

Pollution Detection by Electromagnetic Induction and Electrical Resistivity Methods: An Introductory Note with Case Studies

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Abstract This chapter introduces the combined usage of electromagnetic induction and electrical resistivity methods for the assessment of soil pollution at shallow depths, with a particular focus on situations of potential contamination of groundwater. After a brief introduction of the electrical resistivity tomography (ERT) and the electromagnetic induction (EMI) techniques, three case studies are presented, dealing with potential threats to groundwater resources, in which the synergic usage of ERT and EMI permitted effective investigations about the contamination status and possible threats.

Keywords Electrical resistivity tomography, Electromagnetic induction, Geophysical surveys

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Abbreviations

EM	Electromagnetic
EMI	Electromagnetic induction
EMI-F	Electromagnetic induction frequency domain
ERT	Electrical resistivity tomography
GPS	Global positioning system
TEM	Time domain electromagnetic
VES	Vertical electrical sounding

1 Introduction

It is well known that specific electrical resistivity of water (or specific electrical conductivity) depends on its mineralisation, on the presence of suspended particles and of eventual organic compounds. This permits to study the concentration of eventual polluting agents in the water by direct or indirect measurements of specific electrical resistivity.

Shallow earth electromagnetic (EM) survey methods (EM profiling, mapping and sounding) and electrical resistivity tomography (ERT) have increased significantly in the past decades. The pollution of groundwater and surface water can be detected and studied by these methods, by observing the changes of specific electrical resistivity associated with the presence of pollution. The measurement unit of the specific electrical resistivity is Ωm . Its reciprocal value, i.e. the specific electrical conductivity, is measured in S/m (siemens per metre) or mho/m. The electrical conductivity of water is commonly expressed in mS/cm or $\mu\text{S/cm}$.

It is well known that the specific electrical resistivity of the ground depends also on its lithological composition [1]. As a result, pollution of groundwater is usually detectable by measurements of the electrical resistivity of the ground, which is permeated by water, taking into account its lithological characteristics.

The main features characterising the shallow depth earth (i.e. “soil” or “ground”) are:

- Lithological porous skeleton with water of various salinity
- Various particle size distribution (i.e. clay, sand, gravel, rocks) and water content
- Altered levels possibly interbedded to no altered ones
- Pieces of (armoured) concrete, bricks, wood and waste (artificial ground)

- Voids: tunnels, karst, pipes, low-density (excavated) areas, etc.
- Local targets: buried objects and archaeological targets

The main features characterising the bedrock are:

- Presence of flat or inclined stratification
- Discontinuities due to faults, fractures (at large or small scale) or cavities (i.e. karst pits), eventually filled with water and/or clay and sand

The combination of lithological knowledge, hydrological and hydrogeological information and chemical analyses of water (at least the principal anions and cations contributing to its electrical conductivity) is a fundamental aspect for the definition of the observed scenario and its interpretation.

Groundwater is always present in every kind of soil. The presence of water affects the specific electrical resistivity of the soil. The specific resistivity of fresh water is varying between 40 and 150 Ωm , according to the natural mineralisation and temperature. Soluble (ionic) pollutants can change the resistivity drastically, by decreasing the resistivity to the a few Ωm and even lower than 1 Ωm in case of high concentration of sulphates [2]; for example, in a sandy soil, the addition of 25 ppm of ionic species to the groundwater increases ground conductivity by approximately 1 mS/m [3]. In the case of oil and organic pollution, resistivity can be increased by tens of Ωm . Organic contaminants are generally characterised by a high dielectric constant and very low conductivity, thus contributing to increase the ground resistivity, although with a much lower incidence with respect to an equivalent percentage of ionic contaminant. This is mainly due to the fact that most organics are not found in emulsion with water and the stratified pattern alters significantly only the electrical properties of a thin layer, making organics in water still detectable by resistivity measurements but at a lesser degree than ionic compounds.

In general, the contamination of water can be studied by in situ measurements of specific electrical resistivity of the ground by using non-invasive near-surface geophysical methods. The methods and instruments necessary to perform such a study must be sensitive enough, especially in case of organic contamination, to permit a sufficiently low detection threshold for the practical usage.

2 In Situ Methods

The electrical conductivity measurement of groundwater samples, squeezed from soil samples, is a very important reference for in situ surveys. Conductivity measurements in the laboratory are typically performed at a controlled reference temperature, which is usually set at 25°C. The mere measurement of the conductivity of water samples extracted from samples of the investigated soil is a fundamental support to the interpretation of data collected by the non-invasive geophysical campaigns [4].

2.1 Electrical Resistivity Tomography

The electrical resistivity tomography (ERT) method is based on what is considered the oldest geophysical technique: the four-electrode electrical resistivity measurement, so-called electrical resistivity method, developed by Schlumberger brothers in the beginning of the twentieth century [5]. The aim of this section is to illustrate practical arrangements for the execution of geoelectrical measurements according to the ERT technique, while more basic information can be found in the chapter by Bavusi et al. inside this book.

Figure 1 shows a hypothetic electrode arrangement and a simplified representation of the investigated layers. Electrodes A and B (often called *current electrodes*) are connected to a transmitter, which generates a known direct electric current I , while electrodes M and N (*potential electrodes*) are connected to a receiver, which measures the voltage U across the MN pair of electrodes. In order to get information about the soil at different depths, the measurement is repeated ($A'B'$, $A''B''$, etc.) by increasing the depth of the current penetration by broadening the A to B distance (Fig. 1). The apparent electrical resistivity ρ_a can be calculated as

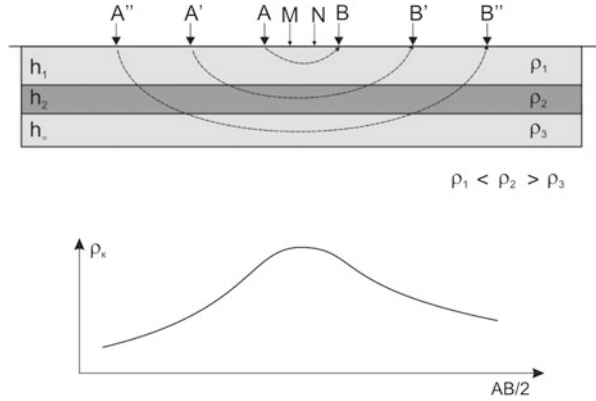
$$\rho_a = K \cdot (U/I)$$

where $K = \frac{2\pi}{\frac{1}{|AM|} + \frac{1}{|BM|} + \frac{1}{|AN|} + \frac{1}{|BN|}}$ is a geometric factor [1] and the square brackets contain distances in meters

At the bottom of Fig. 1, there is the plot of ρ_a vs. $AB/2$, which is known as the *sounding curve* of the VES (vertical electrical sounding). Another embodiment of electrical resistivity method is the electrical profiling. In this case the same arrangement of AMNB electrodes is rigidly shifted along the measurement line. The result in this case is in the form of a diagram (*profiling curve*) of ρ_a vs. the measurement position along the line [6].

During the 1980s new devices for the application of electrical resistivity methods took place. Such devices can connect many (usually 12–50) electrodes, which are typically placed with a regular spacing along the measurement line, for most of the practical arrangements. The layout of an ERT device on the field, thus, consists in a multielectrode configuration where the role of each electrode is determined by an automatic switch. In fact, using an internal automatic switchboard, an electrical resistivity tomography (ERT) device can make hundreds of measurements along one line within few minutes. ERT surveys involve the acquisition of the numerous combinations of four-electrode resistivity measurements that are possible between multiple arrays of electrodes. The configurations may use two surface electrode arrays, one surface and one downhole array (surface to borehole), two downhole electrode arrays (cross-borehole), or even two boreholes and one surface array. This type of survey, referred to as tomography, generates a high-resolution image of the planar surface containing the electrode array [7]. Such data can be also used to build 2D geoelectrical cross sections. With a number of parallel 2D cross sections and/or surface distribution of electrodes, a sort of 3D visualisation can be built. The

Fig. 1 Simplified representation of the investigated layers with hypothetical electrode arrangements. The bottom picture represents a generic sounding curve



electrical resistivity methods are developing for about one century. The measurement speed increased by hundreds of times and the capability of 2D and 3D data representation, aided by fast data inversion systems, permit to build a complete description of subsurface electrical conductivity distribution and visualise the resulting patterns in few hours. However, the further increase of data acquisition speed is limited by the nature of the mechanisms underlying the electrical current flow in geological media, which require proper settling times in order to perform each measurement session correctly.

2.2 Electromagnetic Induction Methods

Electromagnetic methods have a special place in the arsenal of geophysical tools available for environmental investigations in general and groundwater contamination study in particular. They owe their status to a number of factors. First, electromagnetic methods are directly influenced by the electrical properties of the pore fluids. Second, electromagnetic methods are sensitive to changes in geological layers and allow them to be used for geological mapping, which is a very appreciable feature for environmental tasks. Third, there is a wide range of electromagnetic equipment available in the market, in terms of methodology of investigation and different degrees of performance. The equipment is generally user-friendly and operational costs are relatively low. Fourth, electromagnetic survey techniques are non-invasive [8].

There have been a number of notable publications and reviews about electromagnetic methods for general and environmental studies within the past 50 years. The focus and applications of these methods shifted from traditional mineral deposit prospecting to groundwater and, more recently, to more general environmental studies. The interested reader could be addressed to a two-volume set edited by Misac N. Nabighian [9, 10] on applied electromagnetic methods, which covers theory, field methods and data interpretation of the active source electromagnetic

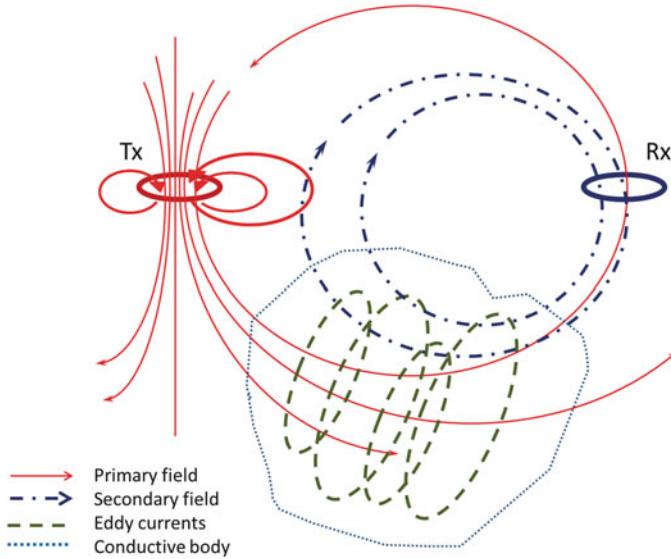


Fig. 2 Simplified sketch of the electromagnetic mechanisms underlying the electromagnetic induction methods

techniques, such as the one discussed here. Several chapters concerning environmental problems are found in Volume 1 [9]. Volume 2 [10] gives more practical results than can be directly applied to environmental studies.

The electromagnetic induction methods (EMI) are based on the physical phenomena of induction. The principles of the method are illustrated by the sketch shown in Fig. 2. Since the soil is electrically conductive (at different degrees, as discussed in the previous section), it is always possible to induce an electromagnetic (secondary) field in it, by placing the electromagnetic transmitter (Tx) of the primary electromagnetic field near the ground. The primary field induces an Eddy current, which in turn produces the secondary field. Then, the secondary field can be measured by an electric and/or magnetic receiver (Rx) at the surface. The sounding factors in EMI methods are (1) the spacing between transmitter and receiver, (2) the duration of signal recording after the cut-off of the transmitting signal (time domain), and (3) the transmitting signal frequency (frequency domain). Deeper discussion of these aspects can be found in Balkov et al. [11].

EMI devices characterised by various configurations of transmitter(s) and receiver(s), working in time domain (TEM) or in frequency domain (EMI-F) modes, are forming a large array of devices that are produced worldwide and are intended to explore the Earth from the first metres to the deep mantle [12]. In particular, the EMI-F devices for near-surface exploration are widely used for environmental studies and water pollution exploration. Some examples of successful TEM application for water pollution exploration are also known [3].

2.3 Data Output and Representation

The methodology of near-surface ERT and EM induction surveys includes linear and areal exploration approaches. The first approach gives vertical cross sections (ERT and EM sounding) and linear diagrams (EM profiling). Instead, the areal exploration results can be presented as maps and 3D pictures. An EM shallow depth instrument usually can be used by one operator, while an ERT crew should include three to five persons. Survey speed can reach up to 10 km of linear survey per day. It is very important to bind the measurement points (stations) to the map of the area explored, because precise geo-referencing is a necessary requirement for a proper interpretation of the results.

3 Case Studies

This section presents an overview of case studies in which an electrical resistivity survey was used for groundwater contamination study and assessment, by combination of EMI and ERT techniques.

3.1 Case 1: Belovo

The acid drainage from an abandoned zinc factory is leaking to a nearby swamp, producing a remarkable environmental problem. The drainage consists of a mixture of copper, silver and other water-soluble sulphates. The polluted area was studied first by EMI mapping. The obtained map of the polluted area is shown in Fig. 3. An electrical resistivity tomography made along the red dotted line (see Fig. 4) gives the cross section shown in Fig. 4. Field works were performed in the winter time and took a total time of 3 h. The observable pattern in Fig. 4 suggests a particular interpretation of this cross section, i.e. not only the swamp contains highly mineralised water characterised by low resistivity, but contamination also reaches a groundwater layer below the swamp bottom.

By combination of the information provided by EMI mapping and by ERT profiling, an evaluation of the contaminated volume of water can be done. In fact, the area of contamination can be assessed by EMI mapping, while a cross section with an indication of the contaminated water depth is given by the ERT measurement. The concentrations of the various metals dissolved in water, determined by analytical measurements, enable also the further calculation of the volumetric contribution of each metal.

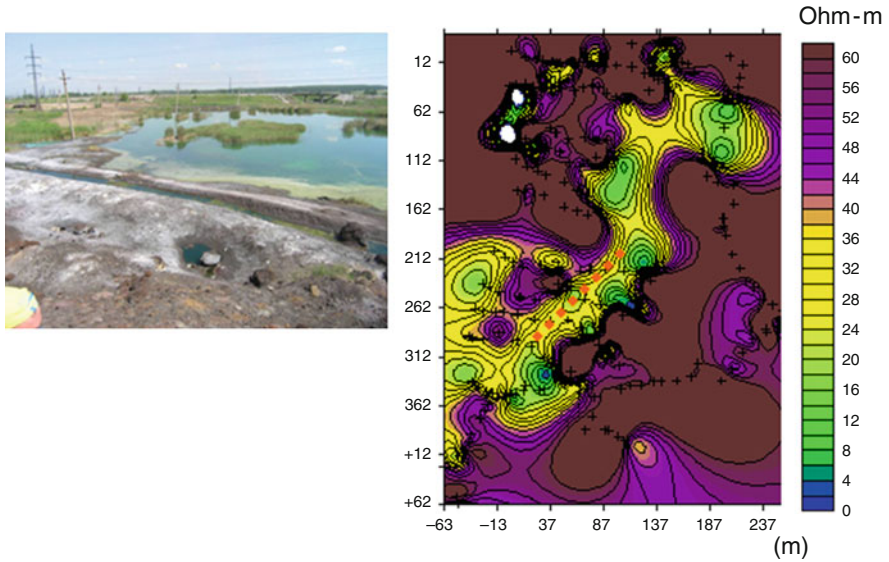


Fig. 3 Map of the polluted area made by the electromagnetic induction method (Belovo site). The left picture shows a view of the site

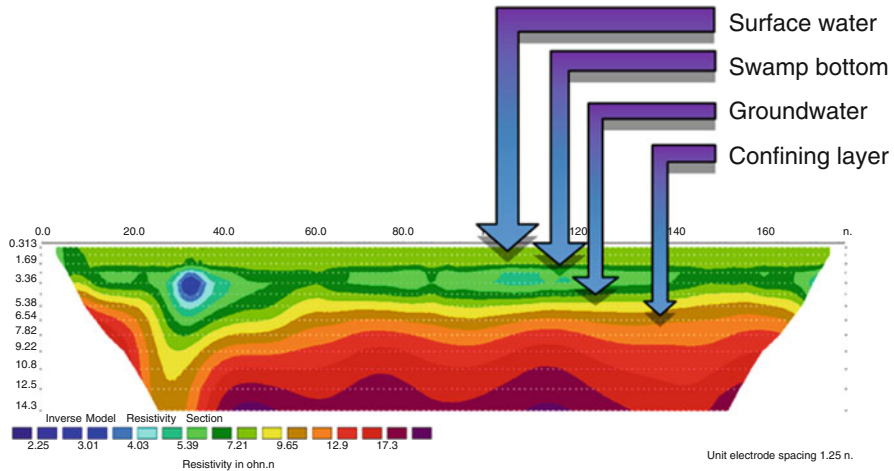


Fig. 4 ERT cross section made along the dotted line shown in Fig. 3 (Belovo site)

3.2 Case 2: Petroleum Contamination

The land along an oil pipeline can be monitored periodically by using EMI devices, in order to check possible minor leakages of oil. The result of one of such studies is presented in Fig. 5. Data representation is in the form of a cross section of

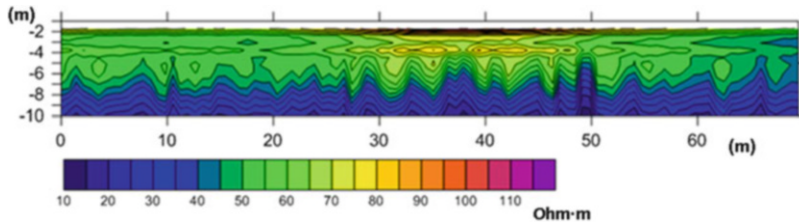


Fig. 5 Cross section of a resistivity measurement obtained with an EMI multifrequency instrument

pseudoresistivity, obtained by an EMI multifrequency instrument after reconstruction algorithms [11, 13].

Regular measurement surveys are performed by the security department of the pipeline service company, which is using the instrument since more than 5 years at the time of writing this chapter, mainly for surveillance purposes, such as the detection of leakages and of illegal connections to the pipe.

By observing Fig. 5, it is apparent how the natural horizontal layering of the cross section is disturbed by a resistive anomaly approximately 20 m long (see the pattern between 27th and 47th m, about 4 m deep). The excavation work done in the area following this survey showed an actual soil contamination with oil. Duration of the field work for the line shown has been approximately 3 min, proving the high effectiveness of this technique.

3.3 Case 3: Pesticide Contamination

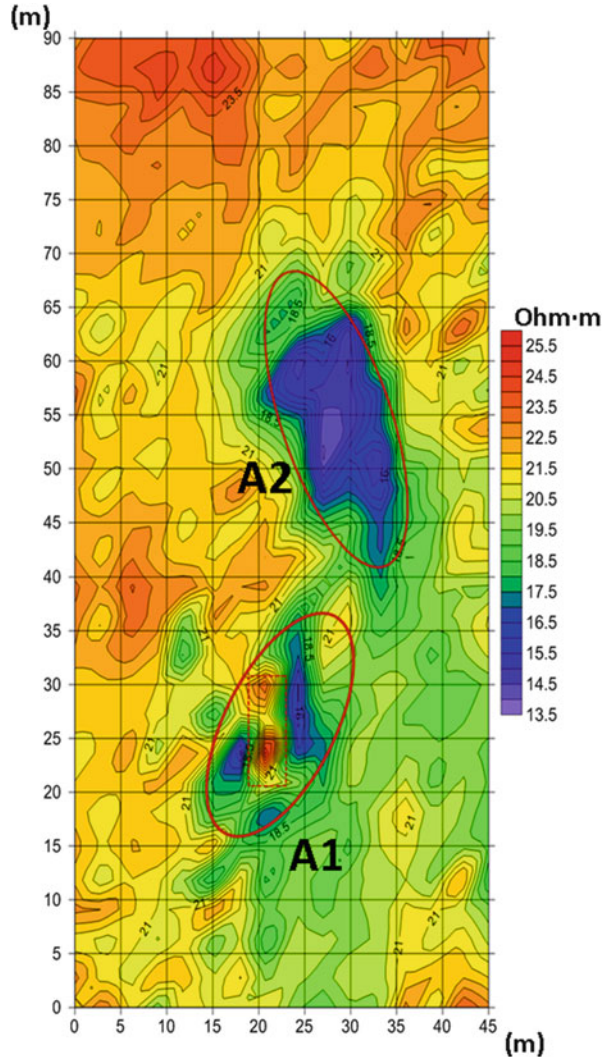
This experience regards a contaminated site, where in the late 1980s a quantity of expired pesticides were buried in a 5 m-deep pit, covered by loamy soil and a concrete covering over a portion about 4×10 m. The total weight of the buried pesticides was about 5 t and the total size of the investigated area was 90×45 m.

The area of the pit was firstly studied by EMI mapping with a 3×3 m grid, followed by ERT and EMI with a thinner grid in specific portions. Field activities took one working day.

The map of electrical resistivity is shown in Fig. 6. The red dotted rectangle shows the location of the concrete covering of the pit. Average resistivity outside of the pit is $18\text{--}22 \Omega\text{m}$. Two areas of decreased resistivity can be noted: the first one is around the pit (A1) and the second one about 10 m to the north (A2). The anomalous areas are shown with red ovals.

After individuation of the areas containing detectable anomalies, a detailed study was performed by EMI mapping with a thinner grid (1×1 m) and by parallel ERT lines. A 3D representation of data, which permits an easy identification of anomalies, is shown in Fig. 7. The subpanels of Fig. 7 show the 3D results from three different viewpoints.

Fig. 6 Map of electrical resistivity (pesticide contamination study)



Two soil samples were taken inside the A1 and A2 areas, respectively. Laboratory analysis showed that the content of pesticides was 1,000 times higher than regulatory limits at A1 and an additional ten times higher than regulatory limits at the A2 area.

One geoelectrical cross section across both A1 and A2 areas shows that deeper than the anomalous volumes there is a more resistive layer, the upper boundary of which is shown as a red line in Fig. 8. Most probably it is a layer with less content of clay consisting in a more sandy soil, compared to the upper layer. In case of infiltration down to this presumably more permeable layer, the overall contamination can easily go further the confined volumes.

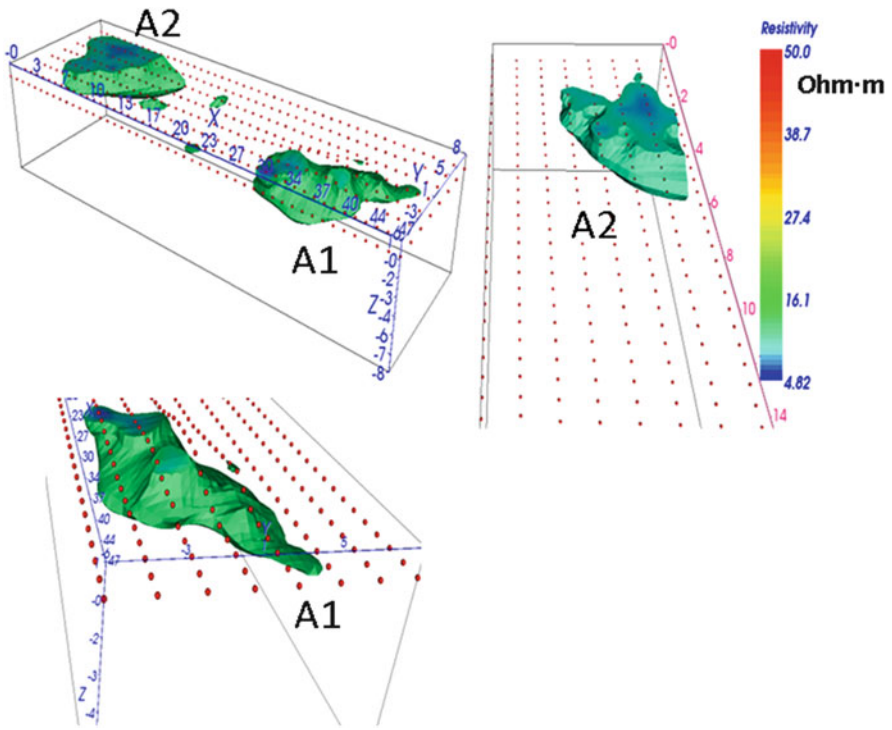


Fig. 7 3D representation of EMI data (pesticide contamination study)

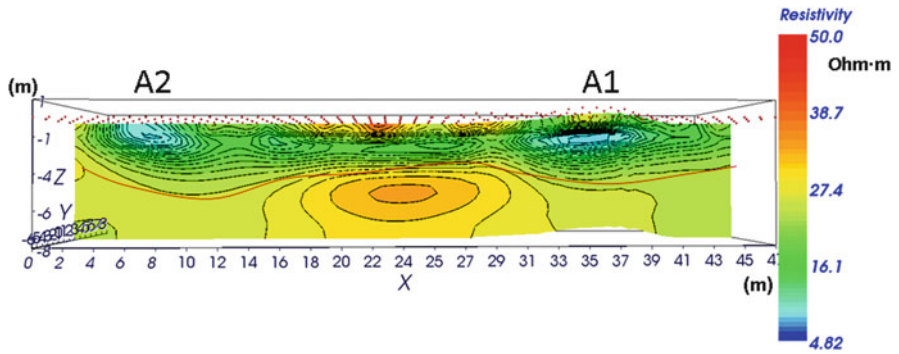


Fig. 8 ERT cross section across A1 and A2 areas (pesticide contamination study)

4 Conclusions

Electromagnetic induction and electrical resistivity surveys are very fast and effective techniques for soil and water contamination studies and are also useful tools for the assessment of environmental risks, particularly concerning the threats to groundwater resources.

The current state of the art of ERT and EMI measurement techniques, with the aid of adequate data analysis and interpretation tools, reached a sufficient degree of maturity for a cost-effective pollution risk management.

Nowadays, the most important action finalised to improve the effectiveness of such investigation techniques is the dissemination of best practice cases between water protection bodies, administrations and other stakeholders, focused on the management of risks about the pollution of water and environmental risks in general. This chapter aims at giving a useful contribution also to those who are not necessarily familiar with geophysical methods, but who may be directly or indirectly users of the geophysical techniques discussed, in the framework of groundwater contamination studies.

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