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Characterization of Hydrocarbon-Contaminated Sites Based on Geoelectrical Methods of Geophysical Exploration

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Abstract

Electrical methods are effective tools for the characterization of oil-contaminated sites and are applied in defining the geometry of the contaminated plume and in designing the remedial process. The optimal methodology integrates geoelectric methods, data processing, and interpretation techniques. Electromagnetic profiling is a reliable and fast method used to provide the configuration of oil-contaminated plume from apparent resistivity map and used to guide the subsequent electrical resistivity tomography survey. From advanced field work methods, data processing, and interpretation procedures, electrical resistivity tomography survey provides the three-dimensional (3D) configuration of the contaminated plume, migration pathways, location of active contaminated sources, and information about lithology. For separate contaminated and clean zones, a petrophysical modeling is used for the calculation of soil resistivity based on groundwater salinity. Taking the pore-water salinity value into account, an inversion algorithm recalculates resistivity maps into maps of clay content, porosity, and cation exchange capacity, allowing a more accurate determination of the volume of contaminated soil. From clay content data, hydraulic conductivity values are calculated for determining the groundwater vulnerability due to vertical migration of contaminants from upper layers. The optimal geoelectric methodology is an efficient procedure to assess hydrocarbon-contaminated sites, with emphasis on large sites with deeper groundwater table.

Keywords: oil-contaminated soil, geoelectrical characterization, petrophysical modeling, contaminated plume, OGEOMET

1. Introduction

In many countries, the growth of oil industry has been accompanied by the contamination of environment owing to exploitation, transportation, refining, and distribution of hydrocarbons. Over the years, great interest has been focused on the study of the environmental impact from oil industry. The spill of oil products can be a devastating event, with obvious consequences. Oil spills have a wide range of negative effects on the environment and economy. The spillage damages waterways, animal life, and plants. Determining the presence and concentration of hydrocarbon contaminants in the subsurface is performed by drilling and chemical analysis of soil samples collected from wells. The steps involved before the results of chemical analyses are obtained are very boring, expensive, and time-consuming. Moreover, in most geological situations, the oil contaminants are concentrated above the water table, implying that it is necessary to drill up to the aquifer, thereby increasing its vulnerability by the infiltration of contaminants from the surface. In most cases, geological conditions such as the presence of hard formations and deeper groundwater table make the drilling works more complicated, expensive, and time-consuming. The location of drilling points without prior knowledge of the spatial distribution of contaminants in subsoil ("blind" selection of drilling points) decreases the efficiency of this procedure.

The resistivity contrast between clean and contaminated rocks depends on the age of the spill. In the case of recent spills, the presence of high-resistivity anomalies is expected. A low-resistivity anomaly arises in contaminated zones between 4 and 6 months after the spill has occurred, depending on the lithological and weather condition of the study area. Sauck [1] proposed that the low-resistivity anomaly is created by the intense action of bacteria on hydrocarbons in the lower part of the vadose zone. The organic and inorganic acids yielded during biodegradation process increase the dissolution of minerals, releasing ions that increase the total dissolved solids (TDSs) in the pore water. Abdel-Aal et al. [2] found some important details of this biodegradation process and changes in the electrical properties of contaminated zones. They demonstrated that the increase of soil conductivity contaminated by hydrocarbons due to the biodegradation process is mainly related to high-surface conductivity of biofilms between solid and liquid components created by bacteria in the pores of the affected rocks. Thus, the application of geoelectric methods is very useful for characterizing both recent and matured oil-contaminated zones [1–3].

Several investigations have demonstrated the successful application of the surface resistivity methods for configuration (in plan and depth) of the hydrocarbon-contaminated zones. Electrical resistivity tomography (ERT) and electromagnetic profiling (EMP) methods are useful for the delimitation of the resistivity anomalies caused by different types of hydrocarbon contaminants and rocks in rural [4, 5], industrial [6], and urban [7] sites. Soil resistivity depends mainly on water content and its salinity, clay content, and porosity. There are many models describing the dependence of soil resistivity on these factors (e.g., [8, 9]). The methodology shown in this chapter includes the use of the petrophysical model explained in detail by Shevnin et al. [10]. In the laboratory, the behavior of soil resistivity versus water salinity in clean soil samples is measured, and clay content, porosity, and cation exchange capacity (CEC) are determined. The knowledge of these petrophysical parameters is used to define the geoelectric

boundary between contaminated and clean zones. It is also possible to obtain cross sections and maps of clay content, porosity, and CEC, using interpreted resistivity data from ERT survey and groundwater salinity information [11]. For uncontaminated soil, these parameters (clay content, porosity, and cation exchange capacity) are close to true petrophysical parameters, estimated with traditional methods in the laboratory. In contaminated soils, petrophysical parameters reach anomalous values. This helps in defining the contaminated plume.

This chapter presents an optimal geoelectric methodology for the characterization of hydrocarbon-contaminated sites that include the application of EMP and ERT methods with advanced petrophysical inversion of the geoelectrical data in order to define the geoelectric boundary between clean and contaminated soil and to estimate soil petrophysical parameters.

2. Optimal geoelectric methodology (OGEOMET)

The optimal geoelectric methodology (OGEOMET) integrates the field and laboratory methods for measuring the soil and water resistivity in situ and on samples, respectively. OGEOMET also includes advanced petrophysical interpretation of the geoelectric data in order to define the geoelectric boundary between clean and contaminated soil and to estimate some soil petrophysical parameters. The field operations include EMP and ERT methods to obtain the spatial distribution of the soil resistivity and the groundwater resistivity measurements (WRMs). In addition, we perform the resistivity measurements in soil samples (RMSSs) to determine clay content, porosity, CEC, and hydraulic conductivity required for the characterization of the contaminated site. **Figure 1** shows the flowchart of field operations, processing, and representation of results obtained from the OGEOMET.

2.1. Application of the electromagnetic profiling (EMP) method

EMP is a reliable and fast method to provide the configuration of the surface contaminated by oil plume from apparent resistivity map. The application of the EMP method involves measuring the response of the subsurface in an induced electromagnetic field. Using the EM31-MK2 equipment [12] (**Figure 2**), an electromagnetic field is generated by a transmitter antenna, inducing eddy currents within the ground. These induced currents generate a secondary magnetic field. Both primary and secondary magnetic fields are measured in a receiver antenna. The ground conductivity (mS/m) is calculated from the ratio of the secondary and primary magnetic fields, and it is affected by a number of factors including clay content, moisture and salinity of pore water, conductive (metal) objects, and conductive contaminants. The EMP results, although not providing detailed stratigraphic information (layers and their thicknesses), can offer the horizontal changes in soil apparent conductivity.

In **Figure 3**, an example of EMP application on one rural site is presented [4]. The depth of the local aquifer is 4 m. The resistivity map has been constructed from the EMP data obtained using EM31-MK2 equipment [12] for the vertical polarization of the magnetic field, ensuring a maximal depth of investigation of 6 m. Twenty-two EMP profiles were performed on the

study site. Each measured conductivity value (mS/m) was converted to a resistivity (Ohm-m) value. The low-resistivity anomalies (blue zones, **Figure 3**) indicate the presence of hydrocarbon contaminants affected by biodegradation process (“mature” contamination). This result is useful to plan the ERT survey (see flowchart in **Figure 1**).

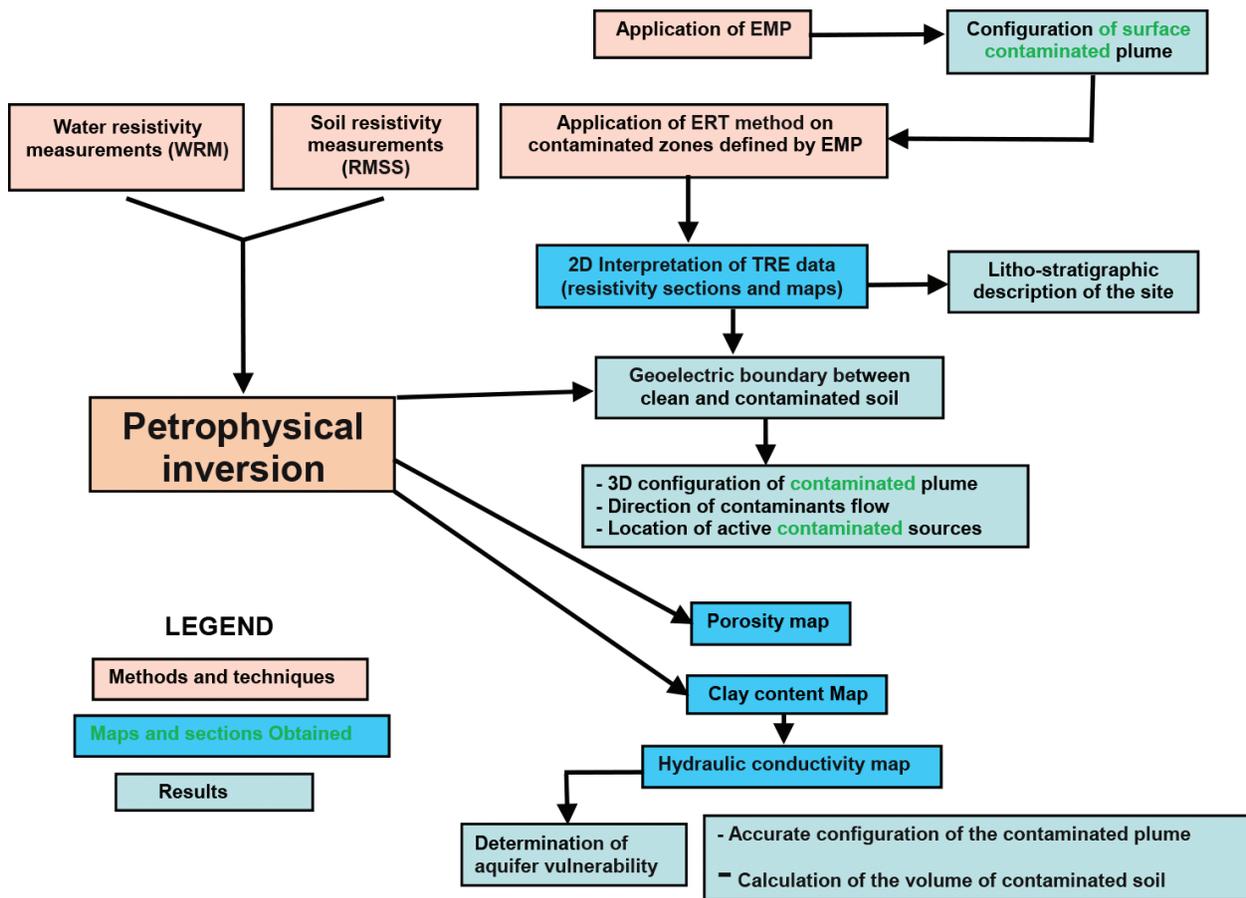


Figure 1. Flowchart of the OGEOMET for the characterization of hydrocarbon-contaminated sites.



Figure 2. EM31-MK2 ground conductivity meter in field operations [12].

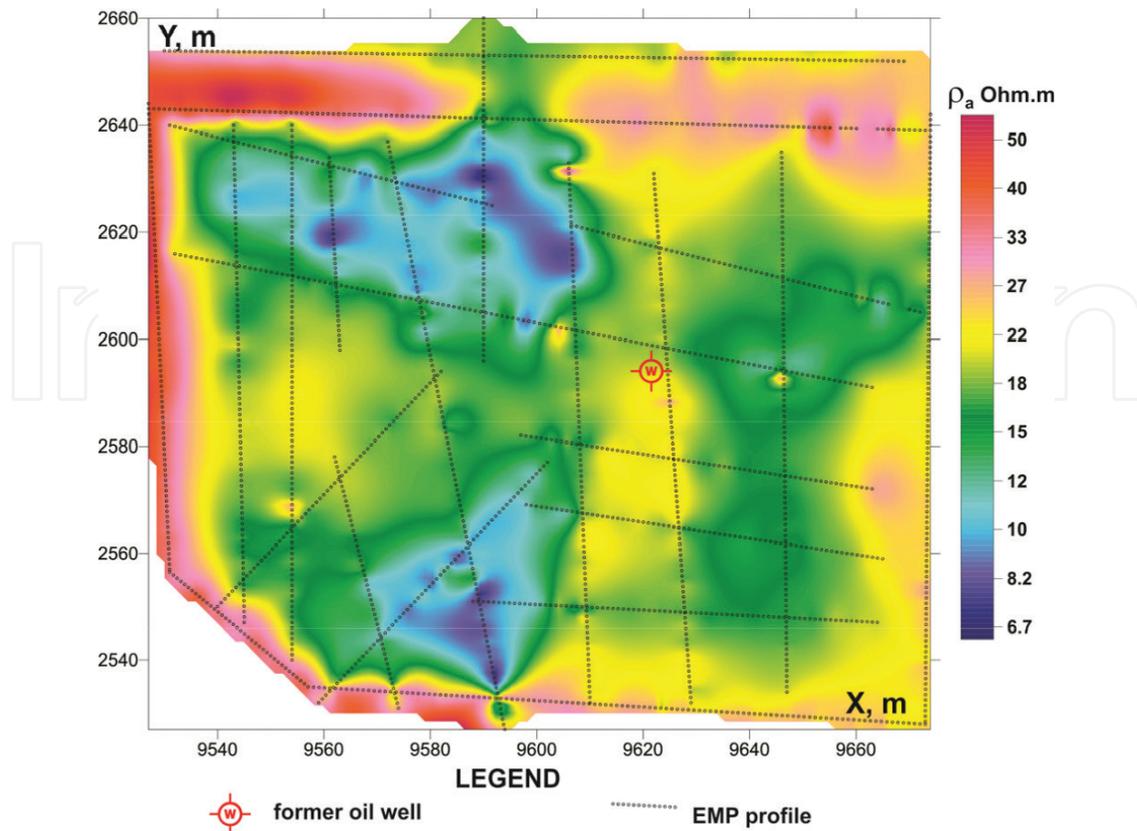


Figure 3. Resistivity map obtained by EMP in a rural site.

2.2. Water resistivity measurements (WRMs)

The procedure for WRM is simple and includes the collection of water samples (~250 ml) in previously selected sampling points (e.g., wells, lagoons, swamps, etc.) using a plastic or a glass container (do not use metal container). A portable tester (e.g., HI98130) is placed in a container, and water conductivity (mS/cm) and temperature (°C) are measured. The water temperature variations are corrected using a reference temperature of 20°C. In some sites, the number of sampling points and their spatial distribution allow the production of water resistivity map. This map gives the preliminary delimitation of main contaminated zones. For example, **Figure 4** shows the water resistivity map obtained in the same rural site where the EMP method was applied (**Figure 3**). Forty-four water samples were collected from wells and pit. The water resistivity map shows low-resistivity anomalies (blue zones in **Figure 4**) as potentially contaminated zones, corresponding to the main low-resistivity anomalies determined by the EMP method (see **Figure 3**). The decrease of the water resistivity in the contaminated zones demonstrates that the biodegradation process of hydrocarbon contaminants increases the values of TDS in pore water of the affected soil.

Frequently, a water resistivity map is not obtained due to lack of water-sampling points. In this case, clean groundwater must be collected, in at least one sampling point, for the calculation of water resistivity and salinity values, useful for the petrophysical inversion procedure and the determination of geoelectric boundary between clean and contaminated soils.

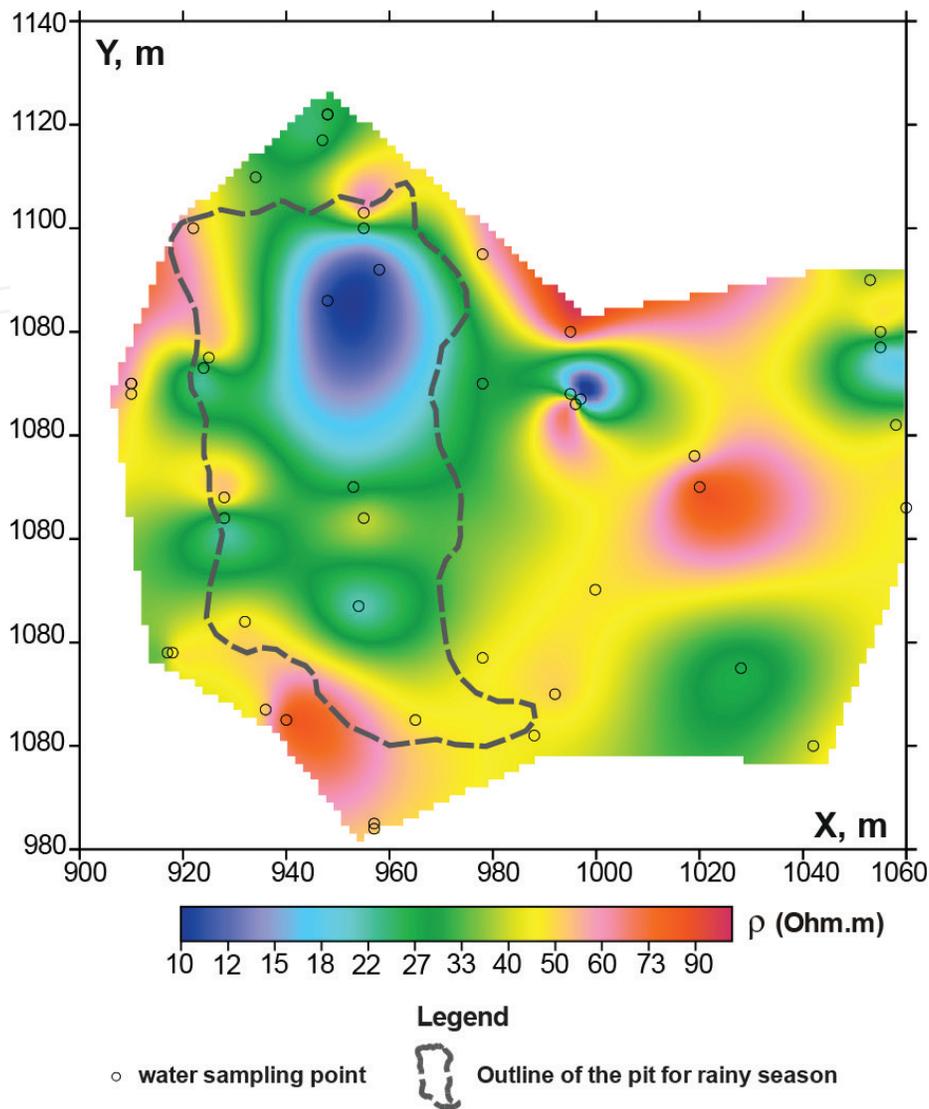


Figure 4. Water resistivity map obtained by the application of WRM in a rural hydrocarbon-contaminated site.

2.3. Resistivity measurements of soil samples (RMSSs)

The soil samples should represent different soil types of the site. For this purpose, a drilling point, outside the contaminated area, is selected, and some soil samples are collected at different depths. A laboratory procedure that gives the characteristics of soil resistivity versus pore water salinity is applied. Each soil sample is dried and homogenized and, then, divided into five similar parts (subsamples) and placed into five soil boxes. Each soil box consists of a rectangular plastic (insulated) container with four electrodes (two to inject current and two to measure voltage). Once the subsample is placed into soil box, the water of known salinity (different for each soil box) in the range between 0.1 and 70 g/l is added to completely saturate each subsample. Taking into account that the electrokinetic process requires significant time (especially for clayed sediments) to achieve an equilibrium, we perform the resistivity measurements 1 h after water deposition. The measurements are performed in the low-frequency range to avoid problem with the electrode polarization and induction effect. The resistivity

values are corrected to reference temperature (e.g., 20°C). Thus, we have five soil electrical resistivity values (one for each soil box) depending on the salinity of the pore water ($\rho_{\text{exp}}(C)$) [11]. The soil resistivity obtained as a function of the pore water salinity is used for the petrophysical inversion.

2.4. Petrophysical inversion

From WRM and RMSS, and resistivity data obtained by ERT, it is possible to determine parameters such as clay content, porosity, and cation exchange capacity (CEC), which are important in determining the geoelectric boundary between clean and contaminated soil, and the hydraulic conductivity (K), useful for the assessment of the aquifer vulnerability.

The experimental resistivity versus salinity curve ($\rho_{\text{exp}}(C)$) and electrical resistivity values calculated ($\rho_{\text{th}}(C)$) using the theoretical model developed by [10, 11] were subjected to a curve-fitting process to calculate the different geological parameters. The theoretical model considers the geometrical microstructure of the components as well as electrochemical processes occurring in the soil for a wide range of the pore-water salinity and clay content. Different parameters are used for petrophysical modeling, including the following: water salinity (including types of anions and cations with their valence, hydration number, sorption constant, and mobility), porosity, capillary radii, humidity, cementation exponent m , the CEC for each component of soil, including sand and clay, and the temperature of the soil. The result of the modeling is the calculated soil resistivity as a function of water salinity. We need to estimate three soil parameters: clay content, porosity, and CEC. Once local groundwater (or salinity) and soil resistivity are known, the clay content and porosity are estimated for clean soils of the study site, and the geoelectric boundary is defined. K was calculated based on the clay content using the empirical formula proposed by Shevnin et al. [13]

$$K = 7.2 \cdot 10^{-4} \cdot C^{-2} \quad (1)$$

where K is the saturated soil hydraulic conductivity ($\text{m} \cdot \text{day}^{-1}$), and C is the clay content in relative units between 0.01 and 1.

A practical example from **Figure 5** shows the results of the petrophysical modeling for the same rural site depicted in **Figures 2** and **4**, where a soil sample was collected from a clean zone. According to priori information, the collected soil belongs to the layer with a higher clay content. Applying the procedure explained earlier, the modeled sample (dashed curve C) gives the clay content of 43%. A value of resistivity of 27 Ohm-m (salinity of 0.22 g/l) was determined for noncontaminated groundwater. Lithologies from pure sand (curve 0) to sand clay with 40% of clay (curve 40, **Figure 5**) are in the range of 14–120 Ohm-m (vertical line A). The clay content for this resistivity interval is between 4 and 40%. Taking into account that the maximum clay content for the site is 43%, then the resistivity values less than 14 Ohm-m correspond to the contaminated soil (gray rectangle B), the resistivity value of the geoelectric boundary being used on the delineation of contaminated zones in resistivity sections and maps.

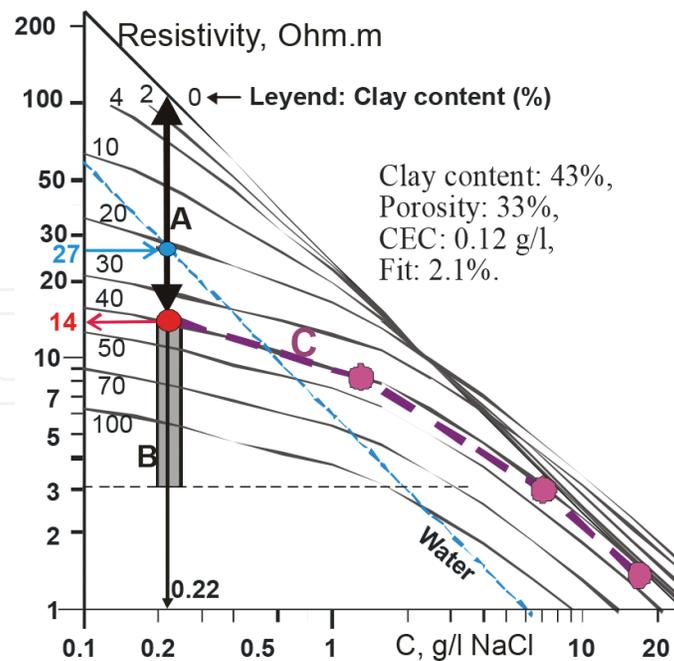


Figure 5. Petrophysical modeling of the rural contaminated site using soil, groundwater, and ERT information.

2.5. Application of the electrical resistivity tomography (ERT) method

ERT uses short spacing for measurements along profiles for two-dimensional (2D) study of inhomogeneous media, and a great number of electrodes are reconnected manually or automatically. The ERT survey has specially selected measuring and current points to obtain high resolution and low distortion caused by near-surface inhomogeneity [14]. In this method, different electrode arrays can be used (pole-dipole, dipole-dipole, and Wenner, Schlumberger).

The 2D inversion of filtered apparent resistivity data provides the high-quality cross sections of the true resistivity distribution. The application of the ERT method allows us to find the depth of contaminated zones and, finally, the 3D configuration of hydrocarbon-contaminated plume. Based on the resistivity cross sections and adding geological information, it is possible to make up lithostratigraphic sections. Figure 6 shows the interpreted resistivity section of ERT profile 6 (see Figure 7) conducted at the same rural site (Figures 2 and 4), whose petrophysical modeling (Figure 5) defined a geoelectric boundary between clean and contaminated soils of 14 Ohm-m (red contour, Figure 6). The contaminated zones are defined in depth accurately allowing a direct soil sampling, reducing the number of soil samples needed for their quantification, and increasing the accuracy of results. For inversion of the apparent resistivity, the software RES2DINV [14] was used.

From 11 interpreted resistivity sections, it was possible to obtain a resistivity map for “target layer.” The target layer, where hydrocarbon contaminants are accumulated, is located in the lower part of the vadose zone. Figure 7 shows the resistivity map for the target layer with a depth interval of 2–4 m, defining the contaminated plumes according to the geoelectric boundary (14 Ohm-m) defined from petrophysical modeling process. Two main

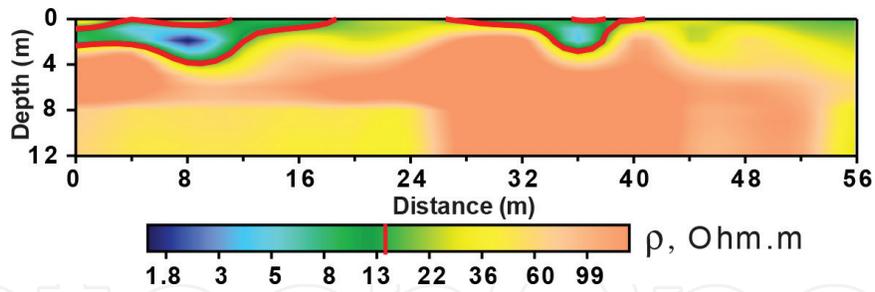


Figure 6. Geoelectric section of profile 6. Contaminated zones are delimited in depth optimizing the soil-sampling work.

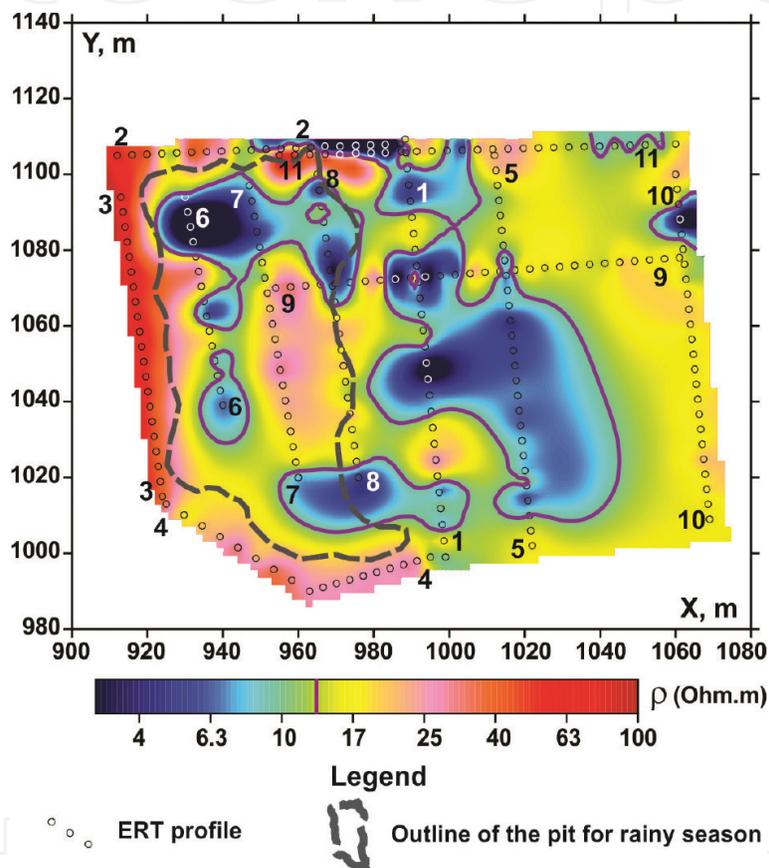


Figure 7. Resistivity map for target layer.

low-resistivity anomalies are related to high contaminated zones. The dashed line shows the pit outline (Figure 7).

2.6. Estimation of petrophysical parameters: determination of the volume of contaminated soil

Soil resistivity maps, determined by ERT and groundwater salinity information, were converted into petrophysical (clay content, porosity, and CEC) maps. The petrophysical parameters estimated for clean soil correspond to their true values, while values of clay content, porosity, and CEC calculated for contaminated soils do not match with their true values;

however, its high contrast (anomalous values—background) allows delineation of the contaminated zones with a high resolution. The contaminated zones are more clearly observed in petrophysical maps, with emphasis on clay content (clay content of $>43\%$, **Figure 8**), than those in resistivity maps (**Figure 7**) for the target layer. In **Figure 8**, three main highly contaminated areas are observed in the pit zone. An additional small anomalous area is defined in the central part of the site (**Figure 8**). Using information about target layer (thicknesses from sections and areas from map), a total volume of hydrocarbon-contaminated soil of 4728 m^3 was obtained.

2.7. Determination of the aquifer vulnerability

The rural site discussed earlier did not require the analysis of vulnerability of the aquifer to hydrocarbons infiltration from the upper layers because there are no active contaminated sources and the oil spill happened over 20 years ago. Therefore, we take another rural site as an example, where 8 months after a gasoline spill caused by pipeline leakage occurred, an ERT survey was performed [5] (**Figure 9**).

A total of 174 ERT points were distributed in six profiles (**Figure 9**). A Schlumberger array with AB/2 spacing from 2 to 20 m was used. **Figure 10** shows the geoelectric section obtained

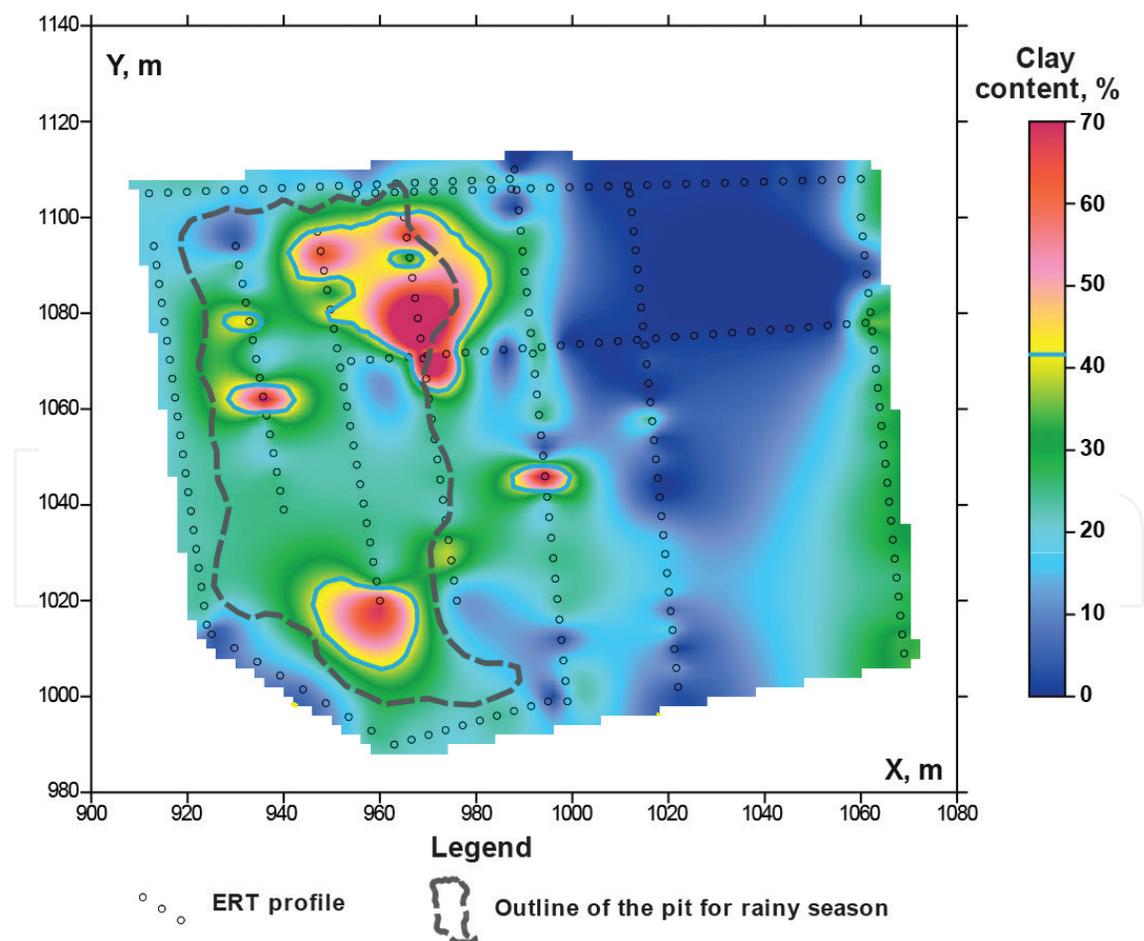


Figure 8. Clay content map for target layer of the rural site.

from ERT profile 1 (see **Figure 9**). The intermediate layer corresponds to high-resistivity sandy aquifer with a maximum clay content of 2%. The portion of the aquifer with a lower resistivity (marked by a dashed line, **Figure 9**) indicates the possible presence of matured contamination.

After determining the clay content values in each layer, the values of K can be estimated using expression (1). The clay content map for the aquitard of the site allows the estimation of a hydraulic conductivity map, which defines the areas where the aquifer is more vulnerable to infiltration of contaminants from upper layers. In **Figure 11**, four areas of the aquitard, near to spill point, with the lowest clay content (**Figure 11A**) or the highest hydraulic conductivity (**Figure 11B**) values, correspond to high aquifer vulnerability zones by infiltration (hydrogeological windows) of gasoline from the aquitard.

Using the information from different ERT sections, an aquifer resistivity map is obtained, showing the main plume associated with a detected pipe leakage point (red diamond, **Figure 12**). Note that another small contaminated zone close to another pipeline is observed in the eastern part of the site (**Figure 12**), although this claim needs to be investigated.

2.8. Estimation of migration pathways of contaminants and location of sources of contamination

Figure 13 shows an industrial-contaminated site, where the presence of mature contamination was evident. An oil-contaminated industrial site was studied using the ERT method [15]. Based on resistivity range, the configuration of the contaminated plumes and the degree of contamination were defined. The minimal anomalous resistivity values are associated with the maximum oil contamination, which is in correspondence with biodegradation process and the presence of conductive biofilm. The configuration of the surface of the maximum zone of contamination helps to locate the unknown active sources of contamination (**Figure 13**). Zoning of

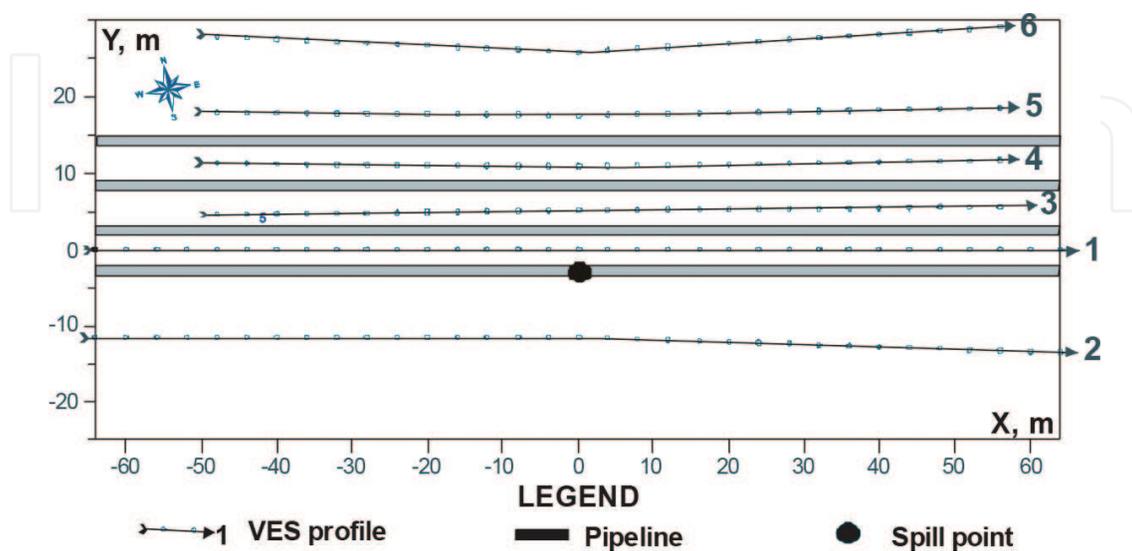


Figure 9. Scheme of the site.

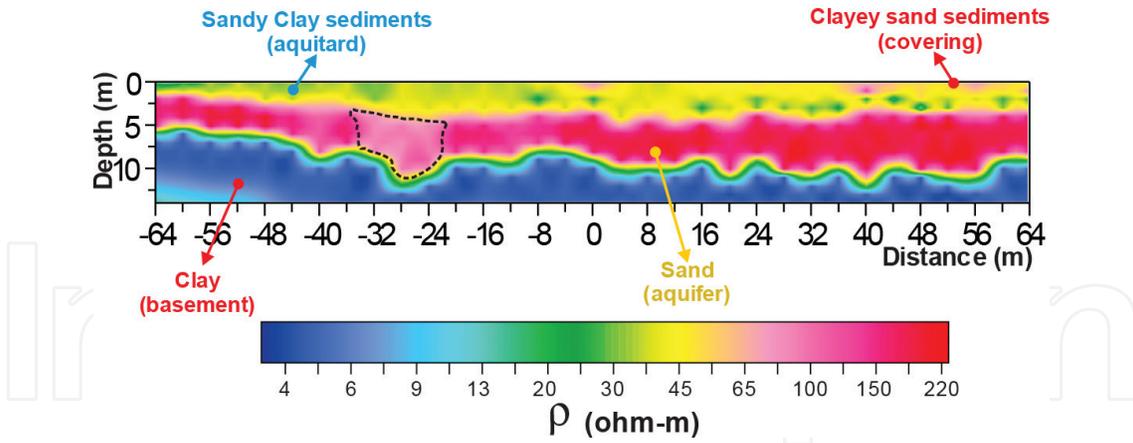


Figure 10. Resistivity section of ERT profile 1.

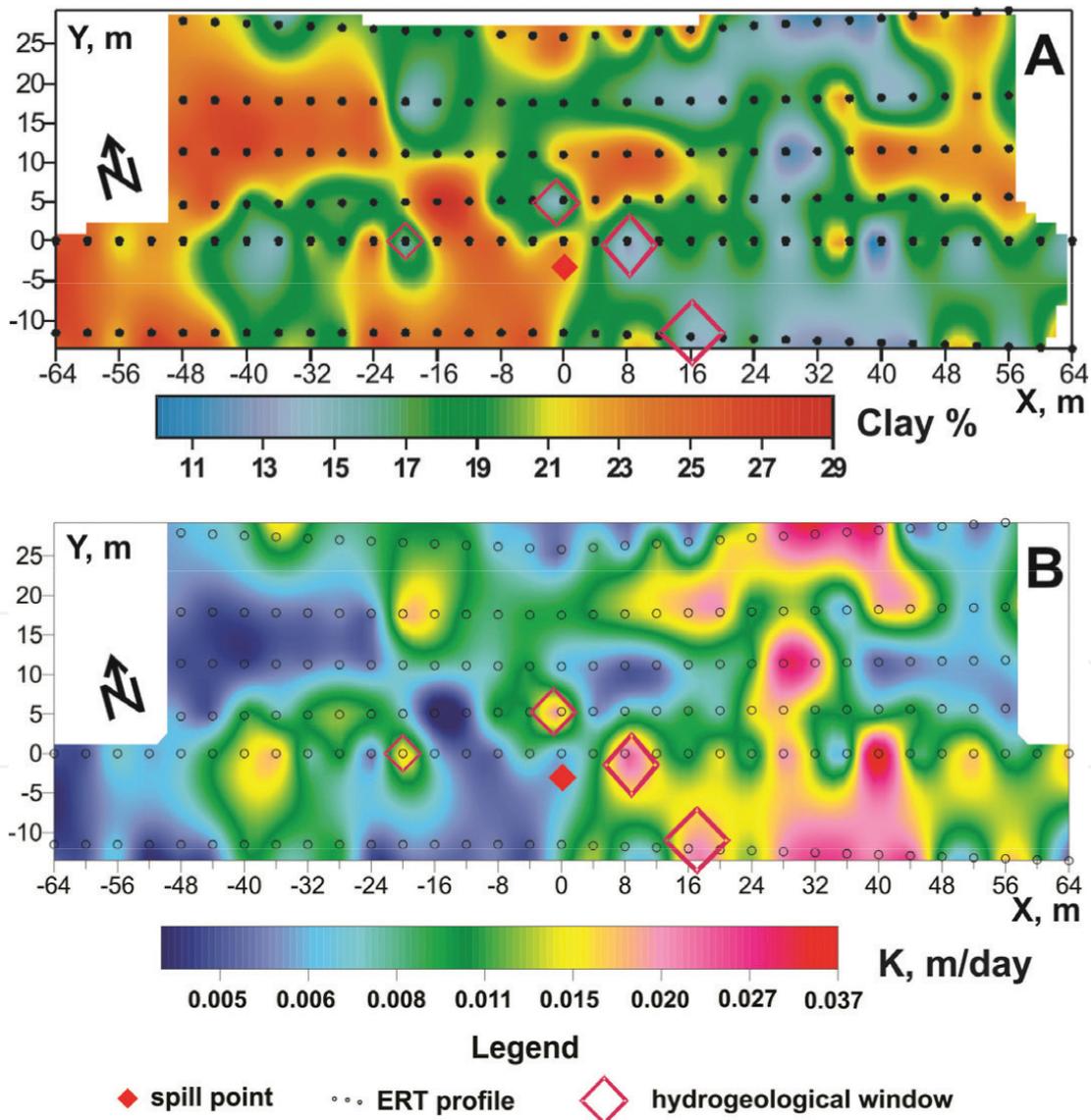


Figure 11. (A) Clay content map and (B) hydraulic conductivity map for the aquitard.

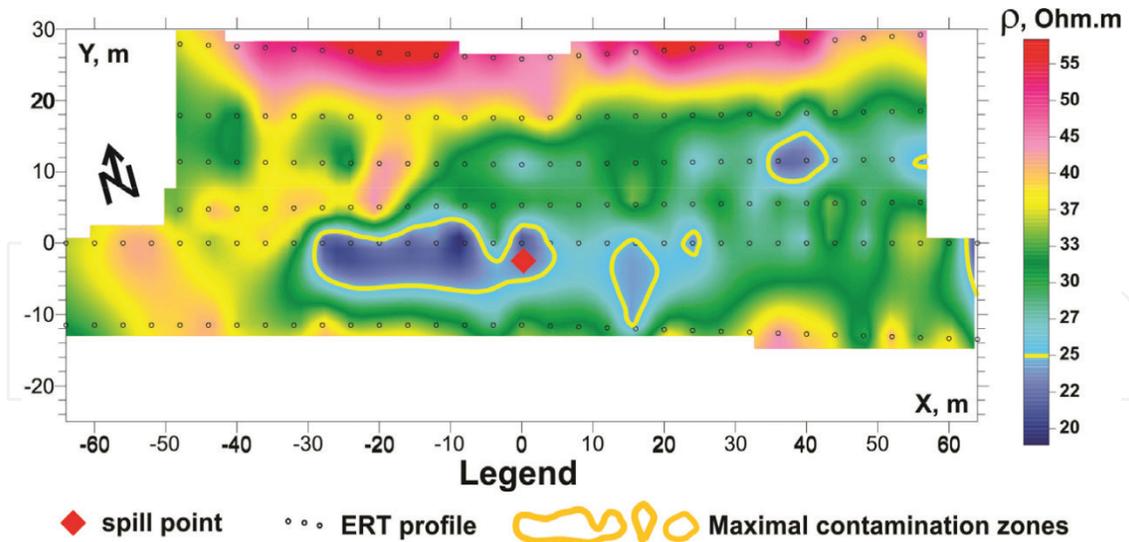


Figure 12. Resistivity map for the aquifer.

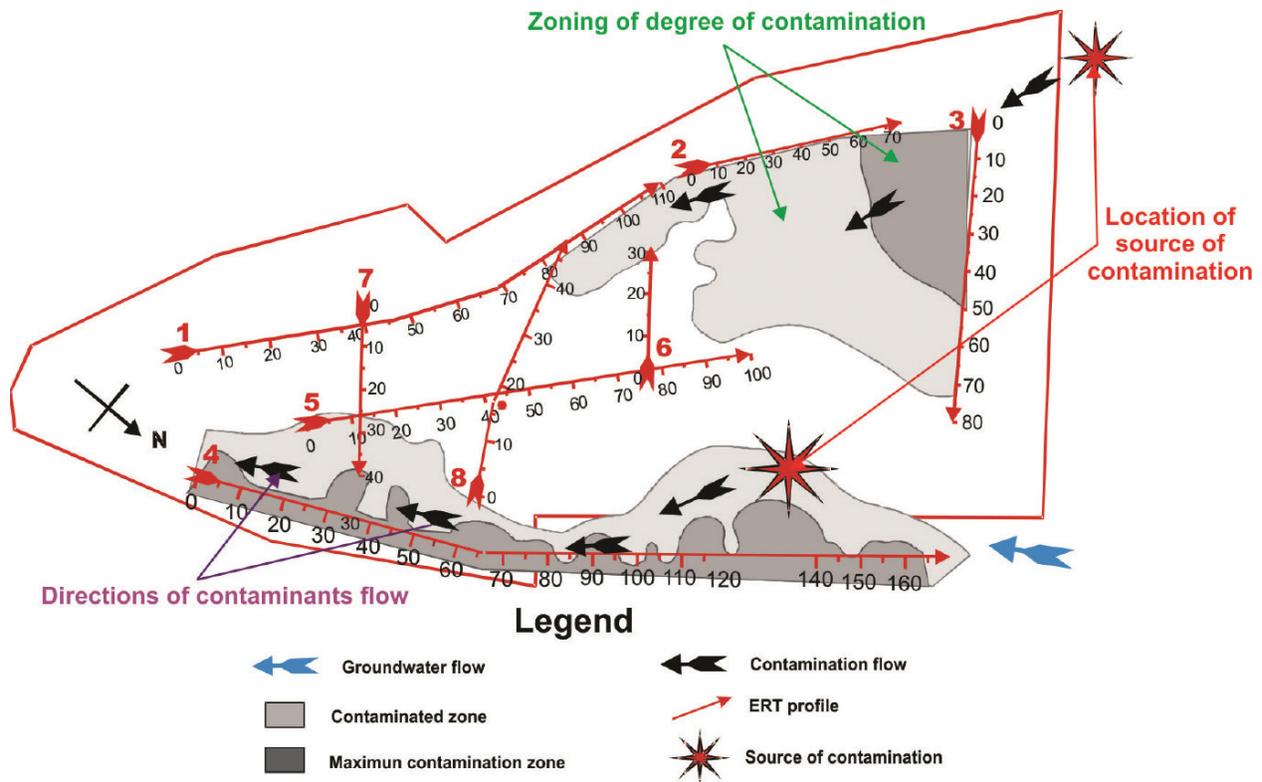


Figure 13. Determination of pathways of contaminants flow and location of sources of contamination in an industrial site.

the contaminated plume (contaminated and maximum zones of contamination) and location of sources of contamination, including information on the regional trend of groundwater flow and topographical characteristics of the site, allow the estimation of the migration pathways of contaminants in the subsurface. Two active sources of contamination, related to minor oil leakage from pipelines, were located.

3. Conclusions

The OGEOMETE effectively integrates the application of different methods and techniques such as the EMP, ERT, WRM, MRSS, and petrophysical modeling.

These methods are efficient tools for the assessment of hydrocarbons of contaminated sites. Useful results have been obtained in sites with different geological-geographical environments, including rural, urban, and industrial sites.

The application of the OGEOMET reduces the number of drillings and soil samples for chemical analysis. Based on our experience, the application of the OGEOMET can reduce the number of drills from ten to five times and the number of soil samples from 20 to 10 times.

The advantages of the application of the OGEOMET are more evident as the size and complexity of the grade of the study site increase. The whole or partial application of the OGEOMET depends on the characteristics and requirements of the study site.

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