AMT and seismic assessment of a Deltaic aquifer system

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SUMMARY

Groundwater research and management requires the understanding of the subsurface properties to constrain multiscale heterogeneities. This work presents a multidisciplinary study focused on the characterization of hydrogeological parameters and processes of a porous aquifer system using geophysical methods sensitive to structures, lithologies, and presence of water, namely Seismic and Audiomangetotelluric (AMT). The hydogeophysical experiment is based on the joint interpretation of classical hydrogeological data with seismic profiles and AMT soundings to typify aquifer units, basement depth and state and evolution of the seawater wedge. Tordera deltaic aquifer system is located in the Mediterranean coast of Spain. Forms a small delta of 21 km^2 of detrític unconsolidated materials building up a complex heterogenic aquifer system, confined by Paleozoic granite rocks. Due to tourist and industrial development groundwater resources have incremented its demand during last fifteen years, thus salt-water wedge has progressed inland. Discussion is based on: well lithology descriptions, hydrochemistry, AMT data analysis, seismic tomography models, comparison of 2D AMT inversion models with seismic reflection profiles, and seawater wedge monitoring along the preferential seawater path.

Keywords: Audiomagnetotellurics, hydrogeophysics, seawater intrusion

INTRODUCTION

Tordera delta (Fig.1) is located in the north-eastern coast of Spain. The deltaic aquifer system is built up by quaternary fluvial-deltaic deposictional facies above the Paleozoic granitic basement (Geoservei, 2000). Geographically, the deltaic zone is bounded by two main poles of touristy and industrial activities that during last decades have experienced a fast development. Consequently, water demand has increased substantially and seawater wedge has progressed inland reaching some water-supply wells.

Deltaic aquifer systems are complex, and their geological and hydrogeological characterization is a difficult task when only scattered information is available. This work presents a multidisciplinary study focused on the characterization of hydrogeological parameters and processes of the Tordera aquifer system using geophysical methods. We use AMT, seismic reflections and refractions as well as hydrogeological data. Given the different degree of resolution and sensitivity to the presence of water of each method joint interpretation of data will optimize the final models.

HYDROGEOPHYSICAL SURVEY

Hydrogeophysical data is composed basically from AMT soundings, two seismic lines, and hydrochemical and lithological information (Figure 1).

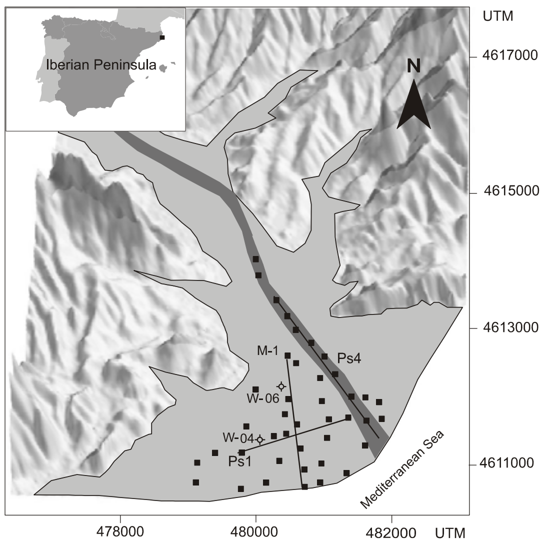

Figure 1. Location map of the studied area (vertical scale x10). The position of CSAMT sites are shown by squares, AMT, seismic profiles PS1, PS4 and M-1 by lines, and wells W-06 and W-04.

During spring 2004, 41 AMT sounding distributed over the western deltaic zone were carried out. In addition two more site lines have been performed, 1) on the actual riverbed due to a collocated seismic line, and 2) along the main seawater intrusion path (M-1). The later has been repeated every four month.
AMT survey has been carried out with Stratagem system (Geometrics, 2000) that record in a frequency range form 10 Hz to 92 KHz. High frequency band (>800 Hz) uses an external source to improve the signal to noise ratio in order to fulfill the plain wave assumption, typical distance among transmitter and receiver system in this area has been among 110-200 m.

Seismic data were acquired using 48-channel digital seismograph, 40 Hz geophones and 5 m shot and receiver spacing (Texidó 2000). A roll-along system allows keeping an end–shooting geometry along the profile. Same center spread shots were additional carried out for refraction purposes. Here we present two lines Ps4 along the riverbed with 2400m length and Ps1 parallel to the shore line with 1200 m length.

According to hydrogeologial data, we present only two recent multitube piezometers w-06 w-04. Lithological description and three independent hydrochemitry analysis (ACA) at depth (chlorine concentration and electric water conductivity) has been considered in order to compare and to calibrate the geophysical models (Fig.3).

RESULTS

AMT data analysis has been done through resistivity pseudo-sections of the impedance tensor determinant at different frequencies. Moreover, dimensionality analysis has also been done with WAL invariants (Weaver, 2000) following the scheme proposed by Martí et al., (2004). Although pseudo-sections and WAL invariants show three-dimensional data behavior dominancy, 2D inverse models were obtained along selected lines as first approximations (Fig.2, 4). Ps1 and Ps4 models (collocated with the seismic lines) fit the apparent resistivity and phases of the impedance tensor determinant, using the algorithm of Siripunvaraporn and Egbert (2000) and following the modifications by Pedersen and Engels (2005).

Main preferential seawater path has been monitored every four month. Electrical resistivity time variation values are expected due to seawater variation conditions. Six models beginning on April 2004 until December 2006 has been performed. Models has also been inverted using the determinant of the impedance tensor, however in those cases we used same layered initial model to emphasize variations only due to seawater content (Fig.4).

Seismic lines PS1 and PS4, has been reprocessed to obtain reflection and refraction models. In these study they has been used both models to constrain basement depth for the AMT collocated models, reducing the inverse equivalence problem.

DISCUSSION

Data analysis of the apparent resistivity frequency pseudo-sections show main features of the aquifer deltaic system. Has been well recognized the main sea-water intrusion paths over the deltaic space related to an ancient paleochannel oblique to the actual Tordera River, leading the decision of monitoring this specific profile every four month (M-1). Basement presence is also well recorded with AMT data however seismic lines has been used to constrain the depth.

Seismic lines present variable data quality due to variations on the water table, thus to delineate basement depth has been used reflection and refraction models looking for deep reflectors and high velocity values. (Fig.2).

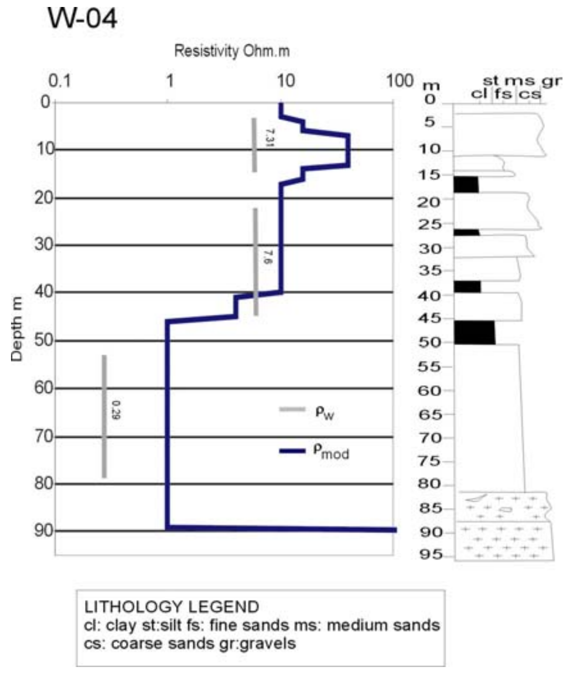

Figure 3. Plot diagram of water resistivity (ρ_w) and AMT bulk resistivity (ρ_{mod}) on wells W-04. Resisitivity data is correlated in depth with lithologies.

AMT inverse seismic constrained models have been interpreted using calibration between chlorine concentration, water resistivity and bulk resistivity of the 2D models (Fig.3). Aquifer units carrying fresh water presents high resistivity values ranging from 40 to 1000 Ohm.m, whereas zones of lower hydraulic conductivity (clay interbeded layers) present lower resistivity from 10 to 40 Ohm.m. Seawater bearing units have been identified clearly on the three AMT profiles PS1, PS4 and M-1, and its AMT estimated resistivity is around 1 to 5 Ohm.m. The chlorine concentration in w-04 and w-06 are 16000 ppm and 1350 ppm respectively around 50 m depth showing the evolution inland of the mixing zone (see location map Fig. 1).

Regarding to the AMT models it is possible to get a preliminary overview of the aquifer system state over the space. Along the riverbed, Ps4 model, seawater intrusion is restricted from 500 m towards the shoreline whereas on the western part of the delta (Ps1 and M1) models seawater intrudes through an ancient paleochannel. Further north in the Ps4, reflects the geoelectrical aquifer structure, relative low resistivity nearsurfce zone above high resistive unit related with the main freshwater aquifer unit. Ps1, parallel to the shoreline, presents also this relative low resistive upper zone over a wide an almost continuous low resistive area, related with the intrusion path. And finally, M-1 profile shows the far reaching influence of the seawater wedge and mixing zone.

Monitoring sequence models (Fig.4) from April 2004 to December 2006 show changes on the low resistive layer associated to the seawater wedge. Specifically it can be regarded on the upstream zone of the profile. Figure 4 present only three M-1 models as an example of a regression and progression of the seawater influence. These tendencies are well correlated with the hydrologic state of the aquifer system.

CONCLUSIONS

Hydrogeophysical studies provide accurate image of the aquifer properties and hydrodynamic processes. Previous hydrogeological and geophysical data has supplied important preliminary information, however joint interpretation of hydrogeological, AMT and seismic models have contributed to get more insight into the system. Velocity tomography model have witnessed distinct thickness of low velocity materials, morphology and depth of the fresh granite basement. Moreover, they help to constrain AMT basement depth.

Distinct hydrofacies can be recognized according to resistivity model values, and specifically on seawater intrusion influence on the aquifer system. Results provide validation for the inversion models linking the material properties and water quality.

Monitoring profile has tested AMT as a sensitive method to monitor changes in fluid electrical resistivity. Sequence models show the dynamic of the seawater mixing zone as a expression of the hydrologic state of the system.

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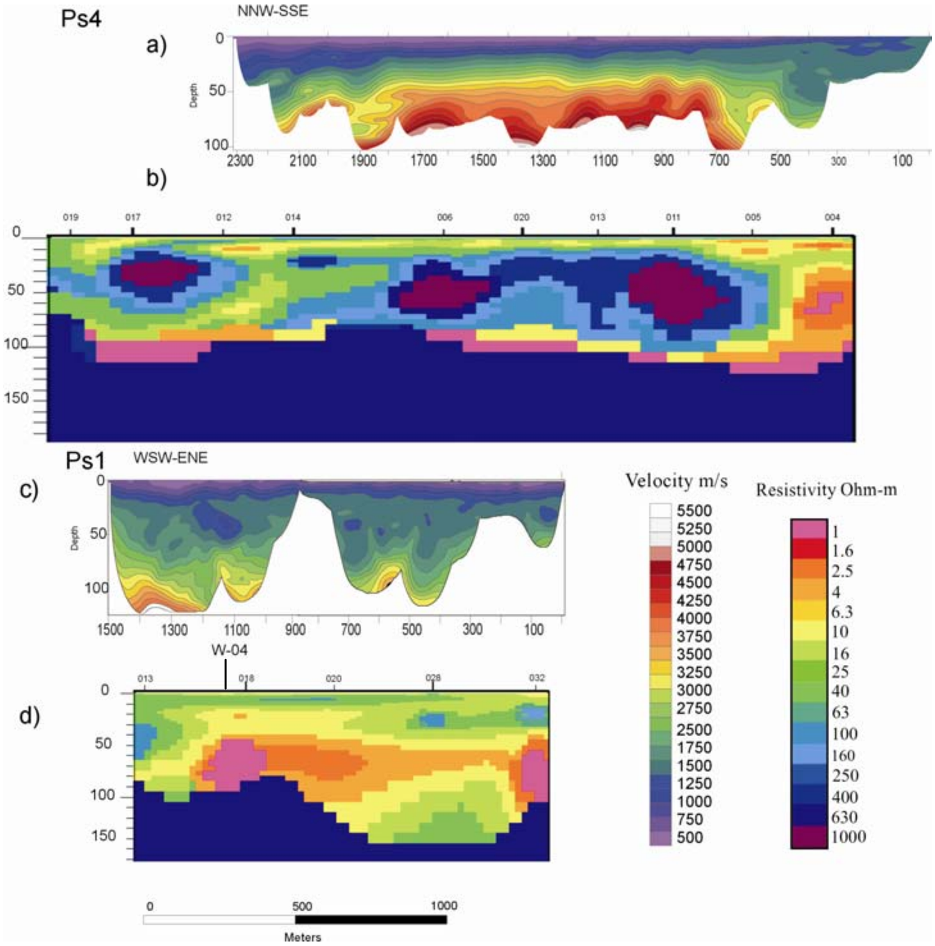

Figure 2. AMT and seismic velocity tomography collocated profiles (PS1, PS4), see figure 1 for location. All models are in the same length scale a) PS4 seismic velocity tomography, b) PS4 CSAMT model, c) PS1 seismic velocity tomography, and d) PS1 CSAMT model.

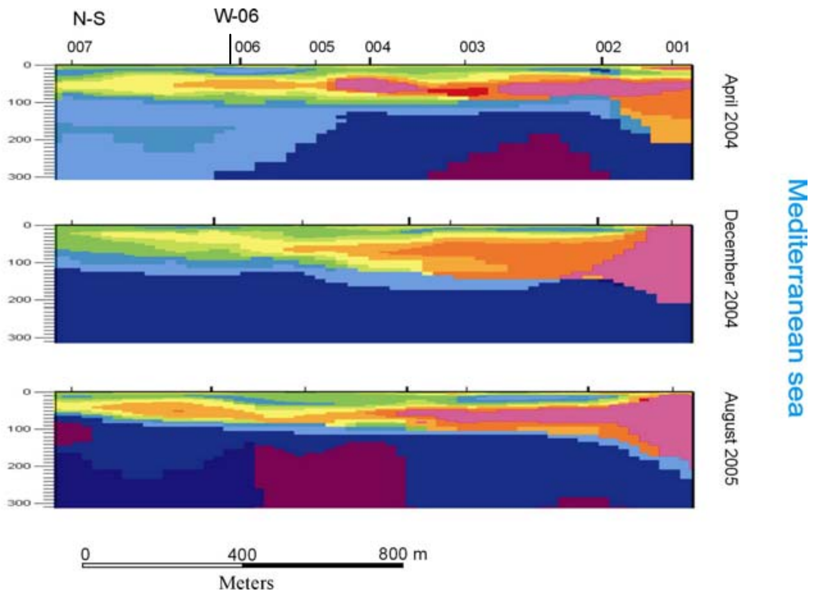

Figure 4. Time-lapse AMT modelling. Northern part of the models shows variations on the deep resistivity layer, associated to changes in water salinity content. Resistivity colour-scale same as in figure 2.