Sensitivity analysis of multi-electrode arrays for characterizing the non-saturated zone in groundwater vulnerability assessment

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Abstract

The near-surface environment acts as a filter and buffer for contaminants introduced from the surface by anthropogenic activities. For this reason there is a great need to improve our understanding of the shallow subsurface taking into account the increasing demand for vulnerability maps which illustrates the exposure of aquifers against pollution. These maps are designed to show areas of greatest potential for groundwater contamination on the basis of local subsurface conditions.

A shallow, unconfined sand-and-gravel aquifer is highly vulnerable to pollutants because rapid recharge gives little time to contaminants to degrade naturally or be adsorbed before reaching the aquifer. Conversely, a deep, confined aquifer has a very low vulnerability. Infiltrating recharge could take years to reach the aquifer, allowing time for contaminants to abate or degrade.

Therefore, parameters affecting vulnerability are mainly the permeability and the thickness of each protective layer. For unconsolidated sediments, the permeability is strongly related to the clay content, which can be deduced from indirect resistivity methods, like electrical resistivity tomography. Such geophysical method can be of great help in groundwater vulnerability studies because they do not alter the structure of the soil. In this paper the sensibility of different geoelectrical multi-electrode arrays for assessing groundwater vulnerability is tested.

Groundwater vulnerability assessment

The term vulnerability is applied to represent a group of essential characteristics determining the degree of protection that natural environment provides to an aquifer affected by a polluting load. Vulnerability assessment incorporates both the natural state of the vadose zone and the aquifer, as well as the relative danger posed by present and future land-uses (Anderson and Gosk, 1989).

There is a surprising number of methods available for characterizing aquifer vulnerability (Vrba and Zaporozec, 1994), many of them were developed empirically, according to the local hydrogeologic settings, data sets, and intended objectives of the mapping project (Rupert, 2001).

One of the most widely used method for assessing groundwater vulnerability is DRASTIC, a groundwater quality index for evaluating the pollution potential of large areas using the hydrogeologic settings of the region developed by the US EPA (Aller et al., 1985). This model employs a numerical ranking system which establishes relative weights to various parameters, this helps to evaluate the relative groundwater vulnerability to contamination. The hydrogeologic settings which make up the acronym DRASTIC are:

[D] Depth to water table, [R] Recharge, [A] Aquifer Media, [S] Soil Media, [T] Topography, [I] Impact of Vadose Zone and [C] Conductivity (Hydraulic).

DRASTIC Index = 5 D + 4 R + 3 A + 2 S + 1 T + 5 I + 3 C

The determination of the DRASTIC index involves the impact of the vadose zone (thickness and permeability) that often is not available (Rupert, 2001). Nevertheless, studies using DRASTIC environment allow an investigation of the potential for groundwater pollution on a regional scale, rather than on a site specific basis.

The AVI method (Aquifer Vulnerability Index) developed in Canada by Van Stempvoort et al. (1992) quantifies vulnerability by the hydraulic resistance (c) to the vertical flow of water through the geologic sediments above the aquifer. Hydraulic resistance is calculated from the thickness (d) of each sedimentary layer and the hydraulic conductivity (k) of each of the layers:

$$c = \sum_{i=1}^{n} \frac{d_i}{k_i}$$

Thickness of individual sedimentary layers can be taken directly from the well records. Hydraulic resistance (c) has the dimension of time (e.g. years) and represents the flux–time per unit gradient for water flowing downwards through the various sediment layers to the aquifer. The lower the global hydraulic resistance (c) is the greater the vulnerability of the underlaying aquifer will be.

The gap among boreholes can be filled with geophysical measurements. As geophysical data characterize the rock material by its physical properties, it must be shown that these physical properties are related to the hydraulic properties leading to the infiltration time. If this is true, fast geophysical mapping techniques can be applied to enable a better interpolation between the drillings (Figure 1).

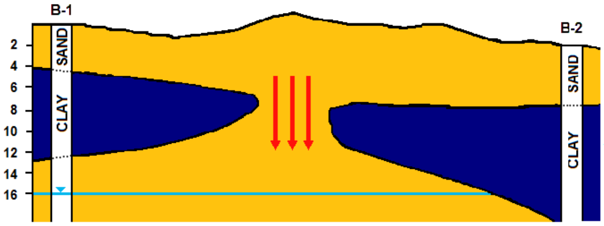

Figure 1: Problem occurred if vulnerability is assessed using only data interpolated between boreholes without additional information. The gap in the clayey layer is not detected and therefore pollutants from the land surface can leach vertically downwards to the water table.

Methodology

Electrical imaging is increasingly being applied for environmental investigations, as they can identify material properties and material boundaries, as well as variations in space and time of relatively large volumes of soil (Dahlin, 1996). Besides, this method is non-destructive which means that it is able to give information without drilling, avoiding boreholes that are potential paths for transmission of pollutants to the aquifer.

Clay dominated layers can be easily identified by resistivity surveys due to the electrical resistivity contrast with permeable sandy layers. For this reason Kalinski et al. (1993) and Kirsch et al. (2003) suggested to replace k (hydraulic conductivity) in AVI method, with the electrical resistivity ρ given the close relationship between both variables.

Then they defined a geophysical based vulnerability index GPI, as:

$$GPI = \sum_{i=1}^{n} \frac{d_i}{\rho_i}$$

This parameter coincides with the longitudinal electrical conductance defined by Maillet (1947) as the second Dar Zarrouk parameter. Opportunely, this fact solves the ambiguity stated by the equivalence principle inherent in the electrical resistivity interpretation because this parameter is independent from the chosen model.

The dimension of the protection index is mS/m, like the one of the conductivity. This protection index takes into account the effect of topography as vulnerability over a hill would be lower than in the surroundings due to the greater depth of the groundwater table. Indeed this reflects the real protection situation, while the normalized protection index gives an overview of the geological conditions down to the reference depth (Kirsck, 2005).

Synthetic data

Synthetic modelling of the electrical resistivity imaging method was conducted in order to optimise survey configurations and establish whether the resolution required for groundwater vulnerability assessment was obtainable. Modelling was used to investigate the resolution of specific geological features such as layering at a range of depths. Different classical electrode arrays, such as Wenner, Schlumberger and dipole–dipole have been tested. The choice of a particular array in ERT can make a substantial difference for the results, also depending on the geometry and resistivity of the investigated structures (Martorana et al., 2009).

Several synthetic models have been generated in order to analyze the sensitivity and resolving power of each array for detecting thin clay layers and leaky windows in the clay layers. The first model (Figure 2) represents a section 98 m long and 20 m depth, that simulates a layered structure. The resistivity values of each layer are respectively: 100 Ω·m, 10 Ω·m and 300 Ω·m. The thickness of the upper layer is fixed to 5 m and the thickness of the conductive intermediate layer ranges from 1 to 10 meters. An array of 48 electrodes is supposed to be carried out over the model, with an electrode step equal to 2 meters.

As can be seen in figure 3, the thickness and resistivities of the inverted models obtained by each array differ significantly because of the equivalence problem inherent in the method, but the electrical conductance remains almost invariable, with values around 0.25 mS/m.

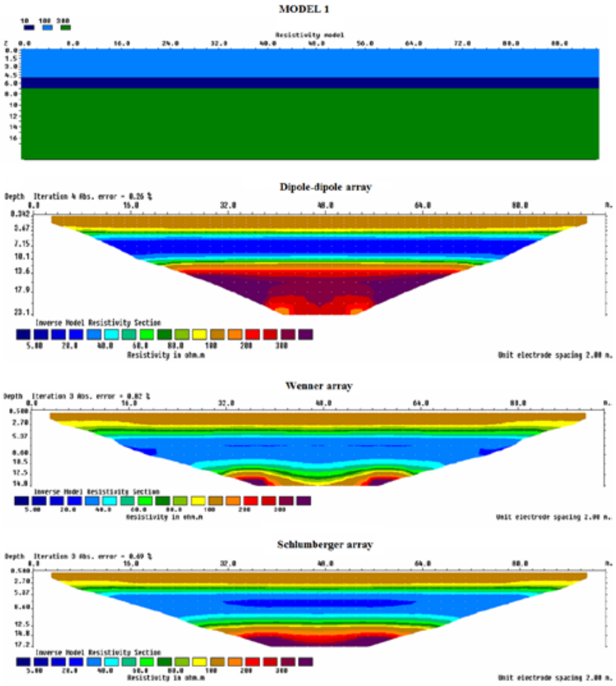

Figure 2: Synthetic model simulating a continuous thin low resistivity layer and inverted resistivity cross-sections obtained from dipole-dipole, Wenner and Schlumberger arrays (top to down).

The second synthetic model has the same geoelectrical parameters of model 1, but the intermediate low resistivity layer includes a gap which acts as a leaching pathway for pollutants through the non-saturated zone (Figure 3).

The models were run using the RES2DMOD modelling software (Loke, 2001a) and the finite difference method (Dey and Morrison, 1979) for obtaining synthetic resistivities. The achieved apparent resistivity values were then inverted using the RES2DINV inversion software (Loke 2001b). The inversion algorithm is an iteratively reweighted least squared method based on the Gauss–Newton method; in addition, the Jacobian matrix of partial derivatives is calculated using the finite-element method.

The first step in the inversion consists in estimating an initial model. Next, the solution is iteratively improved by varying the model parameters to minimize the discrepancies between the observed and the calculated responses. The inversion program uses a 2D model divided into a number of rectangular blocks (pixels of inversion models), whose arrangement is made according to the distribution of the data points in the pseudo-section. The inversions were performed for noise-free data as well as for the same data containing 2% and 5% noise.

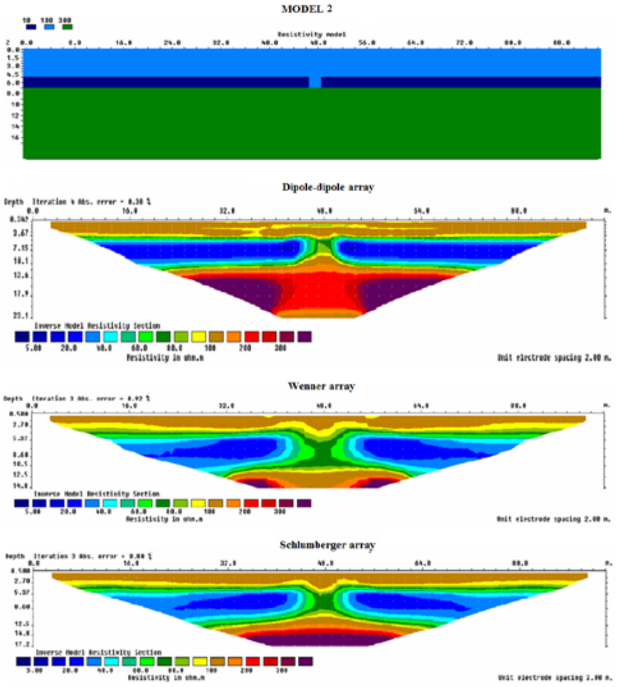

Figure 3: Synthetic model simulating a gap in the thin low resistivity layer and inverted resistivity cross-sections obtained from dipole-dipole, Wenner and Schlumberger arrays (top to down).

The Gauss–Newton smoothness constrained least-squares (l_2) (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996) and Gauss–Newton robust model constrained (l_1), inversion routines were used within RES2DINV.

The l_2 method aims to minimize the sum of the squared differences between the apparent and modelled resistivities; the l_1 method aims to minimize the sum of the absolute values of the differences between the apparent and modelled resistivities (Olayinka and Yaramanci, 2000). In each case the method proceeds by iterative alteration of the model blocks resistivity until the RMS error changes by less than 0.5% between iterations.

Field results

In order to assess the effectiveness of the proposed methodology a pilot study has been carried out at the l'Alt Empordà basin which is affected by the process of diffuse pollution by nitrates (Casas et al., 2008). The upper aquifer which is less protected against pollution can be considered like an unconfined aquifer, partially covered by a silt-clay deposit acting as a protective layer.

Several electrical resistivity tomography profiles have been recorded in this area with an IRIS Syscal multi-electrode system. The Wenner-Schumberger array with 48 electrodes spaced 2 meters. The lateral changes of the low resistivity layer, interpreted as a clayey layer is evident in all the cross-sections of the figure 4.

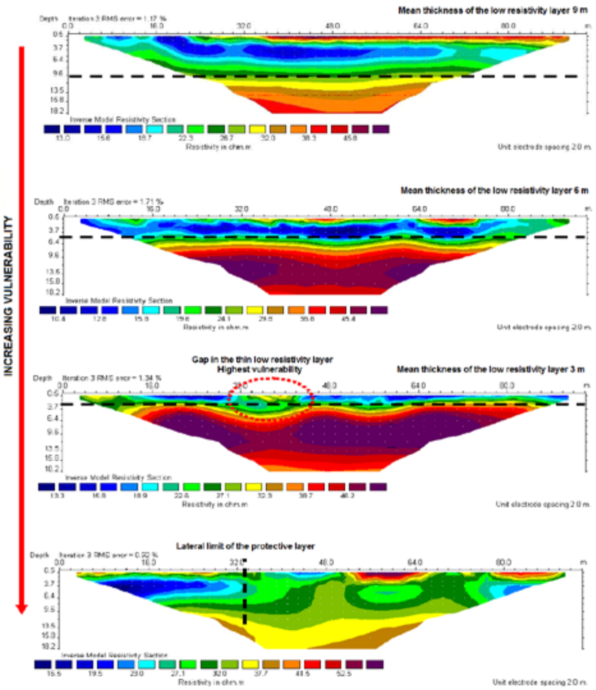

Figure 4: Inverted resistivity cross-sections obtained at the Alt Empordà basin showing different vulnerabilities as a result of the thickness and lateral continuity of a low resistivity (clay dominated) layer depicted in blue.

Zones of poor groundwater protection are found in several profiles due to existence of thin or discontinuous low resistivity layers. The possible effect of salt water salinity was discarded from hydrogeochemical data and induced polarization profiles recorded at the same places.

Conclusions

The vadose zone over shallow aquifers plays a crucial role protecting shallow aquifers against pollutants. But a detailed description of soil spatial distribution is generally difficult to achieve, since soil investigations preformed by drilling auger holes or trenching and laboratory analyses, are faced with both methodological and financial constraints.

High resolution geophysical methods, and particularly electrical imaging techniques, are very well suitable to provide precise information about depth, thickness and lateral continuity of the natural barriers. A basic principle of shallow geophysical methods is to measure different physical parameters without direct access to studied volume. Besides, they are fast, cost-effective and non-destructive, which means they provide subsoil information without drilling; this could represent the development of artificial pathways for transmission of pollutants to the aquifers.

From the results obtained both through synthetic models and field data, clay dominated layers can be easily identified by electrical resistivity tomography due to the electrical resistivity contrast with permeable sandy layers. The vadose zone of the study area consists of inter-bedded fluvial sediments related to the Fluvià and Muga rivers. As a consequence of the complex internal structure of the sedimentary infill, the potentially protective clay layers are discontinuous giving a varying degree of natural protection. This underlines the need for a high resolution groundwater vulnerability assessment using ERT method.

Acknowledgements

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