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ELECTRICAL RESISTIVITY TOMOGRAPHY AS A TECHNIQUE FOR STUDYING AND MODELLING SALINE WATER INTRUSION

E. ARACIL ÁVILA [1, 2,✉]; U. MARURI BROUARD [1]; J. VALLÉS IRISO [1]; J. A. PORRES BENITO [2]; A. B. ESPINOSA GONZÁLEZ [2]; S. IBÁÑEZ GARCÍA [2] y P. MARTÍNEZ PAGÁN [3]

[1] ANÁLISIS Y GESTIÓN DEL SUBSUELO, S.L. c/ Luxemburgo, 4; Oficina 3; E-28224-Pozuelo de Alarcón (Madrid).
E-mail: e.aracil@ags-geofisica.com
[2] BURGOS UNIVERSITY, Escuela Politécnica Superior. Campus La Milanera; E-09001-Burgos.
E-mail: earacil@ubu.es
[3] TECHNICAL UNIVERSITY OF CARTAGENA. Civil Engineering School, Paseo Alfonso XIII, 52. E-30203-Cartagena (Murcia). E-mail: p.martinez@upct.es

Abstract

This paper discusses five geophysical prospecting studies in coastal zones of the Iberian Peninsula in which the form and position of saline intrusion has, with great efficiency, been successfully determined. Geoelectrical prospecting is conclusively shown to be the most appropriate geophysical technique for this type of study, and in particular, electrical tomography, due to its speed, non-destructive nature and low cost. Electrical tomographs obtained in this way allow the position of saline intrusion in subsurface formations to be analysed, and optimising any future exploratory drilling in relation to its foreseen objective.

Key words: electrical tomography, coastal aquifer, saline intrusion, Murcia, Almeria, Cantabria

Introduction

In recent years, research projects with a multitude of aims and using very varied prospecting methods, from simple geophysical prospecting to studies involving surveys of a more exclusive nature, have been carried out into saline water intrusion at various geographical points along the Spanish coastline. On occasions, studies have combined baseline drillings and geophysical prospecting of the surface.

In other cases, the aim has been to define the boundaries of saline water intrusion and to determine its reach inland and the extent of its downward penetration into the terrain. Yet in others, once the latter has been identified attempts have been made to periodically monitor the evolution and the position of the seawater/freshwater interface. In all of these cases baseline drillings were required in order to make the relevant measurements to obtain the necessary results.

✉ Corresponding author

The number of exploratory boreholes that have to be drilled to monitor this hydrological phenomenon is important, since mapping the lateral variations usually associated with saline intrusion requires some degree of precision. Such conditions usually imply high research budgets, and what is technically more important and problematic is that the points where drilling is to be carried out is decided on without prior monitoring of the subsurface.

Geophysical prospecting prior to carrying out drilling provides, in the first place, information on the lithological and hydrological characteristics of the zone and in the second place and as a consequence of the latter, planning the best siting of the test boreholes. As a result, the number of boreholes is reduced, as improved emplacement leads to results that are more representative. Geophysical prospecting is very varied; thus, choosing the most appropriate method might, in principle, be an awkward issue at times. However, bearing in mind that the values to be determined have to be of geological and hydrogeological nature and must, among other points, have to refer to water quality, it is obvious that the most appropriate prospecting method is the geo-electrical one.

This paper presents results using electrical imaging or tomography, which stands out within the group of electrical prospecting techniques due to its versatility.

Description of the ert method

Electrical resistivity tomography (ERT) is a non-destructive geo-electrical prospecting method that analyses subsurface materials in terms of their electrical behaviour, distinguishing between them according to their electrical resistivity, the property that indicates the degree to which a material resists an electrical current passing through it.

The concentration of ions in a rock, therefore, is conditioned by the amount of fluid present in its pores or fractures, an amount that depends on the texture of the rock, which is to say, its degree of weathering and porosity. Greater ion mobility leads, as a consequence, to lower resistivity or, which is much the same, to greater conductivity (Orellana, 1982).

These theoretical aspects describe the behaviour pattern of the different materials (Aracil, 2002; Aracil, *et al.*, 2002 and 2003). Consequently, once the geo-electrical prospecting campaign using tomography is underway, different resistivity values will be determined and attributed to materials that will permit the identification of lithological units of differing natures, lithologies with different textures or degrees of deterioration, structural (fractures) and geomorphological aspects (caves and infills), etc. (Flint *et al.*, 1999; Porres, 2003).

This method is based on the positioning of an array of electrodes along a transversal section, each separated at a particular distance according to the required degree of resolution (less spacing between electrodes, greater resolution) and depth of the investigation (greater spacing between electrodes, greater depth). With all the electrodes connected to the measuring equipment, and using a specific sequential programme created for each objective, the programme 'decides' which groups of electrodes should be in operation at any given time and in what layout (Loke, 2000).

Each one of these four electrode arrays or quadripoles takes a measurement of the resistivity that is attributed to a particular geometric point in the subsurface, whose position and depth in the image depends on the position of the quadripole and on the spacing between the electrodes that constitute it. The electrical images are, in fact, cross-sections of land that reflect the distribution of resistivity values at different depths corresponding to the different layers of investigation.

Therefore, the depth of investigation will depend on the spacing between electrodes. The selected layout may easily run deeper than 100 m, even though shallower test boreholes into the subsurface have the definite advantage of greater resolution, as there is generally less separation between electrodes. As a rule, for images with the same number of electrodes, the resolution of the investigation decreases logarithmically in relation to the depth (Dahlin and Loke, 1998).

When studying complex structures the density of measurements is fundamental, especially where geological 'noise' is present (a distortion provoked by some small-scale geological heterogeneities when measuring an image). Thus a network of very disperse measurements could really overlook important features of the sub-soil or could generate false structures (Dahlin y Loke, 1998).

As an example, Figure 1 shows a device made up of 48 electrodes, each spaced at 4-metre intervals, capable of creating an image of a longitudinal section of 188 metres to a depth of investigation of almost 20 metres.

These images display resistivity values using a colour scale to facilitate comprehension of their variations, and come with a colour-coded chart that is characteristic of, and specific to, each image, although tonalities and range is variable. This range of colours represents the different resistivity values of the formations being analysed (Figure 1).

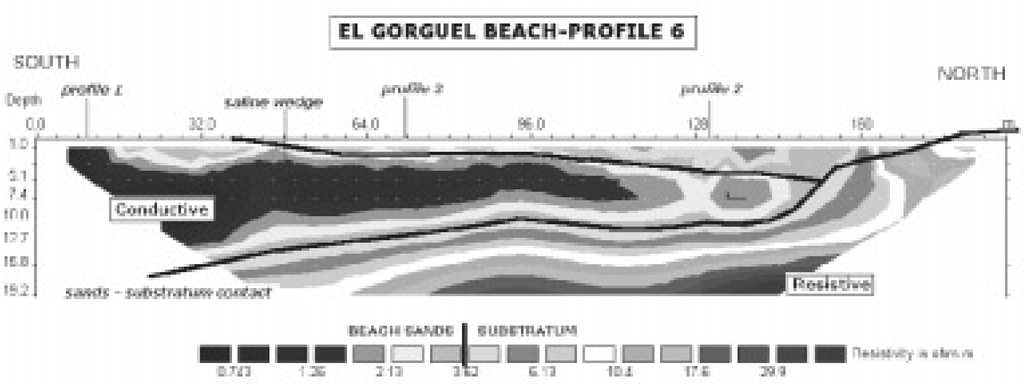

Figure 1. Electrical image (tomography) at El Gorguel site (Murcia, SE Spain).

Examples

In recent years various studies have been carried out prospecting the subsurface of coastal zones to monitor saline intrusion using geo-electrical prospecting. Among them, five studies using electrical imaging tomography are highlighted in this study: El Gorguel beach and at San Pedro del Pinatar (both in the province of Murcia), the beaches of Berria and Santoña (both in the province of Cantabria) and the coastline of Almería.

From the geological perspective, prospecting carried out at the beaches of El Gorguel and San Pedro del Pinatar reveals quite a simple geological structure, as they are composed of a sand unit lying on a schist unit, the metamorphic rocks that form the local substratum. The geological structure is similar to the case of the survey carried out on the coastline of Almería, i.e. a sedimentary unit lying on metamorphic materials but, in this case, the underlying unit is composed of groups of gravels, sands and a clay stratum. The beaches at Berria and Santoña are composed of a sand layer lying over limestone.

Sand on metamorphic substratum. El Gorguel zone.

The El Gorguel and San Pedro del Pinatar zones, as well as the Almería one, respond to this geological structure. In the first case, the beach at El Gorguel is situated a few kilometres to the northeast of Cartagena, between the localities of Escombreras and Portmán. The dimensions of the beach are approximately 500 m in length and 200 m width; the topography is practically flat.

The main aim of the prospecting work centered on establishing the point where the thickness of the saline intrusion wedge was most pronounced. With this in mind, electrical imaging was used for the investigation, using data from sections parallel, as well as, perpendicular to the coastline. The reason for this type of investigation is that the images, being two-dimensional sections of terrain, could help to determine the resources of the aquifer contaminated by saline water intrusion.

The materials forming part of the overlying layers are, in general, very permeable medium-size sands, characteristic of high-energy sedimentary environments. Nevertheless, in the part that is closest to the Triassic outcrops that surround the beach, as well as on the soil surface, there are fine materials derived from mud that accumulated in old mines of the area and was washed down the rivers and deposited around the beach. These fine particles reduce the beach porosity to some extent.

Subsequent to geophysical prospecting the main results were as follows: two types of materials were identified, the sand covering the beach on the surface, and underlying rocky substratum corresponding to the Triassic outcrops surrounding the beach (figures 1 and 2). The high resistivity expected for this rocky substratum is, in fact, lower due to its clayey nature and to surface deterioration and impregnation of its pores by saline water. It was also possible to confirm the position of the boundary between both layers by the increase in resistivity of the overlying formation and by the data from the baseline borehole drilled in the beach. This boundary was established at a resistivity value of about 3 ohm·m: values below this resistivity correspond to sands and values above it correspond to the substratum (Aracil, 2001).

The distribution of orthogonal and parallel images along the coastline allows the morphology of the sand deposit filling the beach to be determined. It shows some symmetry in the east-west orientation, which is to say that it runs parallel to the coastline, since it is thickest in the central part of the beach and starts to taper off as it approaches the rocky outcrops.

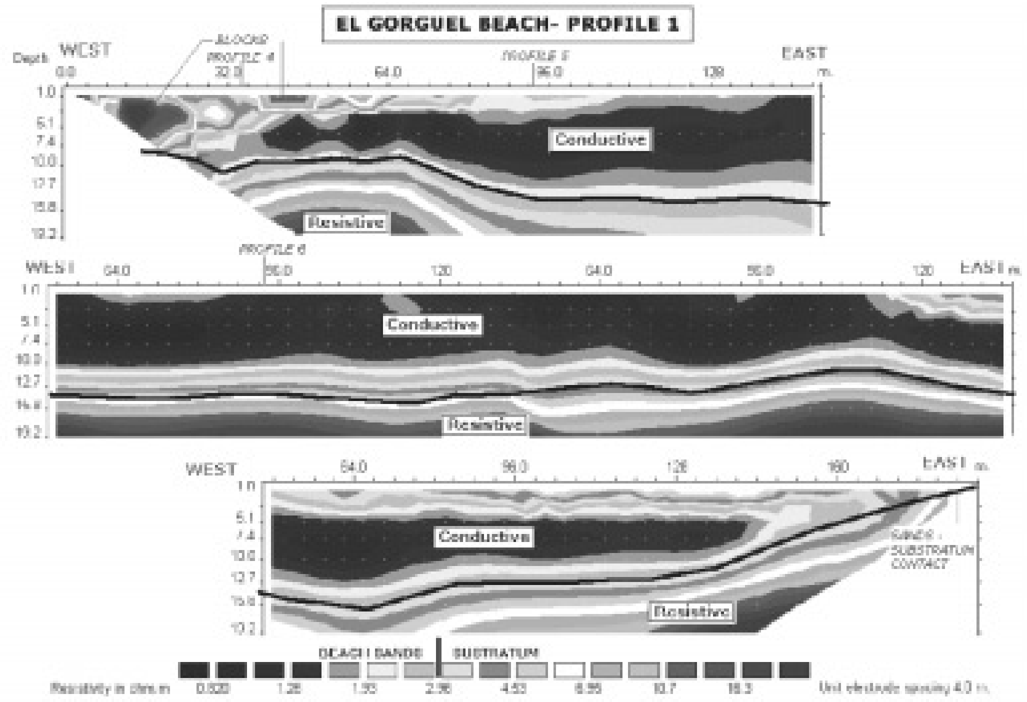

Figure 2. Electrical tomography parallel to the coast, close to the coastline on the El Gorguel. It is constituted by four continuous lines: line 1, to the left, lines 2+3, in the centre, and line 4, on the right.

This means that the thickness of the sand on the beach at the western and eastern extremities is slightly reduced. In a north-south direction, however, the morphology is variable as it is greater at the waterside (where the thickness reach at least 16 m) and it decreases landward towards the outcrops.

As it is an uninterrupted form of prospecting, electrical imaging highlights that the observed decrease in thickness is not progressive: after an inclination at the waterside it remains at a sub-horizontal level along most of the beach, having a relatively homogeneous thickness of between 8 and 10 m, only to sharply tail off once again as it nears the rocky outcrops.

The pores of this material are saturated with saline water which is, as would be expected given its proximity to the sea, something clear from the low resistivity values registered (between < 1 and 3 ohm·m). The morphology of the boundary of the saline water intrusion is clearly observable in the orthogonal images along the coastline, where the more conductive saline water wedge progressively looses its thickness as it moves away from the waterside and approaches the rocky outcrops.

Sands over metamorphic substratum. Almería zone.

With regard to the coastal zone of Almería (confidential area), the geological structure is also composed of a weathered layer of sedimentary materials overlying a metamorphic layer that forms the basement

(Figure 3). However, unlike the previous one, in this zone the sedimentary layer displays greater grain-size heterogeneity and coarser sizes predominate, and the degree of cementation at some levels is quite intense.

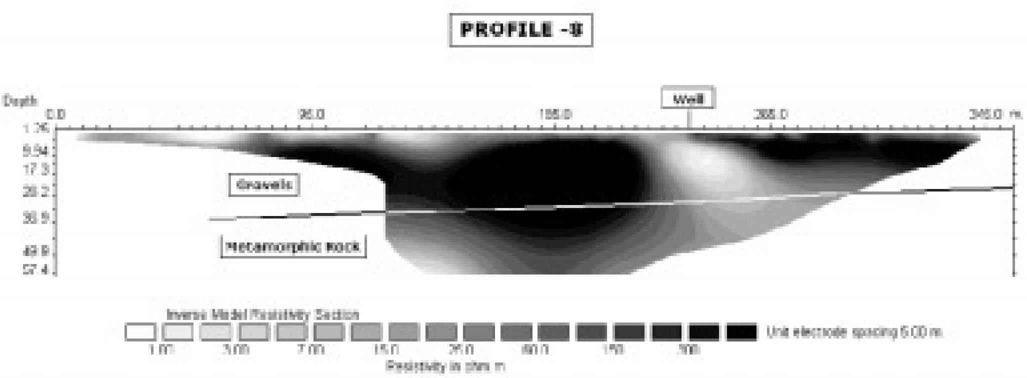

Figure 3. Image perpendicular to the coast showing a decrease in the resistivity sounding due to the presence of saline water.

These lateral changes of facies mean that the resistivity model is not as simple as was the case for El Gorguel, since in this case, different geo-electrical units have been identified. Firstly, there are some sediments characterised by high resistivities (50-500 ohm·m) that correspond to coarse materials (gravel) with variable degrees of cementation. Their extension and development is intermittent, which reduces the porosity and, consequently, the volume of saline water and the conductivity of the section.

This possible scenario is contrasted by surveys that cut through layers of gravel before reaching the phyllitic substratum at an approximate depth of 34-38 m. Once these more resistive deposits are displayed by electrical imaging as cross-sections, it can be seen that their morphology closely coincides with the typical morphology of gravel-channel deposits.

Secondly, some materials have been identified with a slightly smaller grain size (coarse sands and gravels) and low to moderate resistivities (5-50 ohm·m). They usually accompany the more resistive materials whose lateral change of facies has been commented on above.

Thirdly, the presence of other material with a slightly smaller grain size (sand mixed with finer materials) and very low resistivities (1-5 ohm·m) was also observed. They accompany, both laterally and beneath, the moderately resistive materials commented on above, also with a similar change of facies. In this case, it is a matter of quite permeable materials into which the saline water has infiltrated to the point of reducing the global value of resistivity.

Interpreting the data can lead to even more subjective terms, but which are none the less very necessary. Strategic mapping can be carried out in this way, as is the case of sector-maps in which the behaviour of aquifers, located in particular zones, are defined by bands displaying the resistivity of materials analysed through electrical imaging. Quite clearly, the map displays varying degrees of conductivity in groundwater that is to be found saturating the pores of the sedimentary materials, which can be interpreted as a greater or lesser degree of salinity in the waters of the aquifer being studied.

Using this type of mapping process, two drawn-out bands may be identified in the study area running NE-SO, that is parallel to the coastline: one band of high conductivity, corresponding to more conductive materials (with greater concentrations of saline water in their pores); and another of moderate conductivity that reflects the distribution of coarse materials, whose resistivity is normally very high but shows lower resistivity values due to the high concentration of a salt brine in their pores. As a consequence, this leads to a drop in the overall resistivity of the section, which represents the disposition of the aquifer to saline water intrusion.

From a strategic perspective this sector-map is the most interesting result, as it displays the position of the different materials that form the aquifers in parallel bands along the coastline, as might logically be expected to occur in most instances with these deposits close to the sea. Moreover, constructing and analising these maps will contribute to a more coherent setting of borehole tests in the future.

Sand on metamorphic substratum. San Pedro del Pinatar zone.

There is a third case with a similar geological structure, in San Pedro del Pinatar (Murcia). The difference here lies in the materials analysed that correspond solely to layers of detrital sediments: a combination of coastal sedimentary materials which have been covered by a few metres of infilling, the result of human intervention to recover a small area of land from the sea.

The thickness of the detrital layer is relatively great. This fact linked to the electrode array in use, that combined high resolution and shallow depth, meant that the identification of the contact with the metamorphic substratum was made impossible. The readings only correspond to the variations within the detrital layer, in which differentiation can be observed due to the superficial unit corresponding to the landfill materials of human origin. The degree of saline intrusion is very great, helped by the extreme permeability of the materials. However, thanks to the filters employed with this methodology, it may be observed that the surface is slightly less permeable. This reduced permeability is directly related to a lower proportion of pores saturated with saline water which, undoubtedly, leads to a lower level of conductivity (Figure 4).

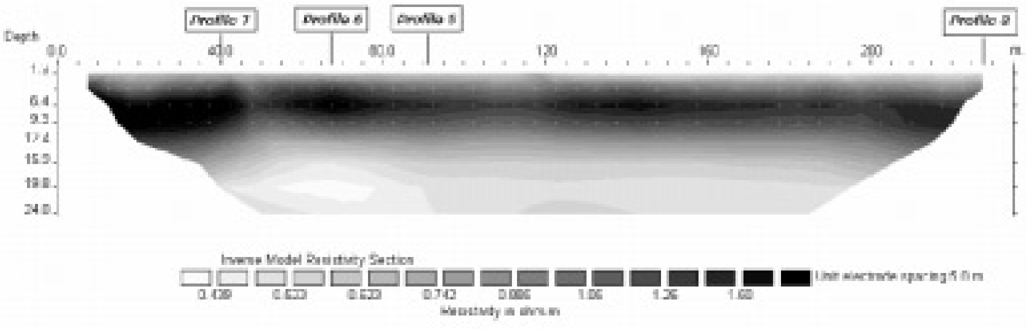

Figure 4. Image parallel to the coastline, 15 m to the coastline, at San Pedro del Pinatar (Murcia, SE Spain). It shows the presence of an interlayered unit of slightly higher resistivity, which corresponds to sand with a clay content that makes it less pervious and, consequently, with a lower proportion of saline water in their pores.

Sand overlying limestone. Santoña Beach.

The geological structure of the beaches at Santoña and Berria consists in sand banks on a limestone basement. In the case of the beach at Santoña, results are available from two electrical images taken on the beach in a direction parallel to the waterside and at a distance of 5 and 25 m, respectively, to the coastline. These electrical images were intended to reach the underlying limestone layers beneath the sand, even though archived data indicated that the contact would be located at depths of around 80 m. The image (Figure 5) taken at a distance of 25 m from the coast (at gardens adjacent to the beach) indicated a depth of 14 m to the sand-limestone boundary, and also displayed severe contamination of the detritus with saline water, as shown the extremely low resistivity values (less than 1.5 ohm . m). This low resistivity contrasts with the high values (more than 1.000 ohm·m) of the compacted limestone that forms the substratum, which in view of its compactness and crystallization has not experienced saline water infiltration.

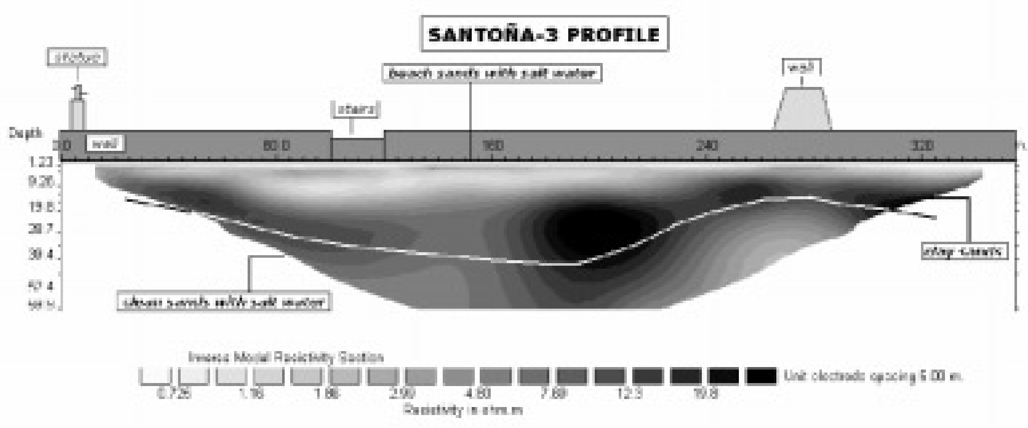

Figure 5. Image parallel to the coast, 5 m to the coastline, at San Martín beach (Santoña, Cantabria, N Spain). It shows the presence of an in-between level of slightly higher resistivity, which corresponds to a relatively less permeable sand with clay and, consequently, with a lower content of saline water due to their porosity being lower.

In the image taken at 5 m from the coastline (on the sand of the beach) the underlying limestone stratum was not reached. In the 65 m investigated, a first unit of sand-beach was detected with a thickness between 2 and 9 m and an extremely low resistivity (1 ohm·m), as corresponds to a very porous, permeable material completely saturated with saline water. Beneath this unit there was a second one of clayey sands which, due to its lower proportion of saline water, has a resistivity that decreased to a lesser extent. A third unit, identified underneath the former one, could correspond to the same sands but having greater porosity, which would imply a greater proportion of pores saturated with saline water and, consequently, with lower resistivity on the whole.

Geophysical data from marine projects obtained at the river mouth, close to the coast of San Martín village, suggest sand thicknesses of over 80 m. Moreover, a test-borehole drilled at the seaside opposite the mouth of the river flowing into Santoña (at Laredo) bored through 14 m of pure beach sands and, at least, a further 16 m of finer sand of clayey nature. The upper sand layer would correspond to the overlying band on the tomography image, while the underlying clayey layer would correspond to the second band in the image.

Sand overlying limestone. Berria beach.

The image of Berria beach was taken parallel to the coast, at a distance of 20 m from the coasline (Figure 6).

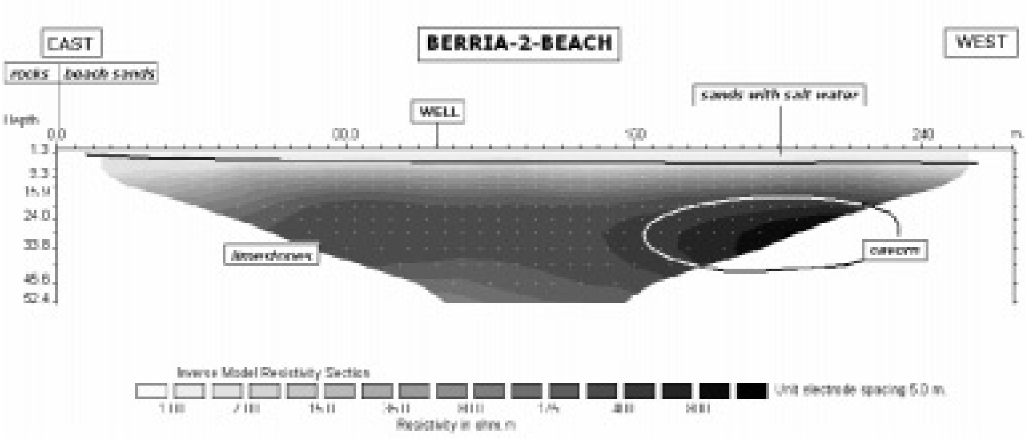

Figure 6. Image parallel to the coast, 20 m to the coastline, at Berria beach (Cantabria, N Spain). The presence of a layer with higher resistivity values and showing a cavity, which corresponds to relatively compact limestone formations, can be observed.

The very low resistivity values indicate that there is a very porous and permeable unit, made up of beach sand, which is fully saturated with saline water and thus has resistivity values almost equivalent to that fluid. At around 3 m below this unit of sand, a resistant limestone unit is found with slightly low resistivity values due to the partial filling of its pores with saline water. The detected anomaly showing high resistivity corresponds to a large and relatively isolated cavity protected from saline water infiltration, due perhaps to the size of the limestone formation. A further survey confirmed the presence of an open cavity at a depth between 15 and 17 m.

Conclusions

The results obtained from the different studies allowed for a close observation of the materials contaminated by saline water, that is to say, affected by the wedge of saline water intrusion since seawater, which is highly conductive, gives rise to extremely low resistivity values in the porous materials that it saturates.

It was possible to determine, as was expected, that the results are optimal when the materials infiltrated by seawater are homogenous since the slight differences in resistivity correspond to variations in the salinity of the water. However, where there are different detritical units, although all of them are porous and permeable they usually show slight variations in resistivity due to the presence of units with more clay content than others. This clay content decreases overall porosity and, consequently, also reduces the saline water content and slightly increases, for that reason, resistivity.

Two examples have also been observed where a unit of detritus rests on limestone whose resistivity, according to its porosity and permeability, is either not reduced at all, when it is very compact, or is partially reduced, wherever the porosity and permeability progressively increase.

The studies, therefore, make it clear to see how easily the presence of saline water intrusion may be identified, specially when the images taken perpendicular to the coast do not have very extensive lengths (less than 200 m) or when the area under study has, at least, one homogenous and permeable unit-layer formed by detritic materials. In the case of the images parallel to the coast, the images closest to the sealine are those that allow the most efficient identification of the seawater intrusion due to greater intensity of the process in those sectors. All of which is own to their being continuous sections of terrain, which provide detailed geometric information.

When working on a larger scale to analyse somewhat more extensive zones, this technique appears to be also an efficient method as it permits large-scale iso-resistivity mapping at different heights. This will provide an idea of the distribution of the lowest resistivities, which are those that correspond to the most widespread intrusion process.

It is clearly a rapid, clean and economic prospecting method that brings with it outstanding results and allows, in a general way, clear observation of the extent and boundaries of the saline water intrusion using large-scale as well as small-scale imaging techniques. At the same time it allows the observation of gradual variations of saline water and, consequently, the intrusion zone, the unaffected zone and the interfase separating the latter two to be defined.

If surveys are available in the zones associated with the studies in which chemical analysis may be performed, the subsequent study phases should progress towards imaging and mapping chloride equivalency concentrations based on formulae to correlate the resistivity of the fluid with the equivalent concentration of this ion. This would allow for improved sitings of future surveys by relating them to concentrations found in groundwater.

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