# Coastal Aquifer Characterization using Electrical methods

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**Abstract:** The electrical resistivity tomography (ERT) method was applied in the area of Argentona. The study focuses on the characterization of a coastal aquifer and its fresh and saline water identification. The device used in the field work consisted of 72 electrodes, two profiles were analyzed, of 720 m perpendicular to the coastline and of 360 m parallel to it. The inverse problem, to determine the resistivity model of the ground, was run with BERT software. To improve the model, an L-curve analysis was made as well as an estimation of the local noise influence. Results show the wedge of salted water under the aquifer in the perpendicular profile. Repeating measures in time would allow controlling the evolution of this configuration.

## I. INTRODUCTION

Aquifers are an important source of water supply, complementary to lakes, rivers and the sea. They are useful as they act as reservoirs of fresh water which can be used for irrigation and industries, among others. Coastal aquifers, in particular, play an important role, as most of urbanized areas are located along the coastline. An interesting phenomenon to study about them is the seawater intrusion: because seawater is slightly denser than the freshwater of the aquifer, to reach the equilibrium it is common to see a seawater wedge. When a coastal aquifer is over-exploited, the system can be destabilized, and the study of saltwater intrusion becomes of extreme importance to assure freshwater quality.

In the early 1900s seawater intrusion was more deeply studied by Ghyben and Herzberg who derivated a physical formulation. This relation is an approximation that gives the thickness of saltwater (under sea level) and fresh water (above sea level), considering their respective densities and the hydrostatic equilibrium.

The different geophysical exploration techniques are all based on the measurement of a physical property. In this case, Electrical Resistivity Tomography (ERT) which is based on resistivity (i.e. the opposition that the ground exhibits to an electrical current) is the technique used. The primary reason why this technique is the more suitable for coastal aquifer caracterization, is the high contrast between freshwater and saltwater resistivities.

The main objective of this project is to obtain a model for the subsurface to observe the aquifer and the sea water intrusion, if necessary. Another objective is to optimize the inversion by analyzing the values of the parameters to be used in this particular problem.

## II. FOUNDATIONS

### A. Electric potential in heterogeneous media

Approaching the issue of electrical conduction in the earth implies dealing with a semi-space problem. In a homogeneous media, a current is injected through an electrode A. From the solution to Laplace's equation, with the correspondent boundary conditions, the electrical potential at a distance r from the source is:

$$V = \rho \frac{I}{2\pi} \frac{1}{r} \tag{1}$$

In the field work, two electrodes A and B are placed in the surface, current is injected through A and collected at B, so thatthe intensity I can be controlled. Meanwhile, two other electrodes M and N are placed as well in the surface to measure the potential difference (Fig. 1).

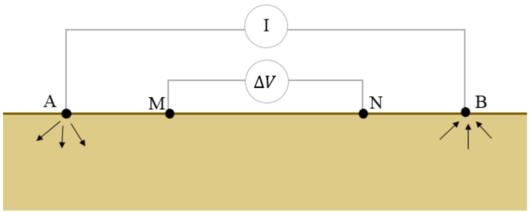

FIG. 1: ERT four electrodes configuration, where current is injected and collected in the inner and outer electrodes respectively

If MA, MB, NA and NB represent the distances between the electrodes in the above figure, the potential difference between M and N is:

$$V_M - V_N = \frac{\rho I}{2\pi}\left(\frac{1}{MA} - \frac{1}{MB} - \frac{1}{NA} + \frac{1}{NB}\right) \tag{2}$$

And from (2) the resistivity $\rho$ of the homogeneous media can be obtained. If the earth is not homogeneous the apparent resistivity magnitude is introduced.

$$\rho_a = \frac{\Delta V}{I} K \tag{3}$$

In this expression there are two terms that can be measured: the one which corresponds to resistance $\frac{\Delta V}{I}$ and a geometric factor K that depends on the electrodes distances as in the expression for the homogeneous media (2).

### B. Resistivity for hydrogeological application

Studying the earth implies a high complexity as its resistivity depends on lots of factors such as the porosity, chemical composition or quantity and type of fluid inside it.

From hydrogeology we know the content of water of aquifers depends on porous fractures or faults. In most cases, the electrical conduction is electrolytic, the porous spaces filled with the fluid are much more conductive than the rock matrix [1].

Particle size analysis allow us to classify the soil from the smallest to the biggest size of the material. Clay and silt correspond to the smallest sizes and can be considered impermeable soil, while sand and gravel are bigger and permit water to flow in the interstices. In this latter case they can be good water reservoirs (e.g. aquifers).

A study on porosity (percentage of void with respect to the total volume) can be conducted using Archie's Law. It gives a relation between the resistivity of the rock $\rho_0$ (supposing it is fully saturated), the resistivity of the fluid $\rho_w$ and the porosity $\phi$

$$\rho_0 = \rho_w \phi^{-m} \tag{4}$$

The exponent $m$ is in the range 1.8-2.0 for consolided rocks while it is about 1.3 for unconsolidated sands (in which water flows through the grains)[2].

### C. Inverse Problem

As the apparent resistivity was previously defined, now another concept must be introduced: the pseudosection. It is a way to represent measured data (apparent resistivities, in this case). It simulates a section of the ground, where the horizontal component corresponds to the midpoint between the injecting electrodes while the vertical component is related to the distance between the electrodes that inject current and those that are measuring the potential difference (at greater spacing, greater pseudo-depth is reached). The aim of the inverse problem is to construct a model of the heterogeneous ground true resistivities which would give the same pseudosection apparent resistivities profile.

From now on, the development of the inversion will be based on the work for BERT software [3] . For the model, we can define a mesh with M cells and associate to each point a physical property $m_j$. On the other hand, there is a number N ($N < M$) of data $d_i$.

The goal of the inversion is to minimize a cost function $\Phi = \Phi(\Phi_d, \Phi_m)$ which takes into account the data fitting and the smoothness of the model.

$$\Phi = \Phi_d + \lambda \Phi_m \tag{5}$$

With $\epsilon_i$ an error associated at each data, the operator to be minimized for the optimal data fitting is defined as:

$$\Phi_d(\vec{m}) = \sum_{i=1}^{N} \left| \frac{d_i - f_i(\vec{m})}{\epsilon_i} \right|^2 \tag{6}$$

$\Phi_m$ is weighted by a parameter $\lambda$, The best regularization parameter $\lambda$ can be obtained plotting the data misfit $\Phi_d$ in front of the model roughness $\Phi_m$ for different values of $\lambda$. The curve is L-shaped and, to have a reasonable trade-off between the two variables, the best value will be the one of the corner.

$\Phi_m$ can be defined in different ways, here we consider

$$\Phi_m(\vec{m}) = \left\| C \cdot (\vec{m} - \vec{m}^0) \right\|^2 \tag{7}$$

Where C is a constraint matrix, and $\vec{m} - \vec{m}^0$ is the difference between the model $\vec{m}$ and a reference model $\vec{m}^0$. In a regular 2D mesh, C considers the first or second order derivative, to assure smoothness between neighbor lines. At each iteration $k$ of the procedure, $\vec{m}$ is updated as

$$m^{k+1} = m^k + \tau \Delta m^k \tag{8}$$

Here, $\tau$ is the line search, determined in order to minimize $\chi^2$, a parameter related to the data fitting as $\chi^2 = \Phi_d/N$.

## III. APPLICATION

ERT method was applied to study the aquifer of the *Riera d´Argentona* in *Maresme* area, north of Barcelona (Spain) along a watercourse discharging in the Mediterranean sea.

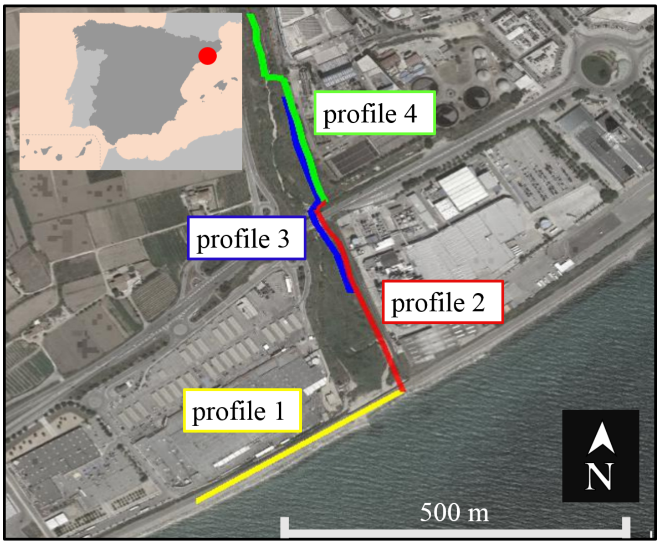

FIG. 2: Profiles location. Profile 1 corresponds to the so called parallel profile, and 2, 3 and 4 correspond to the perpendicular profile

Regarding geological settings, it is a coastal aquifer formed by unconsolidated rock. It is characterized by an impermeable basement made of granite with, above it, intercalation of layers of clays, sands and gravel. In the surface, there is presence of small creeks reaching the coast. In this type of aquifer it is usual to encounter Ghyben-Herzberg condition, and when these formations are overpumped, sea water attains the aquifer deeply [4].

### A. Field data acquisition

Two profiles were made: one of 720m perpendicular to the coast and a shorter one of 360m parallel to it. The experimental device allows to deploy 72 electrodes separated 5 m each. The instrument controls the electrodes used both to inject the current and to measure the potential.
For the perpendicular profile, three overlapping arrays were deployed while for the parallel one, only a single array was necessary (Fig. 2). For both profiles, Wenner-Schlumberger configuration was chosen, as shown in figure 1.

### B. Field data analysis

The instrument has a program that controls injection (the intensity and position), it also logs the position of the electrodes that were used and the correspondent resistance value R. With the electrodes position the geometric factor K can be calculated and subsequently the apparent resistiviy computed simply as $\rho_a = K \cdot R$ from (4).

Regarding data selection, slightly different procedures were carried out for the two final profiles. For the perpendicular profile, from the fact that profile 3 is overlapping the other two, some measures were repeated, giving a first opportunity to filter unreliable data. The measured resistivities which had small ($< 0.001\Omega \cdot m$) and negative values were removed for their probable origin in instrumental error. For the parallel profile, given the location (near the train railway which can induce some noise to the data) a deeper analysis on how to establish the K criterion was made. The more separate the electrodes are, the smallest the potential difference is, meaning that high values of K correspond to small values of the potential measured. This can lead to wrong measurements as some external source of noise (or the instrument noise itself) may have a higher potential value.

Then, the inversion is carried out with software package BERT which is based on Gauss-Newton's method [5].With a triangular mesh and an initial homogeneous resistivity model, all parameters of the inversion are computed and shown ($\chi^2, \tau$...) at each iteration. The model is updated and the forward response calculated until the stopping criterion is reached (in this case, $\delta\Phi < 2\%$).

For the perpendicular profile, the L-curve analysis was made to take the parameter of the inversion in which error induced by data misfit and model roughness in the final model were balanced.

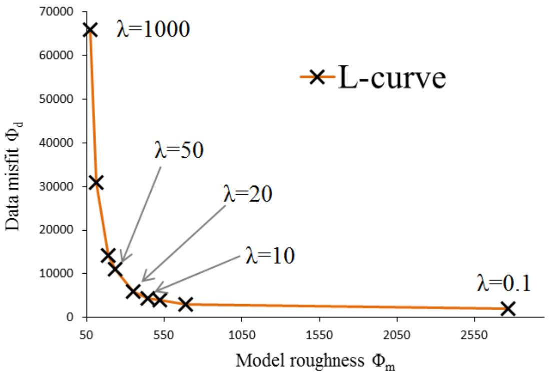

FIG. 3: Data fit in front of model roughness for models with different $\lambda$ value. Points fit and L-curve which $\lambda$ of the corner corresponds to a balanced model.

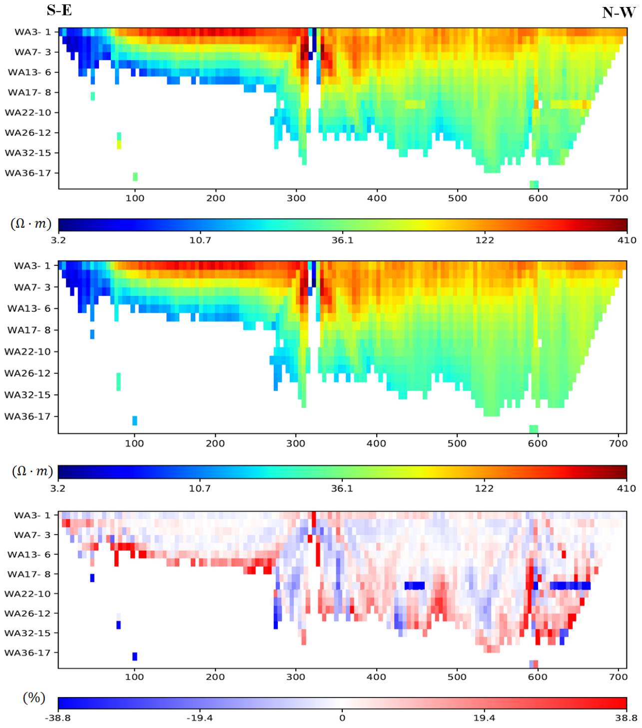

FIG. 4: Pseudosections with apparent resistivity (top), model response (center) in $\Omega \cdot m$ and percentage data misfit (bottom) for the perpendicular profile

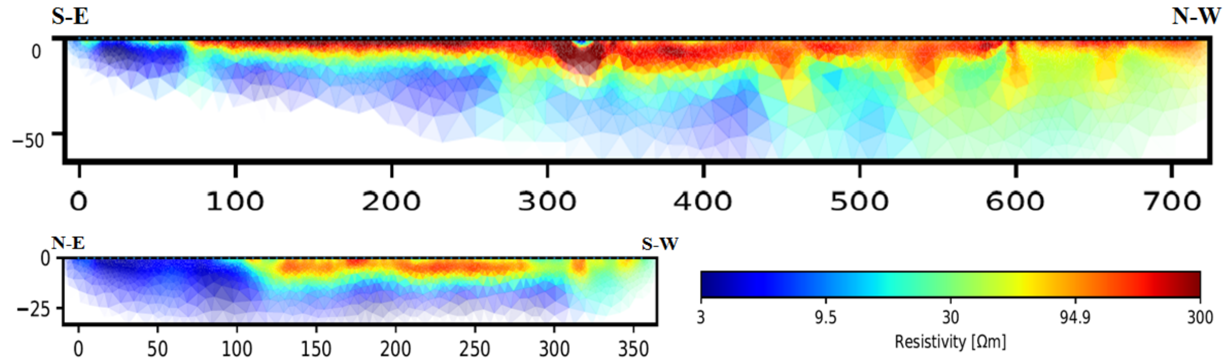

FIG. 5: 2D flat resistivity model of the perpendicular profile (top figure) and the parallel profile (bottom left figure). Horizontal distances and depth are in meters.

## IV. RESULTS

### A. Perpendicular profile

Figure 3 shows that lower values of $\lambda$ correspond to a lower error in data fit but a rough model, while high values correspond to the converse. From the L-curve analysis, an appropriate value of lambda parameter would be between 10 and 50 which are the values found in the corner of the curve.

For a model with $\lambda = 20$, ran in 8 iterations and with $\chi^2 = 4$, figure 4 shows the pseudosections with resistivity values from data, from the forward problem (of the model) and the percentage of difference between the two.

The final model is shown in figure 5. It reaches 50 m depth and reflects a high resistivity layer in the near subsurface and low resistivity under it. Near the coastline, in the first 100m this low resistivity is more important and the high resistivity layer is not present.

### B. Parallel profile

| K criterion | N | data used (%) | $\lambda$ | max misfit (%) |
|---|---|---|---|---|
| $K < 1000$ | 844 | 38 | 10 | 334 |
| | | | 20 | 369 |
| $K < 900$ | 745 | 34 | 10 | 40 |
| | | | 20 | 51 |
| $K < 800$ | 688 | 31 | 10 | 25 |
| | | | 20 | 34 |

TABLE I: Results of different models for the parallel profile, N is the number of data used when K criterion has been applied, for different values of $\lambda$ we present the maximum misfit.

The models obtained gave a high percentage of data misfit (> 300%), as said before, the data selection was based on the hypothesis of the possible noise induced by the railway. Based on the results of table 1, that show the error of the model fit as a function of the maximum K value chosen (i.e. the pseudo-depth), finally, only 688 of the 2197 values acquired in the field were used. With $\lambda = 10$, 6 iterations and $\chi^2 = 2$, figure 6 shows the pseudosections. Figure 7 shows the model itself, with information until a little bit more than 25 meters depth. There are low resistivity values in the first 100 meters of the array and a layer of high resistivity in the near subsurface from 100 meters until the end of the line.

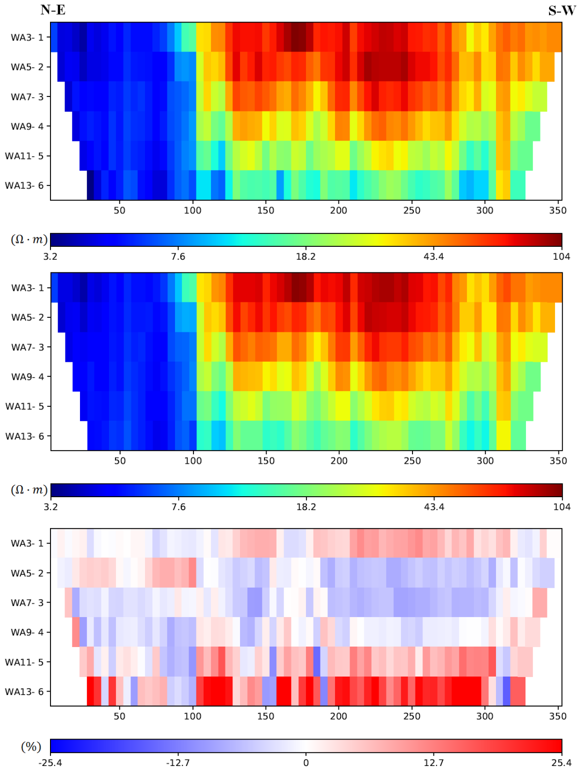

FIG. 6: Pseudosections with apparent resistivity (top), model response (center) in $\Omega \cdot m$ and percentage data misfit (bottom) for the parallel profile.

## V. DISCUSSION

In the perpendicular profile a clear lower resistivity zone is observed in the left side (closer to the coast, in dark blue) which may correspond to a higher saltwater content of the soil. The highest resistivity is in the first few meters of the subsurface and may correspond to a zone with freshwater content in rocks (maybe sand or gravel), of the aquifer itself. Results coincide with the type of aquifer expected in this area: no separate aquifers and sea water encroaching deeply.
From 400 to 700 meters along the line, the discontinuities could be related to the paleochannel hypothesis (remnants of ancient rivers) but further investigation is necessary to confirm it.
The discontinuity around 300m near the surface coincides with the zone where the road crosses, some material or pipe could be at the origin of this punctual high conductivity.

From the resistivities obtained and Archie's law, some speculations can be derived. Assuming that seawater resistivity is around 0.5 $\Omega \cdot m$ (from [6]) and taking a value of 7 $\Omega \cdot m$ for the rock (an average value from figure 5 of the zone identified as containing seawater), the porosity gives 17%. This result was inferred from Archie's law with m=1.5. Now, assuming a constant porosity of the ground and taking $\rho_0$ =200 $\Omega \cdot m$ as a value of the aquifer, freshwater resistivity gives around 20 $\Omega \cdot m$. It is important to recall that there is a transition zone between fresh and saltwater (which in Ghyben-Herzberg is considered a line); in this case, it may correspond to the zone having a value around 30 $\Omega \cdot m$ as seen in figure 5. In this zone, the proportions of fresh and saltwater can be easily determined with Archie's law, still assuming a constant porosity.

The parallel profile model shows a low resistivity near the river mouth and in the non-industrialized zone, which coincides with the first 70m of the perpendicular profile, this was expected since it corresponds to the sandy beach zone. When the industrial zone has been reached, a more resistive layer of 10m depth can be appreciated; this was also expected, as it is a man-made path parallel to the train railway. Based on equation (2), it is possible to estimate the noise induced by the railway. For the final model of the parallel profile, only values under K=800 were taken, this corresponds to the limit where noise starts becoming more important than the data from the ground. With a current injected of 0.1 A and taking a value of about 10 $\Omega \cdot m$ (corresponding to the apparent resistivity values at the greatest pseudo-depth seen in figure 6), the noise induced by the railway could be around 1 mV.

## VI. CONCLUSIONS

Two models of the ground resistivities were obtained in the area studied. From the interpretation, the expected saltwater wedge was observed in the profile perpendicular to the coastline. The L-curve analysis proved to be effective to improve the model quality. With the parallel profile, it was possible to estimate the magnitude of potential noise, as well as highlighting the importance of data selection.

For further characterization of the aquifer, a collaboration with geological or chemical studies could help to know the exact composition of the different layers. In addition, repeating ERT method at different times would allow to follow the evolution of underground saltwater. Nevertheless, in this work, with only two ERT profiles at one time, assumptions were made on the ground configuration, and even on porosity, giving valuable information for possible interventions in the area.

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