Geo-Environmental Investigation: A Brief Review and a Few Suggestions for Brazilian Contaminated Sites

Giulliana Mondelli, Heraldo Luiz Giacheti, John A. Howie

Abstract. This paper presents a brief review about site investigation procedures for contaminated sites recommended by Brazilian and Canadian environmental agencies as well as discusses the theme of geo-environmental investigation as applied to Brazilian practice. The main definitions on the theme are reviewed and some guidelines are proposed for conducting a geo-environmental investigation of Brazilian contaminated sites using different site and laboratory investigation techniques based on the presented review and on the experience obtained from the investigation of a solid waste disposal site in the interior of the state of São Paulo, Brazil.

Keywords: environmental geotechnics, contaminated sites, regulations, MSW disposal site, tropical soils.

1. Introduction

Contaminated or even potentially contaminated sites abandoned in urban areas are subjects of current interest and concern due to their possible impact on the environment and on human health. Environmental agencies in several countries have proposed different site investigation methodologies to diagnose and confirm different contamination degrees in sites with diverse physical characteristics to guide the remediation plan when it is necessary.

The experience already achieved on site investigation has shown that the best methodology is site specific, and depends on subsoil and chemical contaminants; geotechnical, geological and hydrogeological aspects; evolution of the contamination plume and the possible risks it poses. Several site and laboratory investigation techniques (direct and indirect) have been proposed and used. Sometimes one technique is more suitable than another depending on the physical and natural characteristics of the site.

The demand for geo-environmental investigation of contaminated sites in Brazil has been substantially increased in recent years due to lack of space in metropolitan areas for construction of sanitary landfills. Brown fields and old dumps sites also need to be monitored and investigated for site remediation.

It is important to review the existing regulations and definitions for geo-environmental investigation and suggest guidelines to be followed in the Brazilian practice considering it is a developing country with a large territory to protect. The specific objectives of this paper are:

1) Review the term “geo-environmental investigation” in the practice of Geotechnical, Geological and Sanitary Engineering in Brazil.

2) Compare and discuss Brazil’s and Canada’s environmental regulations for geo-environmental investigation.

3) Suggest guidelines for geo-environmental investigation of Brazilian contaminated sites based on the presented review and on the experience obtained from the investigation of a MSW disposal site in the interior of the state of São Paulo, Brazil, which was extensively investigated during more than seven years.

2. Definitions of Geo-Environmental Investigation

Geo-environmental investigation is a relatively new term in geotechnical engineering. There are different interpretations for the meaning of the word “geo-environmental”. According to Davies & Campanella (1995), it can be understood as “the field of study that links geological, geotechnical, and environmental engineering and their related engineering sciences to form an area of study and practice that includes all physical and geochemical concerns within natural or processed geological media.”

Almeida & Miranda Neto (2003) define geo-environmental investigation as the systematic collection of data to determine the degree of contamination of a particular site. These data can be obtained not only by sampling and testing, but also throughout document research, interviews, technical visits, inspections and surveys. According to the authors, the main objective of a geo-environmental investigation is to gather sufficient information of the source, contamination paths and targets to support risk assessment studies and/or site remediation plan, if necessary, aiming to:

• Determine the nature, shape, extension and distribution of any contamination found at the investigated site;

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• Characterize the physical environment, determining its geological, hydrological and geotechnical characteristics;

• Understand the nature of the potential targets of the contamination and the relationship between the source and its effects;

• Provide support for management and remediation decisions.

The Association of Geotechnical & Geo-environmental Specialists (AGS, 2000) proposes to integrate geotechnical and environmental investigations for contamination detection: the first aiming to establish the physical and mechanical properties of soil and the second aiming at determining the chemical composition of soil, water and gases. Brandl & Robertson (1997) comment that the goals of a geo-environmental investigation can be quite different from the traditional geotechnical investigations, since for geo-environmental purposes, in addition to the soil geotechnical characteristics, contaminants distribution and composition must also be identified. In such investigations, the stages of monitoring and sampling should be planned on a long term basis, including the steps of implementation, deactivation and remediation.

Jewell *et al.* (1993) consider the evolution of hydrogeological impact one of the most important aspects to be monitored for heterogeneous municipal solid waste disposal sites. In these particular cases the pollution that reaches the aquifer may spread in different pathways, depending on the type of pollutant (*e.g.* miscible or not) and the characteristics of the aquifer. Thus, a detailed characterization of the aquatic environment must include:

• Assessment of the regional and local geology, including stratigraphy, structure and lithology, weathering characteristics and superficial deposits;

• Assessment of local surface hydrology, including hydrometeorological water balance, major and tributary drainage, flood levels and groundwater contribution to base flow;

• Identification of main hydrogeological units (aquifers and aquitards);

• Assessment of likely groundwater flow mechanisms, and in particular, whether intergranular or fracture flow is likely to be dominant;

• Identification of local structural features which may control groundwater flow;

• Measurement of piezometric levels and calculation of the local hydraulic gradients within hydrogeological units;

• Measurement of the hydraulic conductivity of the main hydrogeological units identified;

• Assessment of the attenuation characteristics of the materials present in both vadose and phreatic zones;

• Analysis of natural groundwater chemistry;

• Identification of any presence or potential beneficial use of groundwater;

• Identification of potential groundwater and surface water receptors of contamination.

In the engineering practice, it is important to keep in mind that it is difficult to identify all the aforementioned factors during a site investigation campaign. Such investigations are constrained by the costs involved, lack of specialists and the geological, hydrogeological and geotechnical natural conditions, which may limit the use of some investigation techniques.

Boscov (2008) defines "geotechnical investigation" and "environmental monitoring" as part of environmental geotechnics, which involves a combination of geotechnical and environmental works. In the present paper, the term "geo-environmental investigation" encompasses all the phases of *in situ* and laboratory testing, field monitoring activities and research, aimed at gaining a better understanding of all the *in situ* geomaterials conditions, and of the aquifers and contaminants present at the site.

It should be noted that "investigation" and "monitoring" do not involve the same activities. Investigation consists of discovering, diagnosing and characterizing *in situ* hydrogeological and geotechnical conditions. Monitoring, on the other hand, involves observing several specific variables over time, for example to evaluate remediation techniques, investigation and/or stability solutions for the conditions at the site. Therefore, monitoring can be considered part of a "geo-environmental investigation", as defined herein.

3. Contaminated Sites

3.1. Definitions

According to CETESB (2004), São Paulo State Environmental Company, a contaminated site can be defined as a location where chemical substances or waste have been deliberately or accidentally disposed, accumulated, stored, buried or infiltrated. However, this definition can be reviewed, since there are two important aspects: natural concentrations of the substances of concern; and allowable concentrations defined by the local environmental agency. Theoretically, a site can be considered clean until the allowable levels are reached. At this site, pollutants or contaminants can be concentrated in the air, in surficial water, soil, sediments or in the groundwater. These pollutants or contaminants can be carried from the site, spreading by the air, soil, groundwater and surface water, altering their natural features or qualities and causing negative impacts and/or risks to a site or its surroundings.

The term "contaminated soil" is more frequently used than "polluted soil". Some authors consider them synonymous and others seek to make a fairly simple distinction between pollutants and contaminants. Yong (2001) and Yong & Mulligan (2004) comment that the term "pollutant" is used to indicate that a given contaminant is becoming a potential source of risk to human health and to the environment. Thus, the term "contaminant" applies more generally to contaminated soils, where site conditions are not sufficiently known to consider the actual existence of risk.

In the context of polluted or contaminated water, this difference is even more complex. Contamination, in this case, refers to the waterborne transmission of microorganisms or substances harmful to human health, which does not necessarily pose a risk to the ecological equilibrium of the environment (Braga *et al.*, 2002). Brazilian Law #6.938/81 defines "pollution" as "the degradation of environmental quality resulting from activity that is directly or indirectly harmful to public health, safety and welfare; creates adverse conditions for social and economic activities; affects the biota; affects the environment's esthetic or sanitary conditions; and discharges materials or energy in violation of the established environmental standards" (Brazil, 1981).

Nass (2002) states that the characteristic that clearly distinguishes "pollution" from "contamination" is the passiveness normally associated with the former. The pollution factor does not usually affect live organisms directly, but impacts the conditions for their survival indirectly, especially in the aquatic medium.

Clearly, the distinction between pollution and contamination depends on the environment that is polluted or contaminated, which can be in air, water or soil. In this paper, it is suggested to adopt the more general term "contaminated soil", which is commonly used by several specialists (*e.g.*, Sánchez, 2001 and Yong, 2001).

The term "contamination plume" is also very common in geo-environmental investigations. A contamination plume is formed when contaminants or pollutants reach the subsoil and spread in vadose and/or saturated zones. Figure 1 illustrates the formation of different types of contamination plumes, depending on the conditions of the site and the characteristics of the contaminants and/or pollutants.

Not all contaminated sites offer risks to the environment or human health. A fundamental aspect is to define the risk of using a contaminated site and it surrounding lands, considering the hazard degree of contamination and its probability to occur. A risk exists only if contaminant concentrations exceed acceptable limits, and if there are sensitive receptors or the possibility of an adverse event to occur. Following the example of countries with tradition in monitoring soil and groundwater quality and controlling contaminated sites, CETESB (2001; 2005) published a preliminary list of guidelines for protecting soil and groundwater, based as far as possible on the Brazilian national data and on human health risk assessment. These quality reference values were established for using as a fast and simple tool to support prevention actions and control soil and groundwater pollution.

The intervention values for groundwater adopted by CETESB (2001; 2005) have been often considered excessively restrictive to assess water quality surrounding a contaminated site, since these values were defined based on the standards for drinking water established by the Brazilian Ministry of Health, Regulation 518 (Brazil, 2004). Similar to CONAMA (2005) (Brazilian Environmental Agency), Resolution 357, which establishes limits for different uses of surface water, CONAMA (2008), Resolution 396, sets limits for different uses of Brazilian groundwater. In addition to the standards for water quality assessment for human consumption, the Resolution 396 also suggests reference values for farm animals, irrigation and recreational uses. Despite recent advances on this resolution, the limit values have not yet been established for several parameters that are important in the assessment of groundwater pollution and contamination, such as biological oxygen demand (BOD), chemical oxygen demand (COD), alkalinity, electrical conductivity, etc.

Sánchez (2001) points out that, although intervention values are helpful, their use may lead to excessively narrow interpretation or, conversely, insufficient protection of a site under investigation. In other words, the use of intervention values represent a limited proposal that does not take into account the site's geological and natural characteristics and its future land use, since certain uses do not require high soil or water quality. Therefore, Sánchez (2001) argues that risk analysis can provide a more reliable basis for decisions about remediation and future use of a site.

3.2. Regulations

Guidelines and regulations for each country establish the way to conduct geo-environmental investigations, considering different local and natural aspects, depending on previous local experience. Some countries, like the United Kingdom and United States have a good experience with brownfield sites, during the transition from areas of heavy industry which are now being redeveloped for residential or "light" industrial use. Countries with recent concern with the environment tend to adapt the more developed countries experience to the reality of their environmental laws, economy, industrialization, size, cultural and social aspects, etc.

The United States Environmental Protection Agency (US EPA, 1996) proposes a detailed plan based on a numerical modeling approach, which provides information about the extension of the contamination plume and of the affected site (Fig. 2). However, this model is not easily applied to complex sites, with heterogeneous geology and hydrogeology, since it is usually difficult to define the stratigraphic profile and particularly the contamination plume. In addition, in sites with complex geology, which is very common in tropical regions, the costs of an investigation program can be very high due to the extensive *in situ* sampling and laboratory testing required by the US EPA (1996) model.

Nnadi (1994) discusses the approach to investigate contaminated sites in North American countries. The au-

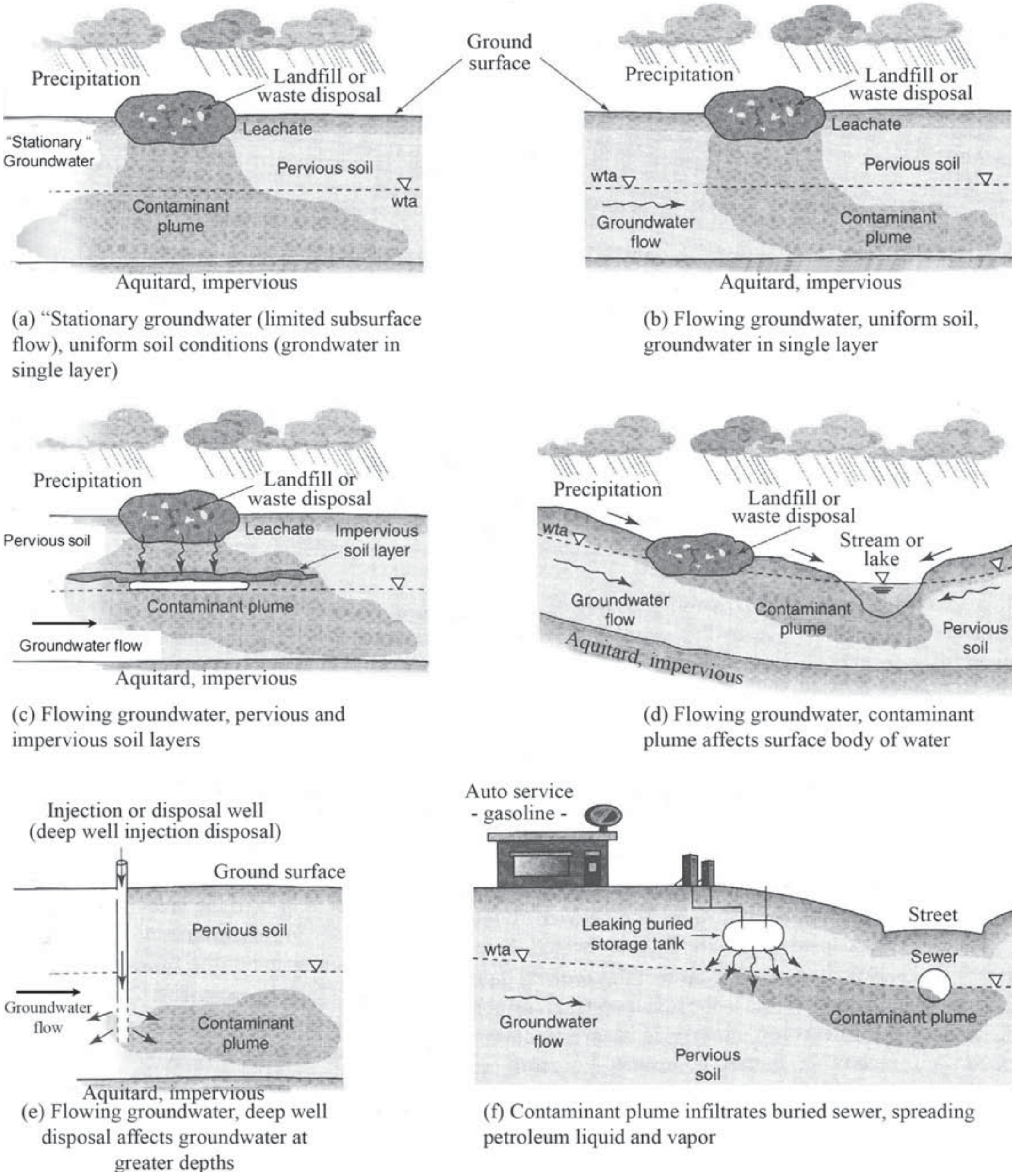

Figure 1 - Contaminant plumes for different site conditions and contaminant sources (McCarthy, 1998).

thor concludes that despite comprehensive environmental laws, United States and Canada differ from Mexico in assessment and enforcement of investigation and remediation of contaminated sites. While the first two countries are proactive, Mexico is reactive due to lack of financing resources and the infrastructure needed to control environmental contamination.

In Brazil, the assessment and registry of potentially contaminated sites (Table 1) began only a decade ago, by CETESB, in the state of São Paulo. Canada has regulations established by Federal law for the entire country, and each province also has its own regulations. The concern with contaminated sites in the state of São Paulo began due to the real estate interests in Greater São Paulo, where there are numerous deactivated industries. Canada, on the other hand, is concerned with the preservation of the natural environment, which includes the health and survival of all living beings that are part of it. Any site development activity can alter the ecosystem, being impossible to return the site to its natural condition. In this case, it is just possible to prevent any further deterioration and restrict the use and occupation of the site.

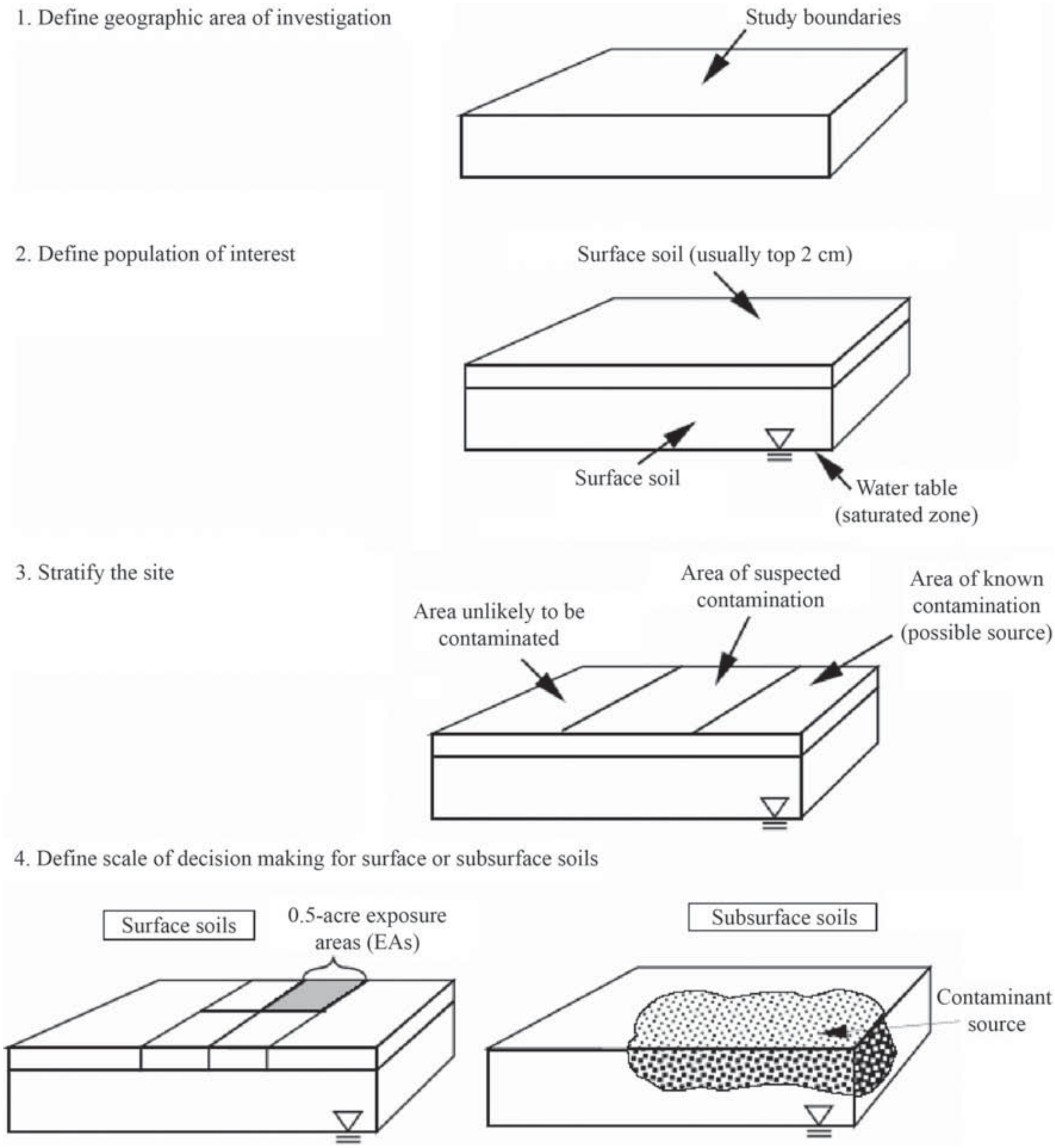

Figure 2 - Geo-environmental investigation of potentially contaminated sites in The United States of America (US EPA, 1996).

Figures 3 and 4 summarize the procedures proposed by CETESB and by Canada Contaminated Sites Management Working Group (CSMWG), respectively. Table 1 compares the regulations from CETESB and from CSMWG, to assess the geo-environmental investigation methodology currently used in both countries, with the objective to explain Figs. 3 and 4.

Independently of the distinction that CETESB does to different phases of investigation to classify the sites as potentially (PS), suspected (SS) and non-contaminated (NS) or contaminated (CS) sites, there are common activities in both procedures summarized in Figs. 3 and 4. These activities are: historical study, initial testing program and detailed investigation. The major difference is that CSMWG presents a more detailed program for remediation and risk management strategies (step 7 in Fig. 4).

CSMWG has a database listing all the potentially contaminated sites in the country, as well as information about the physical environment. This allows for a pre-classification of the site, as described in Table 1. In the state of São Paulo, such records are currently being set up and the investigation proposal is aimed mainly at the preservation of human health and environmental reserves. To expand this database to entire Brazil is a challenge that needs to be carefully planned.

Environmental agencies usually recommend gathering historical information and carry out a site inspection during the preliminary investigation. The real importance

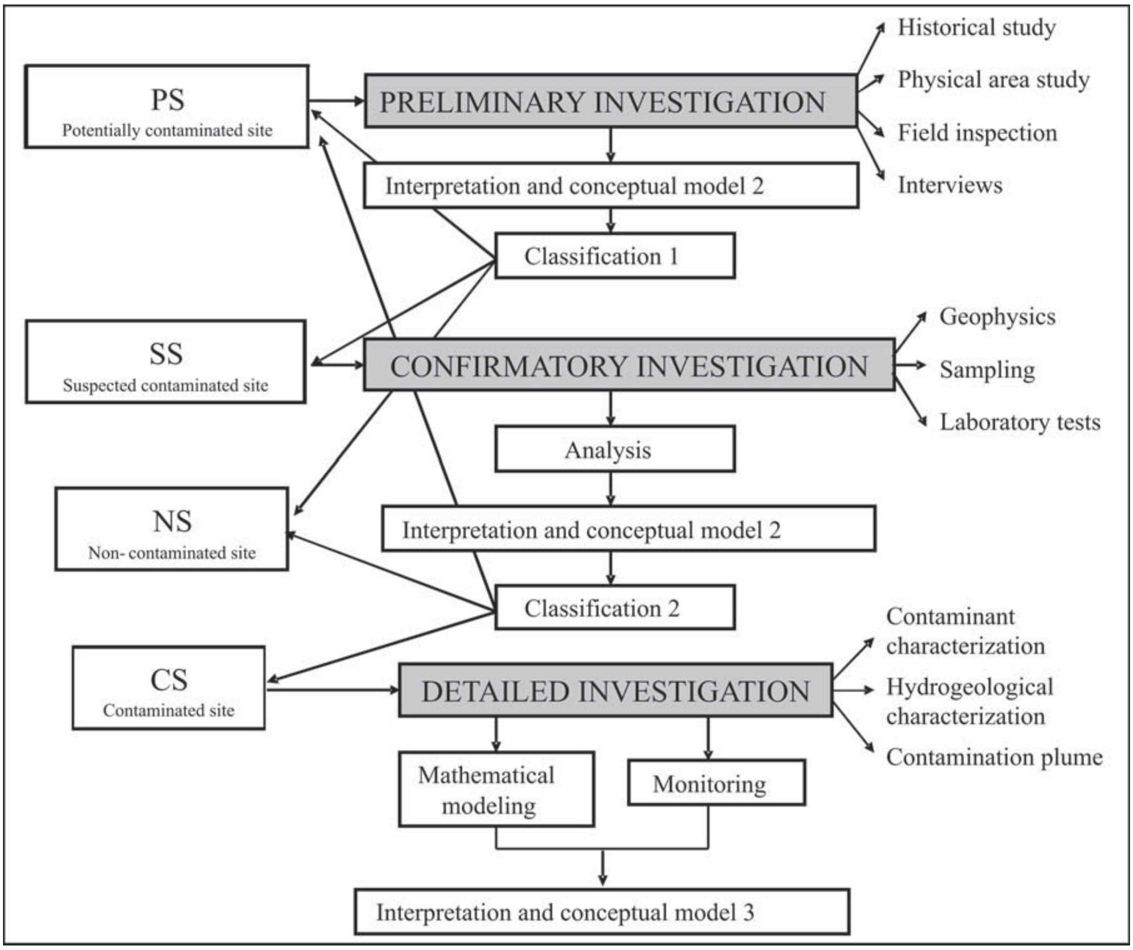

Figure 3 - Summary of different stages of geo-environmental investigation for potentially contaminated sites in São Paulo State, Brazil (CETESB, 1999).

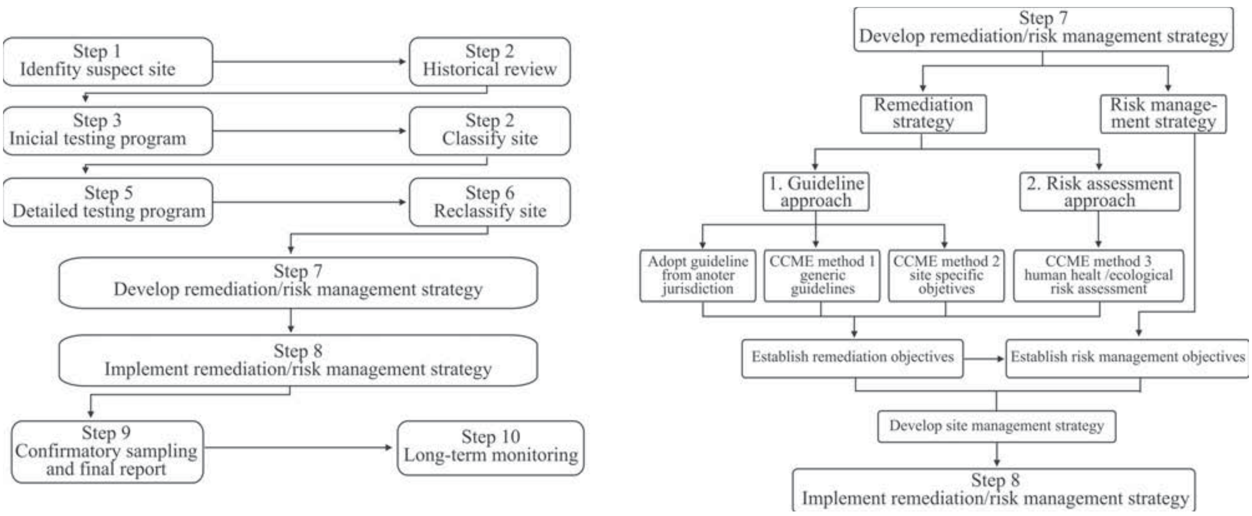

Figure 4 - Canadian proposal for geo-environmental investigation of potentially contaminated sites summarized in a chart (CSMWG, 2000).

Table 1 - Comparing CETESB and CCME regulations for geo-environmental investigation.

	Brazil	Canada
Agency	CETESB (Company of Environmental Sanitation Technology)	CCME (Canadian Council of Ministers of the Environment)
Publication year	1999	1997-2000
Scale	São Paulo State	Federal
Interest	Property and to give the initial step for a federal regulation about this subject	Governmental
Overlapping	Regulation includes notes about the national regulations, added for more detailed information	If there are Provincial and Federal regulations, the most rigorous is used
Objective	Contaminated sites management from São Paulo State	To preserve the natural ecosystem
Groundwater and surface water	Federal (CONAMA e Health Ministry for human supply)	Provincial and Federal (for agricultural use, animal and human supply and aquatic life)
Problems	Who is the guilty or responsible for the contamination?	Who is the guilty or responsible for the contamination?
	Figure 3	Figure 4
	1) Preliminary	1) National Classification System consulting
	2) Registration	2) Assessment of every information about the site
Investigation steps	3) Confirmatory - Geophysics - Sampling - Laboratory characterization	3) Site Investigation - Geophysics - Sampling - Laboratory and field characterization - Hydrogeological investigation - Flow model - Biological assessment
	4) Detailed - Contaminant characterization and hydrogeological investigation - Flow model	4) Detailed - Detailed identification of the limits and every contamination plume paths, to give subsidies for the remediation plan
	5) Risk assessment	5) Remediation Plan (guideline approach or/and risk assessment)
	6) Investigation for Remediation	6) Risk-based environmental management approach (for human health and natural environmental)
	7) Remediation	7) Remediation
Obligatory remediation	To prioritize the most affected sites and close to the major population densities and ecological reserves	Different levels to prioritize: agriculture, parks, residential, commercial and industrial areas
	It is going on now, applying investigation techniques during the different steps are previously described. The sites registration is being built based on detailed information about the sites with potential risk	Study is made with basis on existing site information. There are database and available information registrant. An initial classification can be made, considering the contaminants characteristics, the likely transport paths and the existence or not of targets
	- Potentially Contaminated Site (PS)	- Class 1 (70 to 100 points): action required
Classification	- Suspected Contaminated Site (SS)	- Class 2 (50 to 69,9 points): action likely required
	- Contaminated Site (CS)	- Class 3 (37 to 49,9 points): action may be required
	___	- Class N (< 37 points): action not likely required
	___	- Class I (≥ 15 points): insufficient information
Other aspects	___	- Training courses for workers and for who lives in or around the contaminated or remedied sites - Communication and warning plan to the media and ordinary citizens and residents of the site

of this step was confirmed by Mondelli (2008) in a geo-environmental investigation of the Bauru's municipal solid waste (MSW) disposal site. In this case, the preliminary investigation proved to be very important for the development of future studies, based on the interpretation of the previous and current topography, hydrology, aerial photographs and historical documents. The confirmatory investigation steps in Brazil and Canada differ slightly (Table 1). Both start by using surface geophysics methods, which has proved to be an important in situ testing technique for geo-environmental site investigation and monitoring. Although in Brazilian practice, it has mostly been used only after contamination is detected. In addition to soil and groundwater sampling and laboratory analyses, the Canadian approach includes the option of characterizing all the samples and performing flow modeling and biological assessment in the field.

The greatest difference between the approaches of the two countries is for detailed investigation. The Canadian regulations recommend determining all the requirements for carrying out remediation plans, while CETESB recommend the flow modeling and the hydrogeological and contaminants characterization. According to the CETESB procedures, remediation and/or recovery measures can only be implemented after the phase called "investigation for remediation" (Table 1). In Canada, whether remediation is required or not is one of the first questions to be answered when the site investigation is ongoing. It is important to emphasize herein that the first step is to detect the potential contaminants based on the land use history data. Based on that, site investigation may be required to verify if the levels of any contaminants exceed the maximum accepted values. This is when the question "Is remediation required?" gets asked. When a contaminated site has to be remediated, it can be very expensive and this action may not be effective for its intended use. In these cases, risk assessment came into practice as a way of justifying alternative approaches to deal with the contamination.

Canada's Subsurface Assessment Handbook for Contaminated Sites (CCME, 1994) lists the following investigative steps: review of information; surface and intrusive geophysics; hydraulic and hydrogeological information and monitoring wells; sampling of soil, gas and liquids; chemical, biological, geochemical and geotechnical analyses; mathematical modeling of the contamination plume; and investigation to monitor the remediation program.

Canada has experience in the investigation and control of contaminated sites with the development of modern techniques for site investigation. A very complete investigation program was conducted in a landfill in Cambridge, Ontario, in the late 70s, which was well documented by Dillon Limited (1989). The following steps were taken, which could serve as a reference for investigation of contaminated sites in Brazil:

1) Determine the possible sources and/or targets of contamination.

2) What was the site like before its use as a waste disposal site?

a. Topography, Hydrology, Geology (rocks and deposits), Hydrogeology (aquifers and wells for urban water supply).

b. Determination of the geological and geotechnical profile (mineralogy, grain size distribution, groundwater level and waste density).

3) Determination of changes in Topography, Hydrology, Geology (rocks and deposits), Hydrogeology (aquifers and wells for urban water supply) caused by construction and operation of the landfill.

a. What sorts of materials have been deposited in the landfill?

b. How have the properties of these materials changed since deposition and how are they interacting with the in situ materials and groundwater?

4) Field monitoring activities (monitoring wells, multilevel or not, inside and outside the landfill, sampling of soil, gas, landfill leachate, ground and surface water, *in situ* hydraulic field tests and laboratory characterization tests).

5) Hydraulic gradients, hydraulic conductivities (Hazen formula, pumping and rising-head tests using the monitoring wells), flow speeds, ground and surface flow.

6) Methane gas monitoring (study of the unsaturated-zone contamination plume).

7) Organic and inorganic leachate analysis.

8) Leachate generation study.

9) Assessment of the vegetation.

10) Environmental impact assessment (interpretation).

11) Conclusions and recommendations.

4. Geo-Environmental Investigation of A Municipal Solid Waste Disposal Site Installed In Brazil

Mondelli *et al.* (2007) studied an existing Municipal Solid Waste (MSW) disposal site at Bauru-SP, Brazil with the primary objective of assessing the applicability a wide variety of geo-environmental investigation techniques. Other focus of this study was to assess contamination of a medium size municipal solid waste disposal site, installed over a typical Brazilian tropical soil (residual soils and sandstones from Bauru Group).

A preliminary investigation program was carried out at the site and the previous and current topography, hydrology, aerial photographs and historical documents were used. Figure 5 summarizes the interpretation of all these data, to show an example of integrating all historical data, with tests carried out over the center of the landfill, to support the later investigation programs.

Surface geophysical investigation (geoelectrical survey) and resistivity piezocone penetration tests (RCPTU) were carried out, followed by soil sampling using direct-

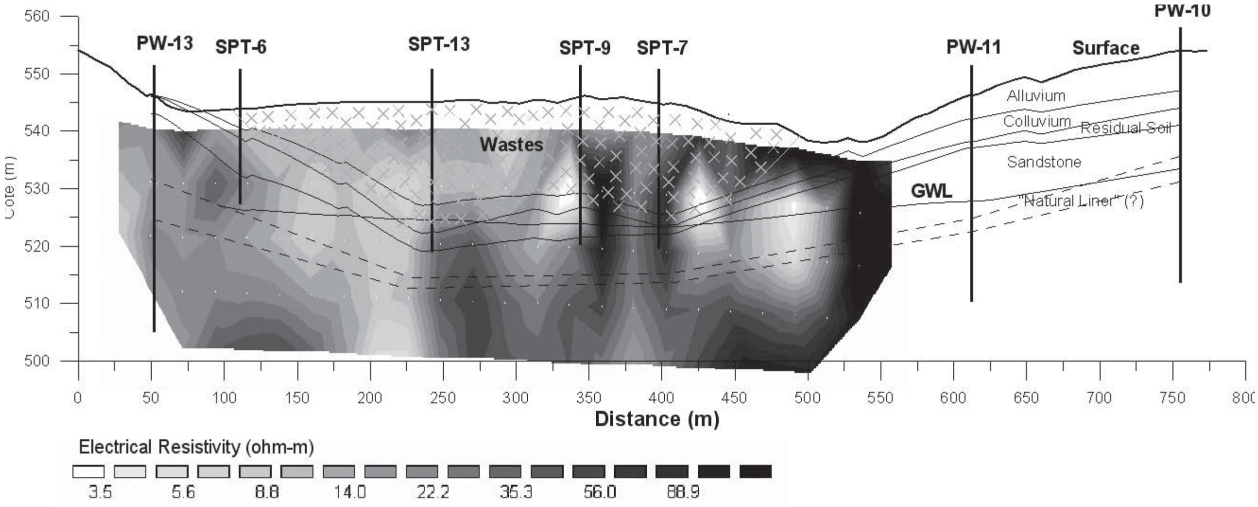

Figure 5 - Results of the dipole-dipole electrical profiling presented together with North-South profile including topographical and geological information (Mondelli *et al.*, 2008).

push samplers and water samples were collected from monitoring wells. The results showed that the application of the geoelectrical methods were indispensable for identifying the presence and flow direction of contamination plumes (leachate) as well as to indicate the most suitable locations for RCPTU tests and soil and water sampling. Chemical analyses of groundwater samples contributed to a better understanding of the flow of the contaminated plume.

A preliminary contamination plume was identified and difficulties in determining a typical soil profile, hydrogeological characteristics and background resistivity values encouraged continuing the site investigation using laboratory tests. The characterization tests included those for geotechnical properties determination and for soil and leachate chemistry (grain size distribution, X-Ray diffraction, blue methyl adsorption and differential thermal analysis). Batch and column tests were carried out using these same geomaterials in disturbed and undisturbed conditions, respectively (Mondelli, 2008). The landfill's leachate was used as a pollutant solution in the laboraratory tests and the dispersion and retardation coefficients were estimated. Electrical resistivity values were measured using different pore fluids and degrees of saturation. The weathering and the fines content of the studied tropical soils was shown to have a significant influence on the resistivity values. It was shown that the laboratory tests could improve the interpretation of the in situ tests and the delineation of the contamination plume occurring at the site (Mondelli, 2008). Figure 6 presents the variation range resistivity values interpreted for the local soils.

5. Suggestions For Geo-Environmental Investigation of Brazilian Contaminated Sites

Based on the review on geo-environmental site characterization and on the experience gained during the investigation of the Bauru MSW disposal site, briefly presented in this paper, a site investigation plan outlined in Fig. 7 is presented, which is considered appropriate for Brazilian contaminated sites. It consists of the following steps:

1) Define the objective of the site investigation.

2) Compile all the existing information about the site (physical and historical), including its topographic, geological, hydrographic, and photographic records and field inspections. This information will be useful for choosing the best investigation techniques, with special attention on additional information such as the position of the groundwater level, texture, evolution, mineralogy and resistance of local soils.

3) Geophysical survey is recommended at the beginning and during any site investigation program, regardless of the potential for or degree of contamination. The types of soils and contaminants should guide the decisions about the method(s) to be chosen.

4) Invasive tests: The choice of invasive technique will depend on the initial studies and on the compilation of all the available geotechnical and hydrogeological information about the site. If the existing information is insufficient, an investigation plan using different invasive techniques is recommended.

5) Direct testing like SPT soundings for subsoil characterization or disturbed soil sampling can be carried out and has been widely used for geotechnical site investigations in Brazil. This test can also be carried out during the construction of monitoring wells.

6) In areas with soft soil and/or clean sand and shallow groundwater levels, which are very common in Brazilian coast, piezocone tests with complementary tools (such as resistivity, pH sensors, MIP detectors and soil and water sampling) are very useful and their uses should be encouraged. These versatile invasive tools cause low

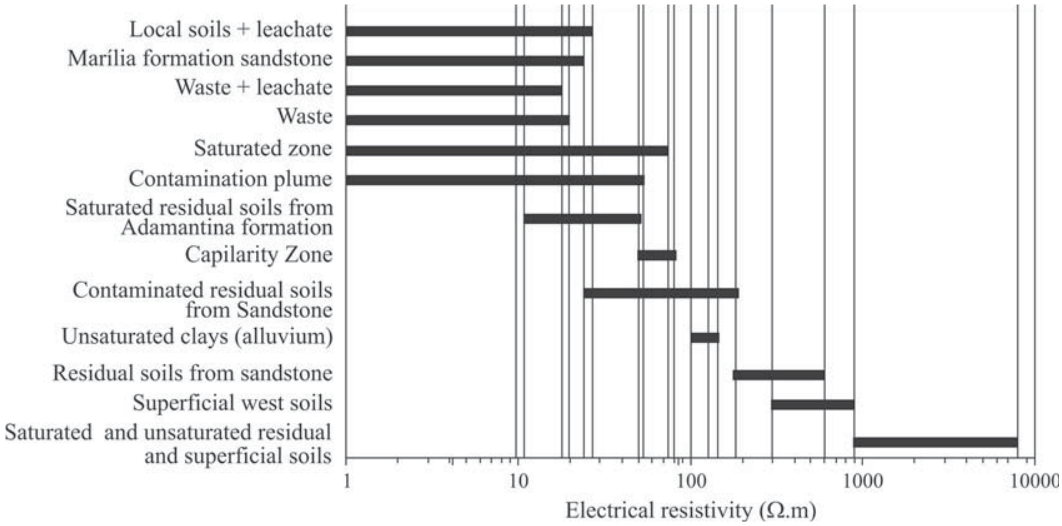

Figure 6 - Range of resistivity values for the study MSW disposal site, based on integration of field and laboratory testing data.

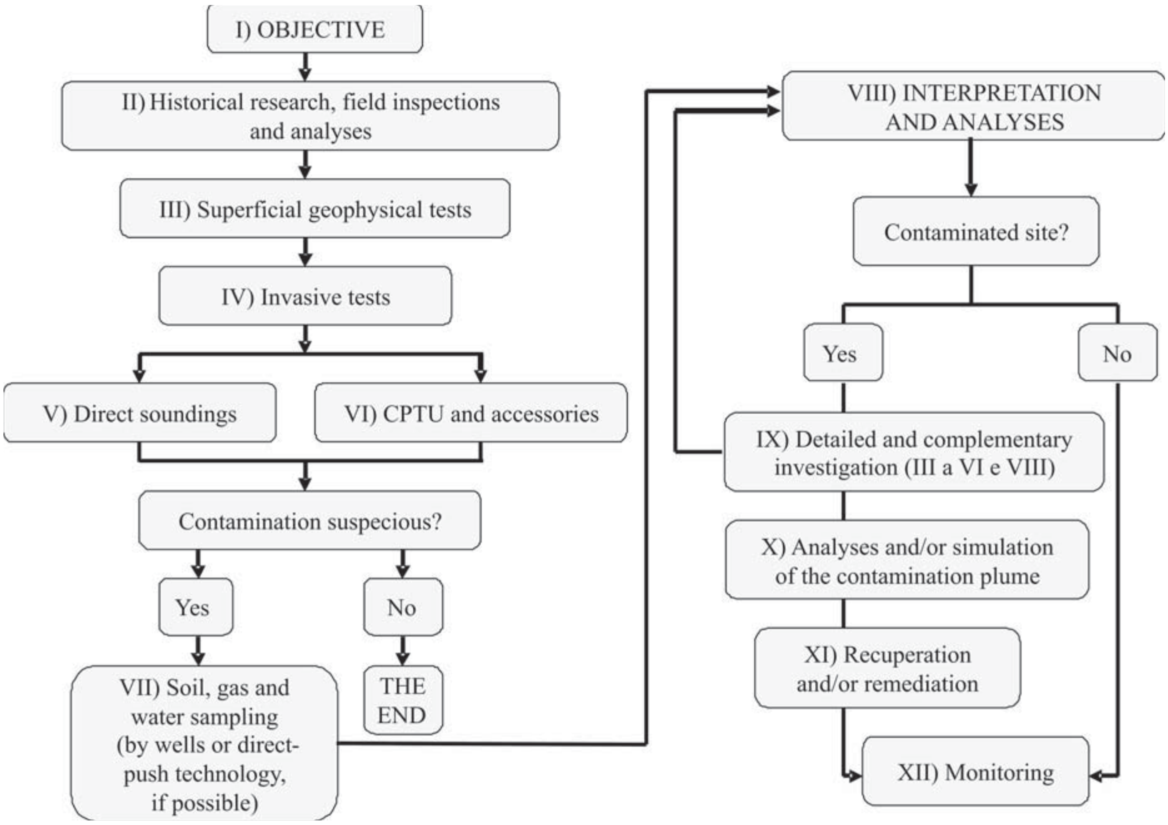

Figure 7 - Proposed geo-environmental investigation plan for Brazilian contaminated sites (Mondelli, 2008).

disturbances, and in contaminated and highly stratified soils allow detailed profiling with high reliability, proving to be very effective for geotechnical and geo-environmental investigations (De Mio *et al.*, 2005). For tropical soils, which can be highly resistant and the groundwater is usually deep, the piezocone test could be used in combination with other direct and hollow penetration techniques, as it was done for the Bauru's MSW disposal site.

7) In areas where geophysical or preliminary tests indicated anomalies or possible contamination, soil, water and gas sampling is recommended for geotechnical and geochemical characterization. This procedure is very im-

portant to confirm contamination. Atterberg limits, grain size distribution and X-ray diffraction can be considered the most appropriate tests for tropical soils for geotechnical characterization based on laboratory tests. The recommended geochemical parameters to monitoring are: temperature, electrical conductivity, pH, Eh and specific tests for possible contaminants likely to be encountered at the site, which are diagnosed in step II and III. With regard to gas sampling, a preliminary identification is required, including propagation pathways and direct contact with individuals that work or live around the site. Monitoring techniques, such as the monitoring wells installation and geophysical survey information, should also be used as the basis for future remediation and recovery plans.

8) An integrated interpretation from the various site investigations testing data is required to define the geological-geotechnical profile and the spatial distribution of the contaminants. The constituents of the contaminants will determine the parameters to be analyzed in geochemical characterization of groundwater and air.

9) A detailed and/or complementary site investigation should be carried out if contamination has been confirmed or if additional data are needed for a conclusive interpretation. This will entail additional sampling of soil, water and gas, laboratory tests to estimate the parameters of pollutant transportation, and additional *in situ* tests during this phase of the site investigation program.

10) After definition of the conceptual model, the contamination (s) plume(s) can be analyzed based on numerical flow modeling and/or on geophysical test results.

11) Remediation plan and remediation phase: If financial resources are insufficient or there is no interest in remediation at that time, a simple plan can be drawn up to recuperate the site or close it.If financial and interest support exists, the remediation plan should be carried out based on risk assessment results.

12) A monitoring plan using surface geophysics and/or monitoring wells is recommended for almost all cases where there is the slightest suspicion of contamination.

6. Conclusions

This paper presents a brief review on geo-environmental site investigation, in order to direct Brazilian environmental specialists to provide an effectiveness investigation plan, considering the practical difficulty of this work for site-specific conditions and different contamination types. It is important to combine the experience of environmental agencies with the knowledge of highly qualified experts, who could benefit from their experience in tackling practical problems, especially for multidisciplinary geo-environmental issues.

In the maintenance of the equilibrium of the natural environment, Canada's environmental agency is also concerned with human health, thus requiring the investigation and remediation of any contamination. The situation in Brazil differs from that of Canada, since only the state of São Paulo has a complete set of environmental regulations, which are primarily concerned with human health and areas of environmental protection. Moreover, Brazil does not have the culture of preservation and people often do not believe in the existence of environmental contamination or do not understand the risks involved on it.

The suggested geo-environmental investigation plan presented herein for Brazilian contaminated sites includes the combination of direct and indirect techniques, since mineralogy and the degree of evolution of tropical soils give rise to a very particular behavior. Therefore, even the guidelines listed here should be followed with restrictions in view of Brazil's wide variety of soils and climates, and should always be complemented by local experience. Indirect tests should be applicable always before sampling and laboratory tests in a site investigation program, to support the decision of their position, number and depth.

The location of monitoring wells based only on topographic and preferential groundwater flow information does not always meet the objective of a geo-environmental site investigation plan, since the contamination plume(s) is(are) influenced by the form, time and location of contamination source. In addition, tropical regions commonly show a complex hydrogeology and a heterogeneous geological evolution of natural materials, as presented herein in the study case of the Bauru's MSW disposal site. The combination and interpretation of different investigative techniques enables these variables to be diagnosed, allowing monitoring wells to be repositioned based on more detailed information, including previously detected contamination spots, and aiding in the interpretation.

It is advisable to use indirect testing methods such as electrical resistivity tests at the outset of any work on contaminated or even potentially contaminated sites to avoid direct contact with contaminants, *e.g.*, domestic or industrial landfills and hazardous waste dumps, since they can provide background values. This step provides a broad picture, facilitating the solution to future problems, especially with regard to the waste disposal on tropical soils, which are highly heterogeneous, and reducing the future investigations costs.

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