Science of the Total Environment 506–507 (2015) 546–553

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Use of electrical tomography methods to determinate the extension and main migration routes of uncontrolled landfill leachates in fractured areas

Ismael Casado [a,b,*], Himi Mahjoub [a,c], Raul Lovera [a], Jesús Fernández [d], Albert Casas [a]

[a] Department of Petrology, Geochemistry and Geological Prospectio, Universitat de Barcelona, Martí i Franquès s/n, 08030 Barcelona, Spain
[b] Department of Geology and Environmental Earth Science, Miami University, 501 East High Street, 45056 Oxford, OH, USA
[c] Ecole Nationale des Sciences Appliquées d'Al Hoceima (ENSAH), University Mohammed Premier, Ajdir, Al Hoceima, Morocco
[d] Department of Agriculture, Ranching and Environment, Diputación General de Aragon (DGA), Plaza de San Pedro Nolasco, 7, 50071 Zaragoza, Spain

HIGHLIGHTS

- The outcrop topographic reconstruction is done using cores and aerial photographs.
- Hydrochemical and geophysical data allow defining two leachate migration paths.
- Conductive anomalies in ERT are linked to high contaminant concentration.
- The distribution of conductive anomalies defines the fractured basement migration.
- The plume direction reflects important tectonic control in the migration process.

ARTICLE INFO

Article history:
Received 29 March 2014
Received in revised form 15 November 2014
Accepted 21 November 2014
Available online 27 November 2014

Editor: Eddy Y. Zeng

Keywords:
Landfill
Resistivity tomography
Fractured aquifer
Polluted site (max 6)

ABSTRACT

This study focuses on the uses of the electrical tomography and its relationship with hydrochemical data in order to characterize contaminated groundwater flows in fractured aquifers. The studied area is contaminated with different hazardous substances like lyndanes, organochlorinated compounds and benzenes coming from the old non-controlled Sardas landfill. The enormous volumes of wastes filling the landfill have generated a convoluted mixture of leachates. Due to the lack of a landfill liner, the leachates have migrated through the fractured Eocene marls towards the Gallego River. The striking correlation between high concentrations of polluted groundwater and low electrical resistivity of the subsurface ($<8\ \Omega\cdot m$) allows defining the principal contaminant migration route thanks to the distribution of these conductive anomalies. This mapping verifies that there is intense tectonical–structural control of the leachate migration, because the deep migration presents the same direction as the geological axis fold.

1. Introduction and background

Uncontrolled landfill sites are one of the main sources of underground and surface water contamination. Large volumes of different types of wastes (urban, industrial, etc.) are accumulated in landfills, with no planning or monitoring. The absence of monitoring leads to the leakage of leachates into the environment, thereby severely contaminating the aquifers of the area. One example is the Sardas's landfill located close to Sabiñánigo (Huesca, Spain). It is an old uncontrolled landfill that has been dumping huge quantities of urban, agriculture and industrial wastes since the 70s. In 1995, the Departamento de Medioambiente de la Diputación General de Aragón (DGA) decided to close the landfill using filling sand, installing an insulation High Density Polyethylene (HDPE) geotextil, and building an insulation wall in the exit flow zone of the dumpsite made of cement–bentonite. Among all the waste residues in Sardas, the most toxic are the leachates of chloro-alkyl industry and the organochlorides generated by the pesticides industry (Breivik et al., 1999; Li, 1999; Vijgen et al., 2011; Fernández et al., 2013). The presence of these leachates in the waters below the landfill area has been observed since 2004, with the presence of a dense non-aqueous phase liquid (DNAPL) being detected on the surface in 2009 (Dirección General de Calidad Ambiental, 2010). This resulted in intense control of the landfill site and initiation of works to extract the different contaminant phases (Fernández et al., 2013).

It is the priority of multidisciplinary studies to reduce the pollution impact in sites such as the Sardas's landfill. Such studies characterize

* Corresponding author at: Department of Geology and Environmental Earth Science, Miami University, 501 East High Street, 45056 Oxford, OH, USA.
E-mail addresses: iscaferr@gmail.com, casadoi@miamioh.edu (I. Casado), jfernandezc@aragon.es (J. Fernández).

http://dx.doi.org/10.1016/j.scitotenv.2014.11.068
0048-9697/© 2014 Elsevier B.V. All rights reserved.

the geological and hydrological movements that are associated with the distribution and nature of different contaminating substances in the leachate. In these types of studies, geophysical, and more specifically, electrical methods (Deceuster and Kaufmann, 2012) are valuable tools, since they provide information on the distribution of the contaminants as well as the petrophysical characteristics of the geological substrate.

2. Material and methods

2.1. Studied area

The Sardas landfill is located near the current industrial area of the city of Sabiñánigo (Huesca, Spain), a few meters from the Sabiñánigo hydroelectric reservoir. Geologically, it is situated within the southern area of the Pyrenees range, specifically in the central-eastern area of the Anticline Basin (Jaca basin), which is defined as a narrow, vergent anticline towards the south (Teixell and García-San Segundo, 1994). The local geology (Fig. 1) is composed of sands and marlstones from the Larres marls Formation, Sabiñánigo sandstone and Pamplona marls that are locally covered by quaternary sediments (gravels, sands and shales). These sediments form glacis or via alluvial terraces that cover the landfill site.

2.2. Data collection and analysis

Previous works, performed by the regional government (Dirección General de Calidad Ambiental, 2010, 2011), included monitoring wells with continuous testing in the polluted site (PS) and in the landfill area (S), piezometers with follow-up of levels, in situ and laboratory hydraulic conductivity trials, electrical conductivity measurements, pH, temperature, redox and dissolved oxygen potential using multiparametric probes, as well as more than 200 leachates, soil and residue analysis (Fernández et al., 2013).

In the current work, a topographic reconstruction was also made of the original geometry of the outcrop over which the Sardas landfill is located. Historical aerial photography from 1956 was used for this and was geo-referenced using software locating analog points between the current orthophotography and that of 1956. The residue

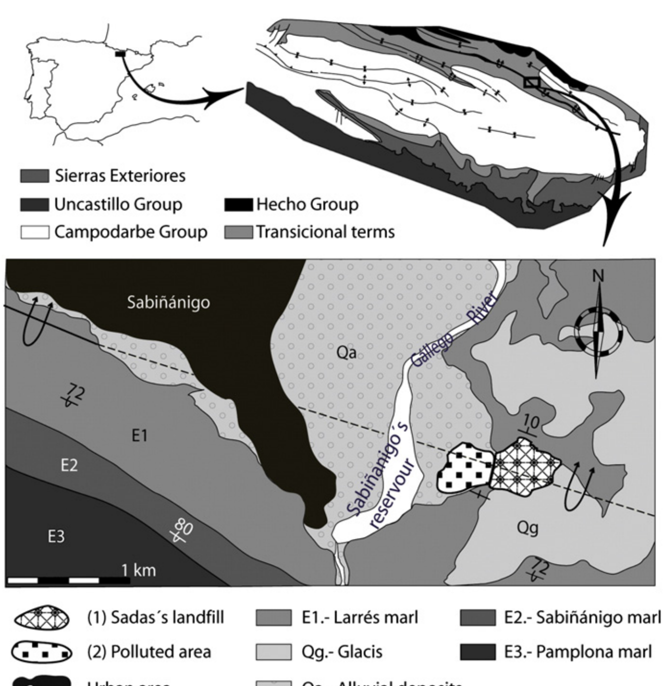

Fig. 1. Location and geological situation of the studied area. Modified from Teixell and García-San Segundo (1994).

thicknesses obtained by cores have helped to determine the substrate level that existed prior of the dumpsite. The core thickness data was superimposed over the geo-referenced data, enabling relative values to be established for the elevated and valley areas, thus achieving its topographic model of the site.

The geophysical prospecting was mainly carried out in the alluvial area. A total of 7 electrical resistivity tomography (ERT) profiles were acquired using a 48-channel SYSCAL PRO resistivity meter using a Wenner–Schlumberger device. Additionally, 6 ERT profiles previously performed by the regional government were reprocessed and inverted. All these profiles are named with the prefix A. Profile A13 was performed with a 0.5 meter spacing between electrodes over a slightly fractured marl outcrop to the north of the dumpsite with the aim of determining the resistivity range of the marl formation. Profile A11 was performed with 5 m spacing between electrodes with the goal of determining the degree of contrast generated by the contaminated water in response to the resistivity of the medium. Profiles A1, A2, A3, A4, A5, A7, A8, A9 and A10 were performed with 2 m spacing between electrodes, these profiles were performed to define the morphology of the contaminating plume. Finally, profiles A6 and A12 were performed at the base of the landfill (Fig. 2) a few meters from the impermeable screen (4 m and 1.5 m respectively) to evaluate the impermeability of the screen.

3. Results

3.1. Geophysical data

The obtained apparent resistivity data were inverted using the RES2DINV software package (Loke and Barker, 1996). This software is used to transform the apparent resistivity of the samples to calculated resistivity values by an inversion process. The inversion process is based on a smoothness-constrained least-squares method (De Groot-Hedlin and Constable, 1990). The results of the inversion process for the ERT profiles show an RMS error of less than 8% after 5 iterations and an apparent resistivity contrast less than 20/1. Moreover, a qualitative analysis was performed on the inversion values in the confluence areas of the previous profiles (Profiles A1, A2, A3, A4, A5 and A6) with the acquired profiles for this study (Profiles A7, A8, A9, A10, A11, A12 and A13; Fig. 2). This qualitative analysis allowed relating the resistivity values estimated by the inversion process of both acquisition campaigns. The comparison of the converging zones showed that they have very similar resistivity values and variations to one another; thus it can be considered as satisfactory analysis.

In general all the profiles, except the parametric profile (A13), are characterized by the presence of a shallow thin layer with resistive materials and relatively low resistivity values under them (Figs. 3 and 4). Many conductive anomalies with resistive values lower than 8 Ω·m and zones with values greater than 42 Ω·m are found within the low resistive layer (Figs. 3 and 4). In order to describe and discuss the meaning of these relationships in the resistivity values, the profiles A13, A11, A2 and A12 will be used as the most representative examples of the medium characteristics, defining with the initials C_x (in order of appearance) the conductive anomalies and with the initials R_x (in order of appearance) the resistive zones (Fig. 4).

3.2. Landfill modeling

As depicted by the 3D topographic model superimposed over the historical aerial photography of 1956 (Fig. 5), the landfill is located in an escarpment zone, with irregularities greater than 30 m and with slopes up to 59%. Two drainage lines converge in the landfill's central area. The urban and industrial wastes have been dumped in these valleys. By comparing the 3D 1956 topographic surface and the present day surface, the calculated total waste capacity of the Sardas's landfill is 240,298 m^3.