GEOPHYSICAL CHARACTERIZATION OF A MEDITERRANEAN COASTAL AQUIFER: THE BAIXA TORDERA FLUVIO-DELTAIC AQUIFER UNIT (BARCELONA, NE SPAIN)

E. FALGÀS[1,✉], J. LEDO[1], T. TEIXIDÓ[2], A. GABÀS[1], F. RIBERA[3], C. ARANGO[1], P. QUERALT[1], J. L. PLATA[4], F. M. RUBIO[4], J. A. PEÑA[5], A. MARTÍ[1], A. MARCUELLO[1]

[1] Department of Geodinamics and Geophysics, University of Barcelona.
E-mail: efalgas@geo.ub.es
[2] Cartographic Institut of Catalonia
[3] Fundation International Centre for Groundwater Hydrology
[4] Geological Survey of Spain
[5] Geophysical Institute of Andalucia, University of Granada

Abstract

The Baixa Tordera alluvial aquifer system is located in the northeastern Mediterranean coast of Spain. This system is considered as a strategic aquifer for planning the management of regional water resources. Since the 1980s, this area has been the subject of an important tourist and industrial development that has incremented the water demand. The aquifer system is composed, in its coastal zone, of an unconfined alluvial aquifer and a confined one (granitic basement), separated by an aquitard of complex geometry, which makes this system heterogeneous. In spite of all the studies undertaken, some of the features of the aquifer system can be still improved: a) aquifer morphology, b) location of more permeable areas inside the aquitard that can trigger local vertical convection between the unconfined and confined aquifers, c) depth to the basement in the delta zone and the wedge and, d) evolution of groundwater flow intrusion, among others. The preliminary results of a project undertaken to improve the current knowledge of the seawater wedge, and the physical and geometrical characteristics of the aquifer system, are presented in this paper. This has been done in three steps: a) summarizing all the available geophysical data; b) acquiring new geophysical data, in particular audiomagnetotellurics (AMT) and electrical resistivity tomography (ERT) data, and c) analyzing and interpreting jointly all data.

Keywords: Vertical electrical sounding, electrical resistivity tomography, audiomagnetotellurics, electrical resistivity tomography, Baixa Tordera.

✉ Corresponding author

Introduction

Deltaic aquifer systems are complex, and their geological and hydrogeological characterization is a difficult task when only well information is available. In order to complement this information and to obtain a more accurate image of the physical properties of these systems, the use of new surface geophysical methods has increased during the last years.

The underlying objective of the methodological project here presented is to improve aquifer characterization using geophysical methods and rock physics theory. In this paper we present the on-going research we are carrying out on geophysical characterization of the Tordera deltaic aquifer system. The Tordera deltaic aquifer is a well-known system in the northeast of the Iberian Peninsula (Figure 1), where geological, hydrogeological and geophysical data has been acquired since late 1960s (REPO, 1971; PHPO, 1985; ACA, 2003; Teixidó, 2000; Himi *et al.*, 2000), although not in well optimized space-time windows. This aquifer system plays a strategic role on the touristic and industrial development of this area, and the excessive withdrawals of groundwater have aggravated the environmental hazards (ACA, 2000, 2003).

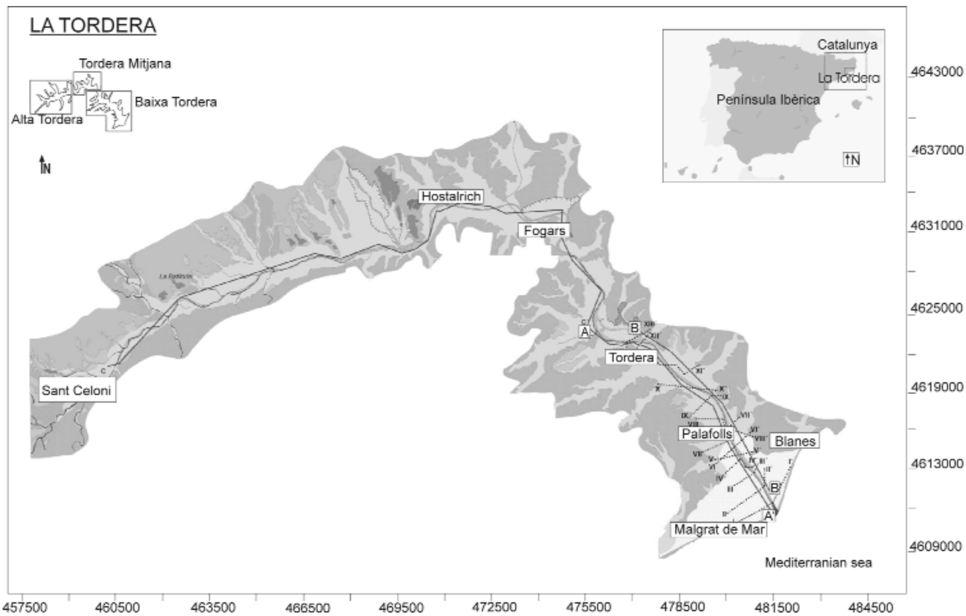

Figure 1. Geographical setting of the Tordera river basin and of the study area, Baixa Tordera.

The advantage of using geophysical data to know aquifer properties such as porosity, permeability, aquifer and aquitard geometry, stems from the fact that geophysical data are less expensive and more spatially abundant than laboratory or field measured data. Within the broad range of geophysical methods we will focus on electric and electromagnetic geophysical methods, which are well suited to study seawater intrusion, given the direct relationship between salt-water content and electrical conductivity. In this paper old and recently acquired geophysical data, that has been reinterpreted using well-log information are presented; in this way we have been able to more accurately define the geometry of the basement and the preferential flow path of the saline water intrusion.

Hydrogeological data

The Tordera river basin (Figure 1) is located 80 km north of Barcelona; the river has a total length of 65 km and it forms a 8 km^2 small delta of Quaternary materials bounded by granitic rocks of Paleozoic age. Quaternary sediments are stratigraphically controlled by 1) torrential deposits forming confined terraces, and 2) a fluvio-deltaic depositional system with continental to marine facies (Geoservei, 2000). Both are formed up of detritic materials with wide granulometric variability: silt, clay, fine sands and coarse gravels. Our study area is located in the delta zone, called Baixa Tordera. Figure 2 shows a stratigraphic section of the Baixa Tordera aquifer system; note the lateral changes of facies in the horizontal direction as well on the vertical. The hydrogeological model of this system is presented in Figure 3; it is composed by three main units: 1) a near surface water–table aquifer that covers the whole delta; with medium and coarse gravels and 6-20 m thick; 2) an intermediate aquitard or zone of low permeability formed by clay, silt and fine sands; the maximum thickness (25 m) is reached close to the coast; this layer has important lateral and vertical discontinuities; 3) a deep confined aquifer, formed by medium and coarse gravels (Geoservei, 2000; Rahola and Casas, 2003). The whole aquifer system is bottom and laterally limited by a granite basement that can locally show a high degree of alteration on its surface.

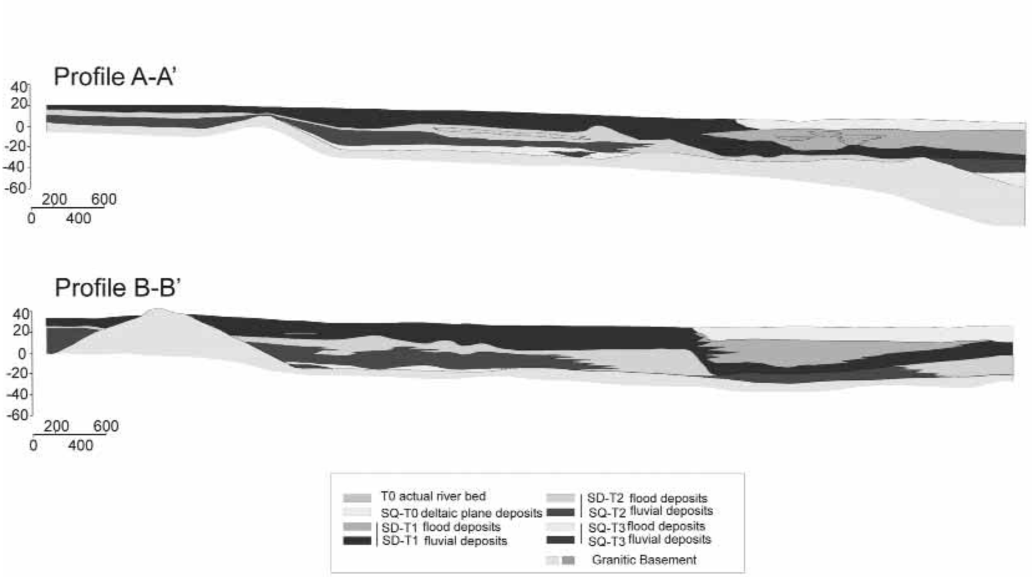

Figure 2. Stratigraphic cross-section along the river. Modified after ACA/Geoservei (2000). (See location in Figure 1).

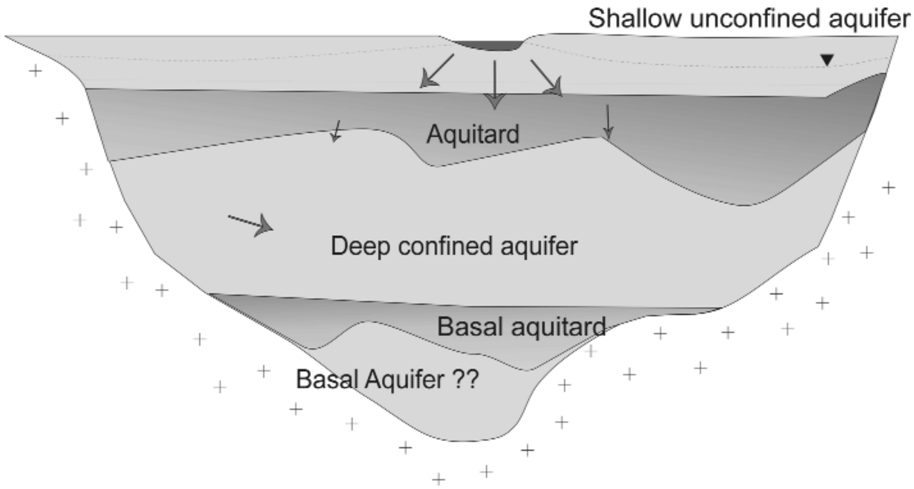

Figure 3. Hydrogeological model of the Baixa Tordera aquifer system.

The main questions to resolve are related to:

A- The basement. To improve the knowledge of the basement morphology and degree of alteration. There are few and sparse wells reaching it; moreover, close to the coast it shows a big step, from 80 m to more than 180 m.

B- The seawater wedge. The water quality monitoring network is far from ideal in both, the number of wells and their distribution. There is a blurred image of the seawater wedge, and the preferential paths for the saline water flow are not accurately determined.

C- Deep basal aquifer. Recently a new hydrogeological model has been proposed. It adds to the aquifer system a deep basal aquifer within the granite basement rocks. The thickness of this basal aquifer is larger close to the coast.

Several local and regional agencies had been collecting information on this area since the late 1960s, and a big effort has been done during the last years to obtain a high quality database. Unfortunately, the database suffers some lacks on the quality of the lithological description and the exact location of the wells. Before using these data a critical evaluation has been done; as a result only 43 out of the 100 wells available have been considered usable. From the analysis of their lithologic logs, we have established eleven categories that have been associated to different permeability structures.

Seawater intrusion in the Baixa Tordera system is localized at the deep aquifer, which supports most of the water extraction for urban and industrial applications. The only two chloride analysis available from the Agència Catalana de l'Aigua (ACA) salinity control network, belong to wells located 1 and 2 km inland respectively (Figure 4), and values of 1580 mg/L and 1420 mg/L of Cl^- were measured in February 2003. This suggests that seawater is present far from the coast.

Besides these high chloride values, the Tordera aquifer has experienced a lowering of the chloride concentrations (ACA, 2003) due to two reasons: the last 2 years were quite rainy, and in October 2002 a seawater desalination plant (ITAM Blanes) begun to supply water for domestic and industrial purposes (ACA, 2003; Arranz *et al.*, 2004).

Geophysical data

As said before, in this study electric and electromagnetic geophysical methods have been used. Vertical Electrical Soundings (VES) acquired in different time-space windows during the last 40 years were considered. Five VES field surveys (Teixidó, 2000, and references therein) were undertaken in the years 1969, 1994, 1995, 1996 and 2002 (Figure 4). Each field survey had different objectives, which makes difficult to integrate all the VES together. In 1996 and 2002 the main objective was to determine the top of the basement in the northern part of the Baixa Tordera. To delineate the seawater wedge, short VES were carried out in 1994, 1995, and 1996; the objective was to found a conductive structure associated to the intrusion. As they were acquired in different years, small to medium variations on electrical conductivity were recorded.

To complement these data (acquired by agencies different to ACA), two profiles of Electrical Resistivity Tomography (ERT) were acquired last fall along the riverbank using a Terrameter SAS 400. Total length was 3 km and electrode spacing 15 m (Figure 4). They allowed obtaining a 2D electrical image of the subsurface along the river. To get a better spatial coverage of the delta, a controlled source audiomagnetotellurics (CSAMT) survey was conducted in the spring of 2004. The CSAMT soundings were distributed in a mesh covering the delta with a maximum distance between soundings of 300 m. The data

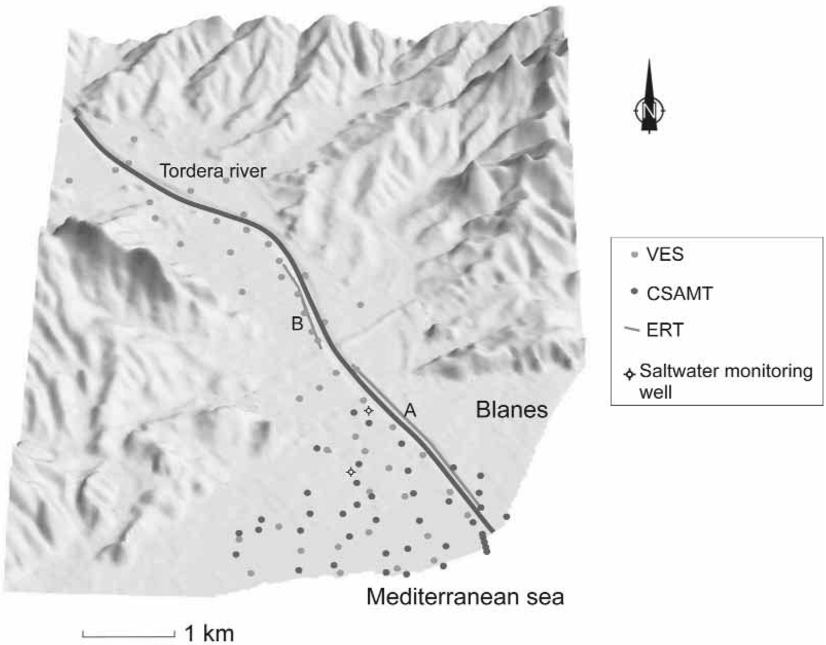

Figure 4. Site location of the geophysical and hydrochemical data. Lines: ERT profiles, light grey points: vertical electrical soundings (VES); dark grey points: control source for audiomagnetotelluric soundings.

was acquired with a Stratagem system whose frequency ranges from 10 Hz to 92,000 Hz. To improve the signal-to-noise ratio, the source was employed for the highest frequencies. A total of 40 sounding were measured, and only two were rejected due to poor data quality.

Joint interpretation of data

To constraint the possible electrical models, the lithological information selected from the well data was considered, where available. The VES closer to the coast show the presence of a conductive layer (1 - 50 ohm·m) at shallow depths that has been associated to the seawater wedge in the upper aquifer (Figure 5). This conductive layer screens the structures below it, and no information can be obtained about the deep electrical structure in this area. This shallow conductor is not observed in the VES inland, and electrical images up to the basement are obtained (Figure 6). Using all the VES and well log data available along the shore of the river an electrical cross-section has been constructed (Figure 7). The basement shows an irregular topography, although depth to the top increases towards the coast.

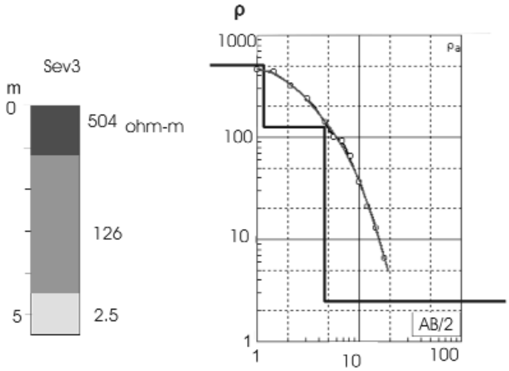

Figure 5. Typical VES near the coast. Note the high conductivity layer at the base of the model, associated to seawater.

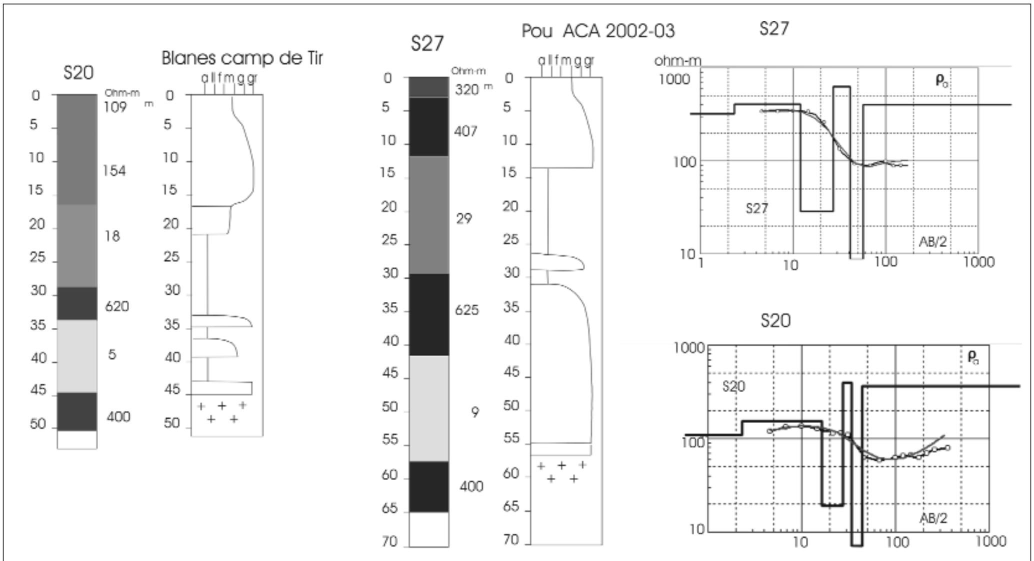

Figure 6. Interpretation of two VES (# 20 and 27) using lithological information. Right diagram: ρ_a-AB/2 (ρ_a=apparent resistivity; AB/2 distance between electrodes) data and interpreted resistivity layer model. Lithology log and interpreted electrical resistivity layer model: note the presence of a conductive structure (a gravel layer) on top of the basement; it has been interpreted as seawater contaminated zone.

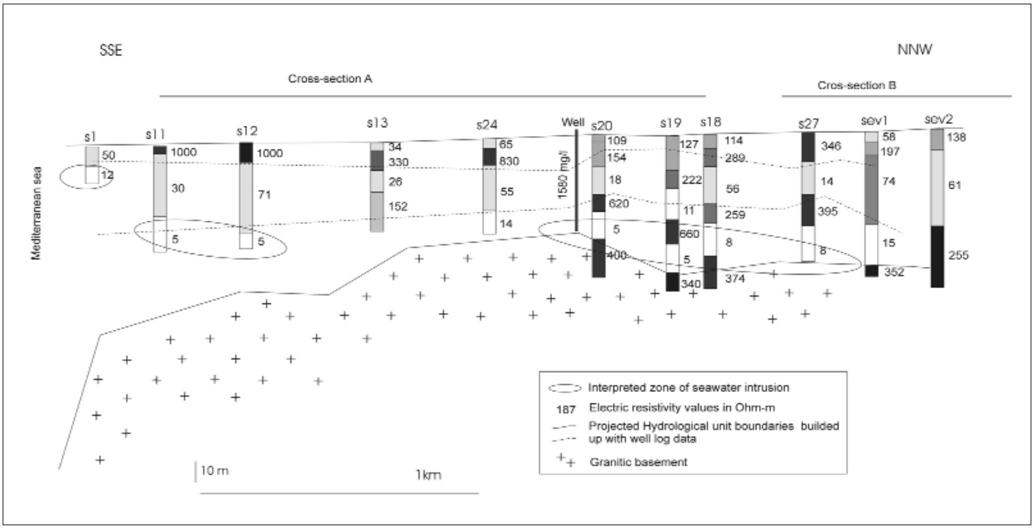

Figure 7. Geoelectrical cross-section along the riverbed obtained from VES data. Dashed lines are the projection of the aquifer unit boundaries after the well lithological logs. Chloride information (in mg/L) is from the ACA monitoring salinity network (February 2003). (VES location is in Figure 4, straight-lined along ERT sections).

The preliminary ERT electrical cross section (Loke, 1999) is presented in Figure 8, where four different sections marked as A, B, C, and D can be clearly distinguished:

- Zone A. Seawater intrusion close to the coast. It shows a high-conductivity structure (between 1 and 50 ohm·m). The zone presents some vertical variations, but with this preliminary model it is difficult to establish any valid association between electrical conductivity and lithology.
- Zone B. Associated to the whole aquifer system, it includes the upper aquifer, the deep aquifers and the intermediate aquitard. Although several structures can be observed in the model, given the separation between electrodes (15 m) the vertical resolution is not enough.
- Zone C. Granitic basement with a low conductivity (150-400 ohm·m). It shows some lateral discontinuities that can be associated to altered granite.
- Zone D. Conductive zone situated 2000 m inland. The electrical conductivity at shallow depths ranges between 50 and 100 ohm·m. This area can be associated to the upper aquifer system. Below this, a high conductivity zone of 20 ohm·m is detected, and an electrical basement is not observed. The disappearance of the basement is probably due to the screening produced by the upper structures.

The preliminary electrical resistivity image of the ERT 2D inversion coincides with the trend determined by the VES and well data. There are two zones (A and D in Figure 8) showing high conductivity values, which can be associated to seawater intrusion, separated by a lower resistivity zone (Figure 7; C in Figure 8). In the coast the salinization is detected in the upper and lower aquifers, although the resolution of the deep electrical structures is limited by the near-surface conductive structures. The detection of a high conductivity zone 2000 m away from the coast line is an unexpected result, although it has been corroborated by the

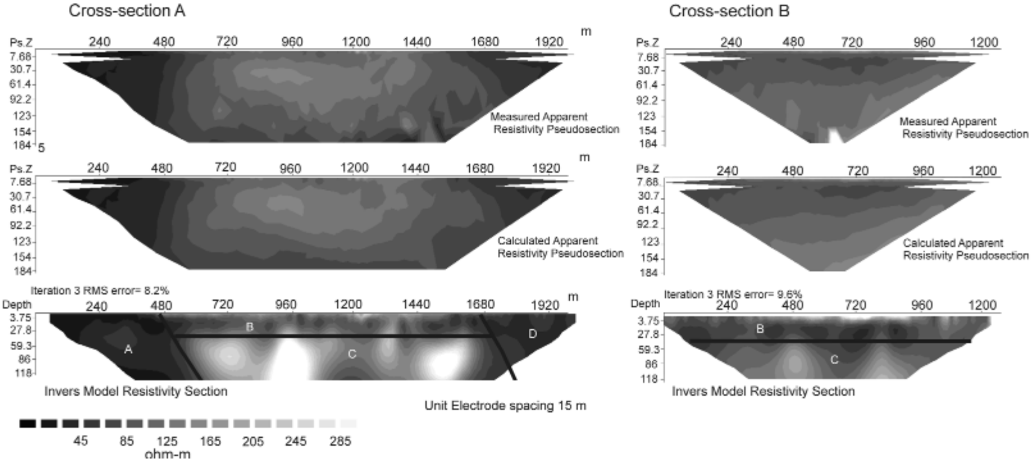

Figure 8. 2D geoelectrical cross-sections obtained from ERT. Top: measured apparent resistivity pseudo-section (PsZ: layer measured depth); middle: calculated apparent resistivity pseudo-section (model response); bottom: inverse model resistivity section. (See location in Figure 4).

water chemistry obtained in the wells located there (more than 1500 mg/L of Cl^-; see Figure 7). The contamination can not be propagated through the resistive basement along the riverbed, because it acts as a natural barrier. Moreover, evidences of this migration would be found in the ERT cross-section.

To found the preferential contamination flow line we planned a CSAMT survey. It presents several advantages from the more classical VES or ERT methods. First of all, the range depth investigated is deeper; data rate acquisition is higher (the forty sites where acquired in six days), and finally interpretation software in 2D and 3D is well developed. Figure 9 shows the apparent resistivity of the audiomagnetotelluric impedance tensor for different frequencies. This parameter has several properties that make it suitable for interpretation when dealing with 3D complex environments (Vozoff, 1972; Ledo, 2004). The highest frequencies show the response of shallow structures, and the decreasing frequencies correspond to increasing depths. To obtain an electrical conductivity distribution of the subsurface a full 3D model is required. This is a laborious task, and at this point of the project, only qualitative interpretations have been done. In spite of this, important conclusions can be drawn (Figure 9):

1. The highest frequencies show a conductive structure close to the coast as a response to the seawater intrusion in the upper aquifer. The rest of the delta shows lower conductivities.
2. In the following images, as the frequency decreases, the conductive zone reveals itself as a tongue intruding inland westwards of the actual riverbed.
3. For the lowest frequencies (< 300 Hz) the seawater intrusion moves back; this is likely due to the presence of the granite basement at shallower depths to the north.
4. All the images show a more resistive structure in the NE, due to the presence of a shallower granite basement in this area.

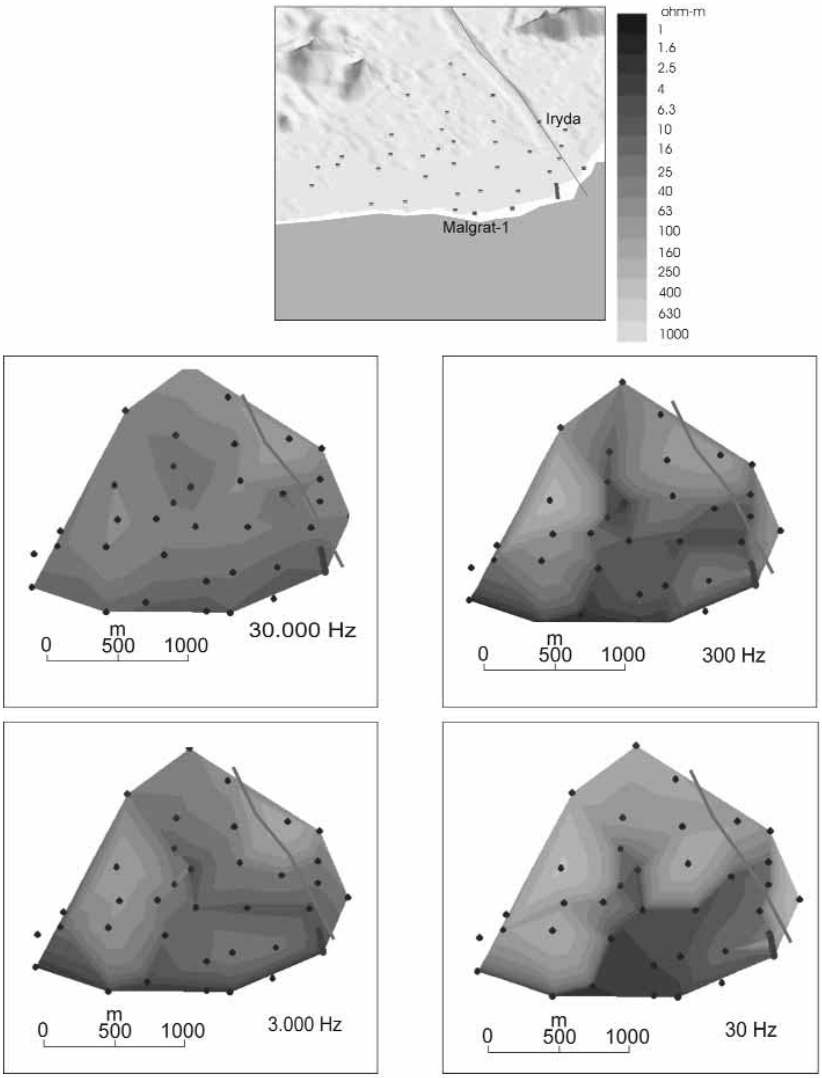

Figure 9. Apparent resistivity maps obtained from the phase determinant of the audiomagnetotelluric impedance tensor.

Conclusions

The main purpose of this work is to improve the aquifer characterization using geophysical methods. At the present early stage, geophysical and well log data have been obtained, although we plan to do some more ERT and CSAMT measurements to clarify and better delineate some of the results already obtained. From the methodological point of view, we can conclude that geophysical measures must be done in the whole delta and not only along the riverbed. For this reconnaissance, the CSAMT has probed to be superior in both depth of penetration and rate of acquisition, even in noisy areas. Joint interpretation of CSAMT, VES and ERT allows improving model resolution. From the aquifer characterization point of view, the integration of direct lithological measures and indirect information (geophysical data) allowed to obtain a clear image of seawater intrusion geometry close to the coast and inland, through flow channels that are not parallel to the river course.

Acknowledgements

This research is supported by the *Ministerio de Educación y Ciencia*, coordinated project REN2002-04538-C02/HID. We would like to thank the *Agència Catalana de l'Aigua* for providing the well log information. Oriol Falivene helped with the use of Gocad to generate some of the figures, Jordi Bausà and Antonio Abellán helped in the field work.

References

AGÈNCIA CATALANA DE L'AIGUA, ACA (2003). Control de Recursos hídrics al tram baix de la Tordera. Període d'estudi: 15/07/2001 30/09/2003. Octubre 2003. Available on line at: http://mediambient.gencat.net/aca/ca//medi/aigues_subterranies/estudis/.

AGÈNCIA CATALANA DE L'AIGUA, ACA. Salinity network control. Available on line at: http://mediambient.gencat.net/aca/ca//medi/aigues_subterranies/resultats/consulta_inte

ARRANZ, D.; IIMI, M.; CASAS, A.; CARMONA, J.M.; VILADEVALL, M.; FONT, X.; LÁZARO, R.; TAPIAS, J.C.; PINTO, V. and L. RIVERO (2004). Evolución de la intrusión salina en el delta del Tordera utilizando FDEM. VI Congreso Geológico de la Sociedad Geológica de España; Zaragoza. Geo-Temas 6(4).

COMISARÍA DE AGUAS DEL PIRINEO ORIENTAL (1985). Plan Hidrológico del Pirineo Oriental, PHPO.

GABÀS, A. (2003). Nous aspectes metodològics en l'exploració elèctrica i electromagnètica. Doctoral thesis, University of Barcelona. (Unpublished).

GEOSERVEI (2000). Actualització i cartografía hidrogeològica del sistema fluvio-deltaic del curs mitjà i baix del riu Tordera. Agència Catalana de l'Aigua, Barcelona. (Internal).

HIMI, M. (2000). Delimitación de la intrusión marina en acuíferos costeros por métodos geofísicos. Doctoral thesis, University of Barcelona. (Unpublished).

HIMI, M.; NAVARRO, J.V.; SABADÍA, J.A. and A. CASAS (2000). Delimitación de la intrusión salina en el delta del río Tordera por métodos electromagnéticos. In: Actualidad de las Técnicas Geofísicas Aplicadas en Hidrogeología. IGME 2000.

LEDO, J. (in press). 2D versus 3D magnetotelluric data interpretation. Surveys in Geophysics.

LOKE, M.H. (1999). Electrical imaging survey for environmental and engineering studies. A practical guide to 2D and 3D survey.

REPO (1971). Estudio de los recursos hidráulicos totales del Pirineo Oriental. Informe hidrogeológico sobre los depósitos aluviales del río Tordera. Servicio Geológico de Obras Públicas y Comisaría de Aguas del Pirineo Oriental. Barcelona, internal.

TEIXIDÒ, T. (2000). Caracterització del subsòl mitjançant sísmica de reflexió d'alta resolució. Doctoral thesis, University of Barcelona. (Unpublished).

RAHOLA, M. and E. CASAS (2003). Actualización hidrogeológica del acuífero del Bajo Tordera. XXXVII International Course on Groundwater Hydrology (CIHS), Technical University of Catalonia, Barcelona. (Unpublished).

VOZOFF, K. (1972). The magnetotelluric method in the exploration of sedimentary basins. Geophysics, 37: 98-141.