0,01 M)	0,843	1,185
Acetic Acid (0,01 M)	6,13	0,163
Xylene	$6{,}998x10^{16}$	$1{,}429x10^{-17}$

Source: Loke (1999)

Figure 7. Flow of electric current in different electrical resistivity material



Source: Greenhouse (1996)

of geological materials based on the fact that soils and rocks have larger or smaller pores and / or cracks and which may be totally or partially occupied by electrolytes. In this case, the electrical resistivity values may vary greatly depending on the kind of soil and rock (Table 2), reflecting the different degrees of saturation as a function of their porosity and/or permeability (Loke, 1999).

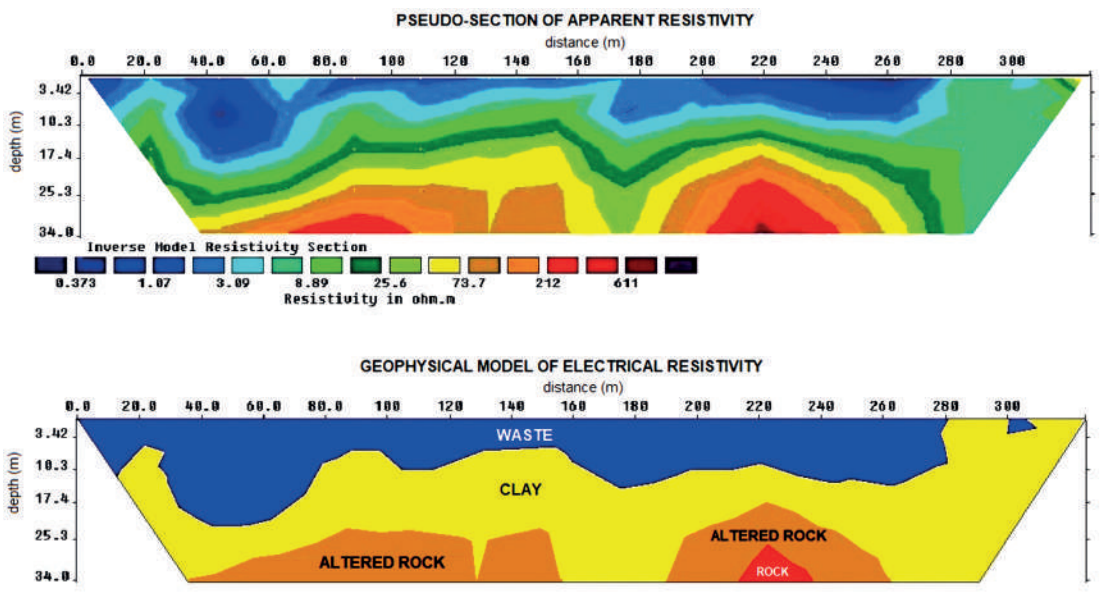
In the execution of the Electrical Resistivity Method, when an electric current is injected into the ground by means of a pair of ground electrodes, the subsurface flow current patterns reflect the resistivity of the materials in depth and are mapped on the surface through another pair of electrodes that measure voltage variations. In this way, when the electric current crosses a material of low or high electrical resistivity (Figure 7), the electric potential decreases or increases, respectively.

The behavior of the lowest values of electrical resistivity, measured in units of Ohm per meter, allows in environmental studies, for example, the detection of the presence of underground inorganic contamination (Greenhouse, 1996).

In the environmental investigation of contaminated areas, the two main techniques of Electrical Resistivity Method, among others, are the Vertical Electrical Sounding (VES) and Electrical Resistivity Tomography (ERT) and that are used in the geological and hydrogeological characterization of sites, in the evaluation of the large trenches containing inorganic residues or buried drums, in the delimitation of contaminant inorganic plumes and in the determination of the lateral limits and depths of landfills or dumps (CETESB, 2001)

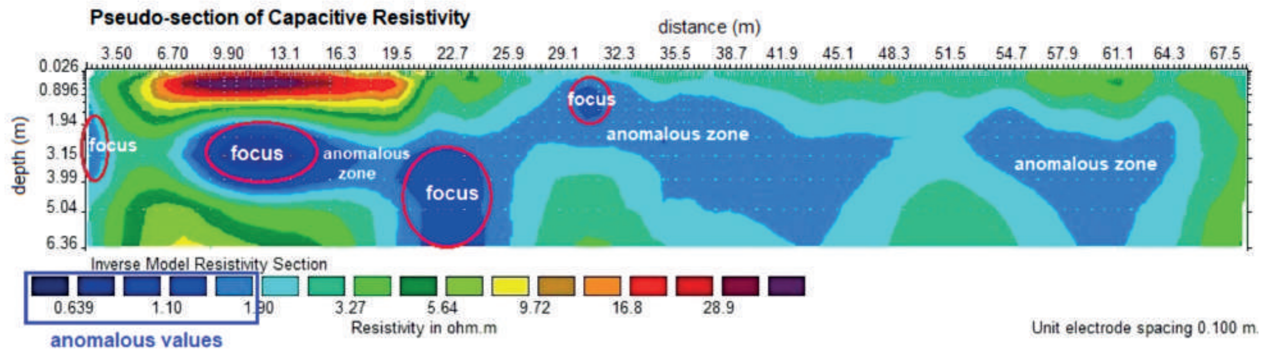
Particularly, in the technique of Vertical Electrical Sounding (VES), the values of apparent

Figure 8. Pseudo-section of electrical resistivity from landfill



Source: GPR Geoscience Geofísica Ltda (2010)

Figure 9. Pseudo-section obtained in Capacitive Resistivity Imaging



Source: Silva (2018)

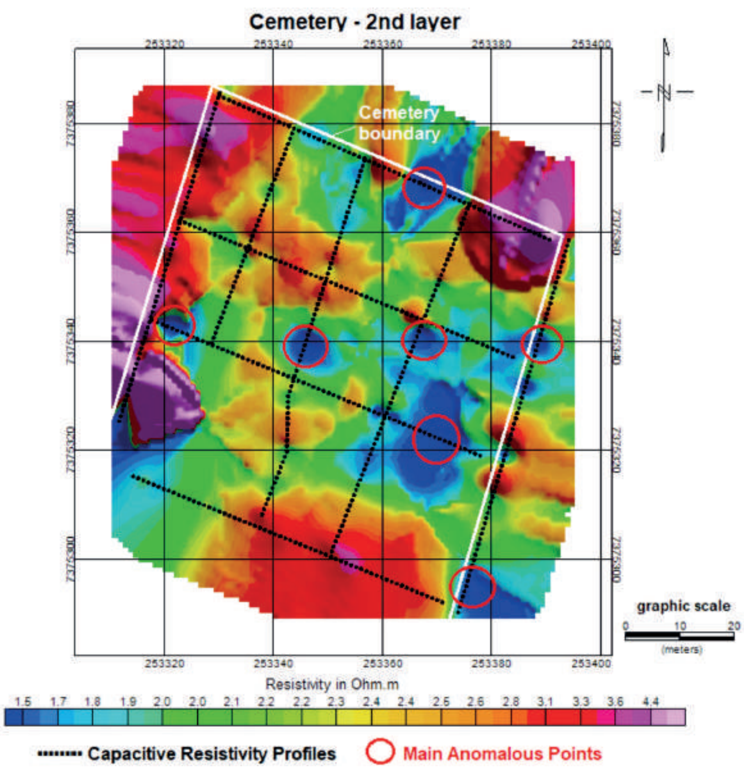
resistivity of the layers of different depths are obtained at a central point of the field arrangement. Subsequently, through the geophysical modeling, it is possible to determine the true values of electrical resistivity and the thicknesses of those layers investigated (Braga, 2006).

According to Reynolds (2011), the Electrical Resistivity Tomography (ERT) technique provides an evaluation of the lateral variations of the electrical resistivity at certain depth levels of investigation, generating sections of subsurface where the interpolated values are presented of the measured electrical resistivity (pseudo-sections) and thus allowing the elaboration of geophysical models (Ex. Figure 8).

Figure 8 shows the pseudo-section of Electrical Resistivity Tomography carried out to identify the domestic waste deposited in trench. In this figure, can also be seen the geological features interpreted as clay soil, alteration of rock (silt) and hard rock.

In places where there are very difficulties to perform the conventional Electrical Resistivity Tomography with electrodes fixation, for example in the interior of industries or cemeteries, the Capacitive Resistivity Imaging (CRI) has been applied more often, because in this technique the electrical properties of the soil are measured in a capacitive way, with only the contact of the sensor of the equipment with the ground (Silva, 2018), with the advantage of measurements of the

Figure 10. Electrical resistivity map at 3.0m depth



Source: Silva (2018)

order of centimeters generating sections with great detail (Figure 9).

Figure 9 corresponds to the electrical pseudo-section of a capacitive survey carried out in a cemetery to investigate points with possible leachate accumulation, associated to low electrical resistivity values and which were subjected to soil sampling and chemical analysis (Silva, 2018). In this work, electric resistivity maps of different depths were also made for visualization on plant of the main anomalous points (Figure 10).

3.1.4. MAGNETOMETRY OR MAGNETIC METHOD

The Magnetometry, or Magnetic Method, is most frequently used in mineral exploration and when applied to investigations of contaminated areas has the main objective of locating magnetic objects present in subsurface (Figure 11). According to Reynolds (2011), in an environmental investigation, the objective of the magnetic survey is to measure induced anomalies which drums and metal tanks or buried ferrous residues can generate in the natural geomagnetic field, whose unit of measure is nanoTesla (nT).

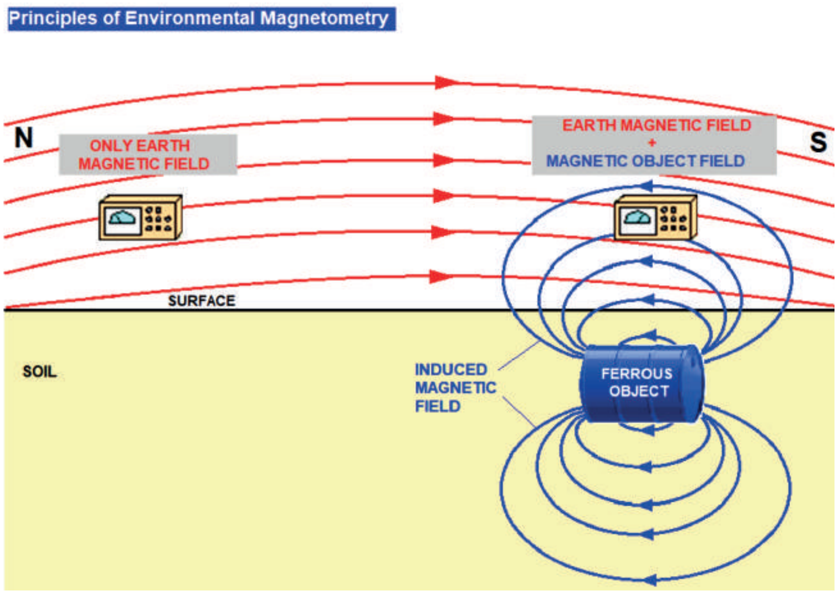
The physical property involved in the Magnetic Method is magnetic susceptibility, which is a measure of the ability of a material to be magnetized. The areas of disposal iron and steel rejects are the main sources of magnetic anomalies, because those materials have high magnetic susceptibility and are classified as ferromagnetic materials and, therefore, contrast strongly with the geological materials, such as soil or sediments which are not magnetic (Greenhouse, 1996).

In this context, the Magnetometry is classified as a passive geophysical method, since it does not require an artificial signal source, unlike the previously presented methods, because the high magnetic susceptibility of the ferromagnetic materials it is an intrinsic property, generating by itself a magnetism in the place where they are (Reynolds, 2011).

The shape of the magnetic anomaly of a buried metal object it will almost always be dipolar, that is, it will have a positive part and a negative part of the signal (Greenhouse, 1996), but the final format observed will also depend on the location on the Earth where it is being performed the survey, because the geomagnetic field varies in intensity and direction thus influences the configuration of the detected anomaly (Figure 12).

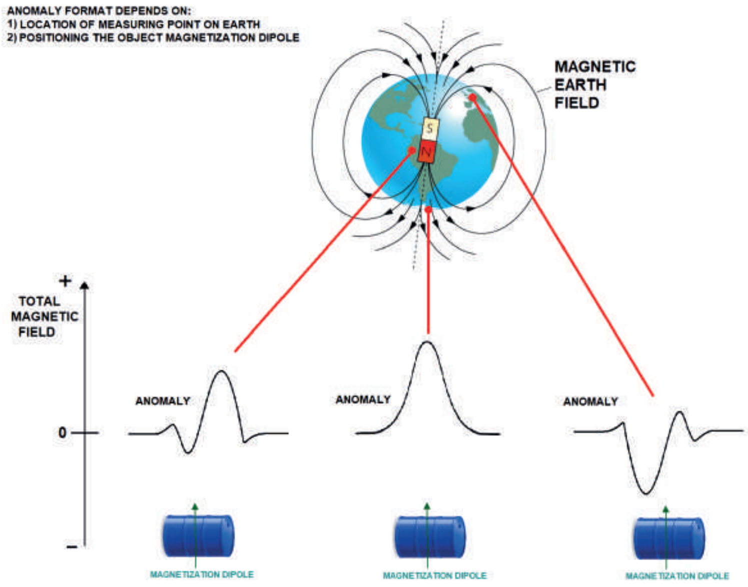
In performing magnetic surveys, profiles are realized at fixed distance intervals to measurement of the magnetic field (stations) or as continuous readings. Subsequently, the data stored in the memory of the measuring equipment (magnetometer) are treated and can be presented in the form of individual graphs of the executed profiles or showed as maps of magnetic anomalies to evaluate the results (Figure 13).

Figure 11. Magnetic field induced by ferromagnetic object in the soil



Source: Adapted from CETESB (2001)

Figure 12. Magnetic anomalies of the same object applied in different places



Source: Elaborated by the authors

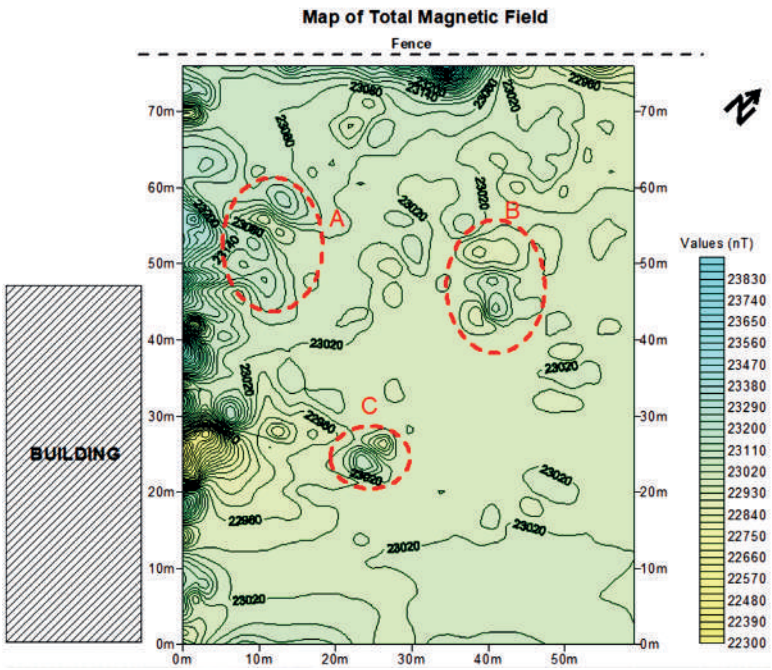
4. RESULTS

4.1 PROTOCOLS FOR SELECTION OF THE GEOPHYSICAL METHOD BY CHARACTERIZATION OF CONTAMINANTS

For the selection of a geophysical method to be used in contaminated areas, the previous knowledge of local geology, of physico-chemical characteristics of groundwater and contaminant, of type of disposal and the wrapper used, as well the proximity of buildings and facilities are relevant.

Among the mentioned factors, it is important to associate the type of contaminant with the best and more efficient geophysical methods, previously based on literature and also on field studies, as shown in Table 3.

Figure 13. Map of magnetic anomaly of the total magnetic field



Source: Bastianon (2005)

Table 3. Characteristics of contaminants and applicability of geophysical methods

TYPE OF CONTAMINANT	PRINCIPLE	APPLICABLE GEOPHYSICAL METHODS	GENERAL OBSERVATIONS
Waste or metal objects	- The main property of the waste or metallic objects is their high electrical conductivity, in addition, if they are ferrous also will be highly magnetic.	• Inductive Electromagnetic; • Magnetometry; • GPR.	- In areas with interference for electrical lines, the use of Magnetometry will be more adequate than the Inductive Electromagnetic. - If the residue is disseminated on the ground, the Inductive Electromagnetic method will provide better results. - In industrial or urban areas, GPR has proved to be efficient for detecting this type of material, due to the high definition of the data and less susceptibility to external interference due to the shielded antennas.
Inorganic waste	- The main property of the waste or metallic objects is their high electrical conductivity, in addition, if they are ferrous also will be highly magnetic. - Inorganic waste generally produces anomalies of high electrical conductivity (low resistivity), in relation to the environment where it is located.	• Inductive Electromagnetic; • GPR; • Electrical Resistivity (alternative method).	- In the detection of small trenches with these residues, GPR and Inductive Electromagnetic are more viable due to the continuity and detailing of the profiles. - The Electrical Resistivity method can be used as an alternative if the area of disposal is big (dumps or landfills), and if need to estimate the depth of the trenches.
Inorganic plume in groundwater (dissolved ions and salts)	- Inorganic contaminants in contact with groundwater increase the concentration of free ions, raising the electrical conductivity of the medium. - Examples are the plumes of contamination from poorly controlled landfills or effluent infiltration.	• Inductive Electromagnetic; • Electrical Resistivity; • GPR (alternative method).	- In this case, the Inductive Electromagnetic method is more indicated than Electrical Resistivity by the speed and precision in the determination of lateral variations. - GPR can be used as an alternative, since the limits of the inorganic plume can be determined by signal attenuation.
Organic waste and organic plume	- Organic compounds have low electrical conductivity and small dielectric coefficient, thus presenting little contrast with the electrical properties of the geological environment where they are arranged, making it difficult to detect them,	• GPR; • Inductive Electromagnetic (under special conditions); • Electrical Resistivity; (under special conditions).	- GPR is the one that has presented the best results for the detection of solid organic wastes and high concentrations of combustible hydrocarbons or chlorinated organic compounds, but does not detect their dissolved phases. - In very special conditions, Electrical Resistivity and Inductive Electromagnetic can be used to map the anomalies of low electrical conductivity contrasting with a natural medium of high conductivity (clayey).

Table 3. Characteristics of contaminants and applicability of geophysical methods (cont.)

TYPE OF CONTAMINANT	PRINCIPLE	APPLICABLE GEOPHYSICAL METHODS	GENERAL OBSERVATIONS
Rejects of Mining	- Rejects of mining are characterized by their high acidity and provide electrically conductive anomalies both in soil and in groundwater.	• Inductive Electromagnetic; • Electrical Resistivity (alternative method). • GPR (alternative method).	- The most suitable method is the Inductive Electromagnetic, with the advantage, in relation to the Electrical Resistivity, by agility of the survey and the greater capacity of detection of the contaminants disseminated in the soil and groundwater. - GPR can be used as an alternative in the detection of this type of contamination thanks to signal attenuation, caused by the high electrical conductivity of the rejects.
Diffuse contamination in agriculture	- The contaminants in agriculture generally have high electrical conductivity, such as vinasse, treatment sludge, fertilizers or effluents.	• Inductive Electromagnetic; • Electrical Resistivity (alternative method).	- The Inductive Electromagnetic method is the one that has presented the best results due to the ability to map the anomalies of high electrical conductivity and the great rapidity in the survey of large areas.
Leachate from cemeteries	- In addition to the presence of organic compounds, buried bodies and their enclosures produce inorganic contamination (ions and salts) as well as metallic, reducing the electrical resistivity of the medium (high conductivity).	• Electrical Resistivity • Inductive Electromagnetic; (alternative method); • GPR (alternative method).	- The Electrical Resistivity by the technique of Capacitive Resistivity Imaging has presented the best results in cemeteries because it does not require electrode fixation and present a bigger detailing of the measurements of the order of centimeters.
Sludge from treatment plants or dredging material	- Both sludge from treatment plant or dredging materials may contain inorganic compounds and metals thereby increasing the electrical conductivity of the medium.	• Inductive Electromagnetic; • Electrical Resistivity • GPR (alternative method).	- In this application, the Inductive Electromagnetic method is more indicated than the Electrical Resistivity due to the rapidity in the field measurements.

Source: Elaborated by the authors

4.2 PROTOCOLS OF SELECTION OF THE GEOPHYSICAL METHOD ACCORDING TO THE POTENTIALITIES AND LIMITATIONS

In addition to the previous aspects presented in Table 3, relating the nature of the contaminant to the applicability of the described geophysical methods, the choice and the success of the methodology to be used in the diagnosis of contaminated areas should also be in line with the main characteristics, potentialities, limitations and susceptibility to interferences of each method, as observed in Table 4.

Table 4. Characteristics and limitations of geophysical methods for contaminated areas.

GEOPHYSICAL METHOD	CHARACTERISTICS AND POTENTIALITIES	LIMITATIONS AND SUSCEPTIBILITIES
GPR	• Continuous and instantaneous sections; • Speed from 0.5 to 2.0 km/h for detailed profiles; • Records (images) can be interpreted in the field; • Good definition for bodies from a few centimeters to one meter, • Adequacy to the sites by the frequency change of the antennas; • Approximate depths are easily established, • Possibility of detection of contamination organic; • Use of shielded antennas in urban and industrial areas; • Application on fresh water, concrete, asphalt or another pavement; • Variety of processing techniques for interpretation; • Detection of ducts or galleries of any material; • Possibility of identification of underground leaks.	• Up to 30m deep; • Not applicable on metal surfaces or sea water; • Interference for unshielded antennas: a) Electric power lines; b) Proximity to metal objects.
Inductive Electromagnetic	• Fast acquisition of data in high density scanning; • Continuous records allow full area coverage; • The limits of the conductivity plume can be detected; • Investigated depth varies from 0.75 to 60m depending on equipment; • Direct readings of electrical conductivity in the field; • Mapping of the different hydrogeological portions; • Definition of the plume flow of contamination in maps or sections; • Monitoring of the migration of contaminants at different times; • Mapping of abandoned mining; • Location of trenches with buried residues; • Detection of drums or metallic tanks buried; • Mapping of underground metal ducts.	• Not applicable on metal surfaces; • Aerial and underground electric line; • Proximity to metal objects.

REFERENCES

American Petroleum Institute (1993). *Guide for assessing and remediating petroleum hydrocarbons in soils*. Washington: API.

Aquino, W. F. (2000). *Métodos geofísicos eletromagnéticos aplicados ao diagnóstico da contaminação do solo e das águas subterrâneas em área de infiltração de resíduos industriais*. Dissertação de mestrado, Universidade de São Paulo, São Paulo, SP, Brasil, 112p.

Associação Brasileira de Normas Técnicas-ABNT. Norma 15.935 em 2011 – *Investigações Ambientais – aplicações de métodos geofísicos*. 21p. Recuperado de https://www.abntcatalogo.com.br/norma.aspx?ID=86681.

Bastianon, D. (2005). *Estudo geofísico pelo método magnético para avaliação de área industrial em Sousas (SP)*. Relatório de Consultoria Ambiental, 22p.

Braga, A.C.O. (2006). *Métodos de Eletrorresistividade e Polarização Induzida Aplicados nos estudos da captação e contaminação de águas subterrâneas: uma abordagem metodológica e prática*. Tese de Livre Docência, Universidade Estadual Paulista, Instituto de Geociências e Ciências Exatas, Rio Claro, SP, Brasil. 126p.

Blakstad, O. (2014). Research designs. Retrieved from https://explorable.com/research-designs.

Companhia Ambiental do Estado de São Paulo – CETESB (2001). *Manual de Áreas Contaminadas.* Programa CETESB/GTZ. São Paulo. 389p. Recuperado de https://cetesb.sp.gov.br/areas-contaminadas/manual-de-gerenciamento-de-areas-contaminadas/.

Côrtes, P.L, Alves A. P., Filho, Ruiz M.S., & Teixeira, C.E. (2011). *Revista de Administração e Inovação, 8* (2),132-163.

Costa, A.F.U., Ferlin C.A. (1993). Aplicação prática de métodos elétricos na detecção e monitoramento da contaminação de água subterrânea. *Anais do Congresso da Sociedade Brasileira de Geofísica, 3*, Rio de Janeiro, 1210-1214.

Daniels, J.J., Roberts, R., & Vendl, M. (1995), Ground penetrating radar for the detection of liquid contaminants. *Journal of Applied Geophysics*, *33*, 195-207.

Davis, J.L., Annan, A.P., 1989, Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy: *Geophysical Prospecting*, *37* (5), 531-551.

Decreto Estadual n. 59.263, de 05 de junho de 2013 (2013). Regulamenta a Lei n. 13.577, de 8 de julho de 2009, que dispõe sobre diretrizes e procedimentos para a proteção da qualidade do solo e gerenciamento de áreas contaminadas, e dá providências correlatas. Recuperado de https://www.al.sp.gov.br/repositorio/legislacao/decreto/2013/decreto-59263-05.06.2013.html

Ellert, N., Greenhouse J.P., Williams, M.M., Mendes, J.M.B., & Hassuda, S. (1986). A geofísica aplicada na identificação da poluição do subsolo por depósito de rejeitos urbanos e industriais. *Anais do Congresso Brasileiro de Águas Subterrâneas, 2* (4), 528-532.

Environmental Protection Agency (1993). *Use of Airborne, Surface and Borehole Geophysical Techniques at Contaminated Sites. A Reference Guide EPA/625/R-92/007.* Washington: Eastern Research Group. Chapter 1: 4–6. Recuperado de https://www.epa.gov/sites/production/files/2015-06/documents/geophysics-guide.pdf.

Salinas, V. C. F. (2015). Contaminação do solo em São Paulo: O caso da operação urbana Bairros do Tamanduateí. *Revista Labverde*, *1* (10), 84-102.

Geométodos Levantamentos Geofísicos Ltda (2018). *Levantamento geofísico de GPR para localização de tanques subterrâneos em posto de combustível no Bairro do Cambuci, São Paulo (SP).* Relatório de Consultoria Ambiental, 24p. Recuperado de https://geometodos.com.br.

Giusti L. (2009). A review of waste management practices and their impact on human health. *Waste Management, 29*(8), 2227-2239.

Goldstein, N.E., Benson S.M., & Alumbaugh, D. (1990). Saline Groundwater Plume Mapping with Electromagnetics. *Geotechnical and Environmental Geophysics, Investigations in Geophysics, S.E.G., II* (5), 17–27.

GPR Geoscience Geofísica Ltda (2010). *Levantamento geofísico para avaliação da profundidade de resíduos na área do Lixão do Alvarenga*. Relatório de Consultoria Ambiental. 25p.

Greenhouse, J.P. (1991). Environmental geophysics: it´s about time. *Geophysics: The Leading Edge*, *10*, 32-34.

_________. (1996). *Aplicações de Metodologias Geofísicas em Estudos Ambientais e Geotécnicos.* Rio Claro: CEA/UNESP, 111p.

Gretsky, P., Barbour, R. & Asimenios, G.S. (1990). Geophysics, Pit Surveys Reduce Uncertainty. *Pollution Engineering*, 102-108.

José, C., & Ellert, N. (1989). Abordagem Geofísica para o Mapeamento e Monitoramento da Pluma de Contaminação na Área de Influência de um Aterro Sanitário Urbano. *Revista Brasileira de Geofísica, 7* (1), 92.

Kist L. T., Rosa, F.R., Moraes, J. A.R., & Machado, E. L. (2018) Diagnosis of hospital waste management in Vale do Rio Pardo, Rio Grande do Sul, Brazil. *Revista de Gestão Ambiental e Sustentabilidade*, *7* (3), 554-569

Lei n. 13.577, de 08 de julho de 2009 (2009). Dispõe sobre diretrizes e procedimentos para a proteção da qualidade do solo e gerenciamento de áreas contaminadas, e dá outras providências correlatas. Recuperado de

https://www.al.sp.gov.br/repositorio/legislacao/lei/2009/lei-13577-08.07.2009.html.

Lima, O.A.L., & Sato H.K. (1993). Detecção da contaminação de águas subterrâneas usando técnicas de Eletrorresistividade. *Anais do Congresso da Sociedade Brasileira de Geofísica, 3*, Rio de Janeiro, 410-420.

_________., Oliveira, A.F., Golin R., Caixeta, D.S., Lima, Z.M., & Morais, E.B. (2017) Gerenciamento de áreas contaminadas por postos de combustíveis em Cuiabá, Mato Grosso, Brasil. *Revista Ambiente & Água, 12* (2), 299-315.

Loke, M.H. (1999) *Electrical imaging surveys for environmental and engineering studies. A practical guide to 2-D and 3-D survey.* 61p. Recuperado de http://pages.mtu.edu/~ctyoung/LOKENOTE.PDF.

Martins, G.A., & Théophilo, C.R. (2009). *Metodologia da Investigação Científica para Ciências Sociais Aplicadas (2 ed.). São Paulo: Editora Atlas*.

McNeill, J. (1980). Electromagnetic Terrain Conductivity Measurement at Low Induction Numbers. *Technical Note*, *6*, 6–15.

Mendes, J.M.B. (1987). *Técnicas geofísicas aplicadas ao mapeamento e monitoramento de poluição e contaminação de águas subterrâneas*. Tese de doutorado, Instituto de Geociências, Universidade de São Paulo, São Paulo, Brasil.

_________., Pacheco, A., & Hassuda, S. (1989). Cemitérios e meio ambiente: a geofísica como método auxiliar na avaliação de sua influência nas águas subterrâneas. *Anais do Encontro Nacional de Estudos Sobre O Meio Ambiente- UFSC, 1* (2), 50-57.

Moreira, C.A., Aquino, W.F., & Dourado, J. C. (2007). Aplicação do método Eletromagnético Indutivo (EM) no monitoramento de contaminantes em subsuperfície. *Revista Brasileira de Geofísica, 25* (4), 413-420.

Reynolds, J.M. (2011) *An introduction to applied and environmental geophysics*, 2ª Edição, Wiley-Blackwell Editores. Oxford. 696p.

Shuttleworth, M. (2014) Establishing cause and effect. Retrieved from https://explorable.com/cause-and-effect.

Silva, F.C. (2018) *Avaliação de metais potencialmente tóxicos em zona não saturada da necrópole de Nossa Senhora Aparecida,* *Piedade, SP.* Tese de doutorado. Universidade Estadual Paulista, Instituto de Ciência e Tecnologia. Sorocaba. 249p.

Souza E.L., Damasceno, F., Schirmer G.K., Ramires M.F., Bisognin R.P., Bohrer. R.E.G., Vasconcelos M.C., & Cezimbra J.C.G. (2018) Resíduos contaminantes nos solo: possibilidades e consequências. *Revista Gestão & Sustentabilidade Ambiental,* Florianópolis, *7* (2), 484-509.

Steeples, D. (1991) Uses and techniques of environmental geophysics. *Geophysics: The Leading Edge*, *10*, 30-31.

World Health Organization (2007). *Population health and waste management: scientific data and policy options.* Report of a WHO workshop Rome, Italy, 29-30 March 2007. Copenhagen: WHO Regional Office for Europe.

Wilson, L. T. (2014). Statistical correlation. Retrieved from https://explorable.com/statistical-correlation.

_________, & Shuttleworth, M. (2014). What is the scientific method? Retrieved from https://explorable.com/what-is-the-scientific-method.