IMAGING GROUNDWATER RESOURCES OF A MEDITERRANEAN COASTAL AQUIFER USING SEISMIC AND CSAMT DATA

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Abstract

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 Control Source Audiomangetotelluric (CSAMT). The hydogeophysical experiment is based on the joint interpretation of classical hydrogeology data with seismic profiles and CSAMT 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, CSAMT data analysis, seismic tomography model, comparison of 2D CSAMT inversion models with seismic reflection profiles, and seawater wedge monitoring along the preferential seawater path.

Introduction

Deltaic aquifer systems are complex, and their geological and hydrogeological characterization is a difficult task when only scattered 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 surface geophysical methods has increased during the last years (Schwinn and Tezkan, 1997; Krivochieva and Chouteau, 2003; Pedersen et al., 2005a; Unsworth et al., 2000; Pellerin 2002).

This work presents a multidisciplinary study focused on the characterization of hydrogeological parameters and processes of the Tordera aquifer unit using geophysical methods. We will use CSAMT, seismic reflection and refraction, as well as well log 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 model. Finally, the models obtained are compared with hydrogeological data.

Previous geophysical and hydrogeological studies have been carried out in the Tordera delta from the sixties due to its groundwater importance. Useful preliminary information was derived from those, however nowadays an integrated study to improve aquifer knowledge is required. To get more insight into real aquifer properties and processes we propose a multidisciplinary study joining previous and new geophysical data as well as hydrogeological information.

Hydrogeological Setting

Tordera delta, Figure 1, is located in the north-eastern coast of Spain (Fig.1). The field site is built up by fluvio-deltaic depositional facies from Tertiary and Quaternary period. Those detritic cover materials conform the aquifer system, which are confined by Paleozoic granite basement. The hydrogeological conceptual model of this system is composed by four main units (Geoservei, 2000): 1) near surface free aquifer, that covers all the delta, with medium and coarse gravels, its thickness varies between 6-20 meters; 2) the aquitard, or zone of low permeability with clay, silt and fine sands, the maximum thickness of 25 meters is reached close to the coast; this level has important discontinuities, in both lateral and vertical directions; 3) a deep confined aquifer, composed by medium and coarse gravels, and finally 4) a basal aquifer, restricted on the coast due to a high displacement fault . The whole system is limited in its base and laterally by a granite basement that can locally show a high degree of alteration in its surface.

The aquifer conceptual model does not reproduce the true heterogeneity of the system. During last decades, water demand has increased substantially and the seawater wedge has progressed inland reaching some water-supply wells. The deep semi-confined aquifer bear excessive withdrawals due to tourism, domestic and industrial activities, and therefore the deep aquifer is the most affected by the seawater intrusion influence. On spring of 2004 has been detected a high content of chlorine more than 1.5 km inland. Specifically, this dramatic increase of the salinity is reported on the western area of the delta, which is associated to an ancient fluvio-deltaic paleochannel and therefore to a dominated sandy area.

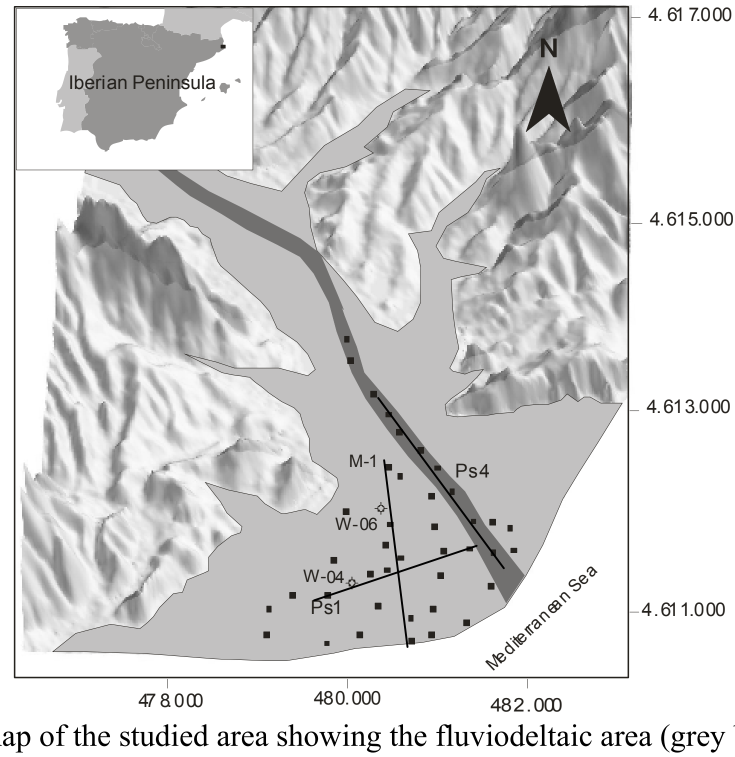

Figure 1. Location map of the studied area showing the fluviodeltaic area (grey background) and the surrounding topography (vertical scale x10). This figure also show the position of CSAMT sites (squares), CSAMT seismic profiles (PS1, PS4 and M-1 lines), and wells W-06 and W-04.

Hydrogeophysical experiment

Analysis of all available hydrogeological data: lithological well description and hydrochemistry data has been done. Distribution wells and careful well log interpretation led to non-complete information of the real heterogeneity of the aquifer system. Although it gives relevant information, it is needed additional information as geophysical data to cover and detail properties and dynamic processes of the system. Here we present only two recent well lithologic description and hydrochemistry analysis from spring of 2004 in order to compare and to calibrate our geophysical data.

Seismic data were acquired using 48-channel digital seismograph, 40-Hz geophones and 5 m shot and receiver spacing (Teixidó, 2000). A roll-along system allowed keeping an end-shooting geometry along the profile. Some center spread shots were additional carried out for refraction purposes. Low-energy explosives (pyrotechnic noisemakers) were employed as seismic source. Seismic lines have been reprocessed to obtain velocity tomography models. In addition, from spring of 2004 until present, CSAMT surveys over the whole delta and along a fixed profile has been carrying out. Data is acquired with Stratagem equipment (Geometrics, 2000), which covers a frequency range from 92.000 to 10 Hz. Typical distance between source and receiver system was 110m due to the low resistivity of near-surface materials.

Preliminary data analysis has been done through resistivity pseudosections 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 pseudosections and WAL invariants show three-dimensional data behaviour dominancy, 2D inverse models were obtained along selected lines as first approximation. These models fit the apparent resistivity and phases of the impedance tensor determinant, using the algorithm of Siripunvaraporn and Egbert (2000) and following the modifications and scheme proposed by Pedersen and Engels (2005b). The error floor of the impedance data is 5% and an initial model of 100 Ωm halfspace has been used.

CSAMT models and seismic velocity models (Fig.2) have been analyzed together getting a better-constrained geoelectric model, reducing the equivalence problem. Afterwards geoelectric models have been compared with lithology and hydrochemical analysis to validate results (Fig.3).

Electrical resistivity time-variation values are expected due to seawater variation conditions. To test CSAMT as a sensitive method to monitor changes in fluid electrical resisitivity, we have collected data along the preferential seawater path every four month since spring of 2004. Five monitoring profiles, beginning on April 2004 until August of 2005 are shown in figure 4. Models have been also inverted using the determinant impedance tensor (Pedersen, 2005b). All the models were obtained using as initial model; a conceptual model of the aquifer system to emphasize the variations only due to seawater content.

Joint interpretation of seismic and CSAMT collocated profiles

Seismic and CSAMT models are analyzed together and compared to hydrogeological data to improve the aquifer image (Fig.2). Seismic velocity tomography is presented in figure 2a-c. Seismic tomography model depth is limited to 80-100 m due to the seismic array geometry, especially where thick deposits of low velocities materials are present. Velocities around 4500 m/s (typically compacted granitic rocks) are attained around 80 m depth in some spots.

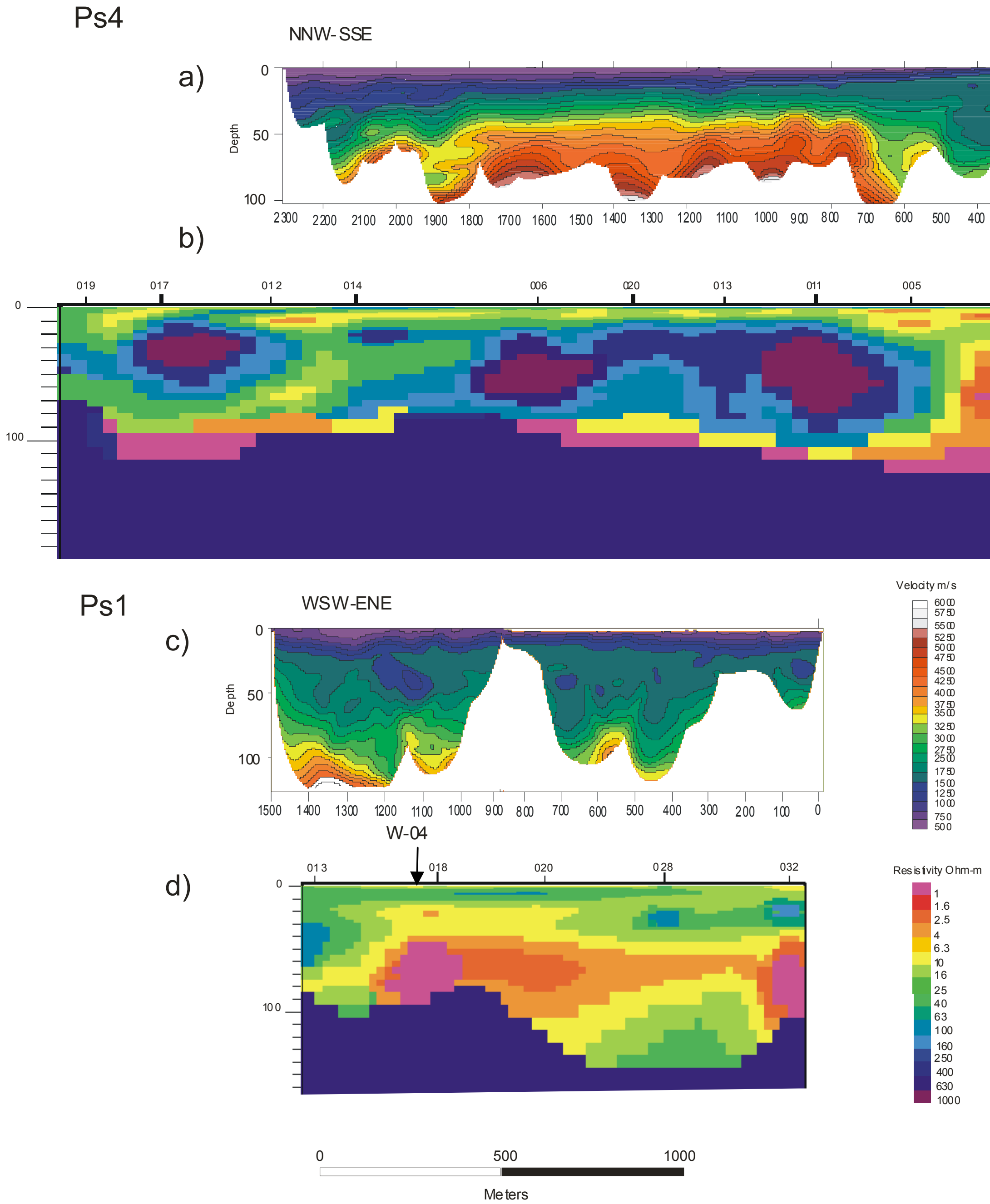

Figure 2. CSAMT and seismic velocity tomography collocated profiles (PS1, PS4), see figure 1 for location. All models are in the same length scale a) PS4 seismic velocity tomography, b) PS4 CSAMT model , c) PS1 seismic velocity tomography, and d) PS1 CSAMT model.

PS4 Profile

The main aquifer features presented in the CSAMT PS4 model can be described as follows (Fig.2b). In the upper zone, up to 20 m, which includes the free upper aquifer and the aquitard, resistivity varies from 10 to 40 Ohm.m. Below a wide high resistivity target -100 to1000 Ohm.m- is imaged north of site 005 that might correspond to the deep semiconfined aquifer composed by medium and coarse gravels containing fresh water. At these depths, a main resistivity change is observed among sites 011and 004-005, from a resistive to a conductive area. The seismic velocity model also imaged a lateral change in this zone, increasing the thickness of the low velocity materials. This implies a deeper basement (Fig.) that can be related to the main fault that confines inland the basal aquifer. Seawater wedge as a continuous front could be described in this profile from site 05 towards the south, thus along the river bed the wedge reach up to 500 m inland. As we will see later, in the western delta area the wedge reach up to 1500 m. Another low resistive zone (<4 Ohm.m) appear almost continuously above the basement. It disappears when basement is high enough to exercise a structural limit. Lateral brackish water flux flow must be affecting PS4 line due to the apparition of the deep conductor on the far north position of the profile.

PS1 Profile

PS1 model intersect in the southern part of PS4. Its main features could be related with lateral extension of PS4 features, nevertheless specific features has been assessed. As in the previous model, the upper 20 meters resistivity range goes from 10 to 40 Ohm.m belonging to the aquifer and aquitard units (Fig.2d). A low resisitive zone in the entire deep semiconfined aquifer is imaged, related to seawater wearing sediments. The highest thickness of this low resisitivity target is located between sites 18 and 20. This also coincides with low velocity values in the seismic tomography model. All these indicators correlate with the paleochannel's position and so the main seawater intrusion path. In both models a deeper zone with almost homogeneous resistivity >600 Ohm.m, represents the basement.

Basement reported from both geophysical methods in both profiles is located deeper than the position described by the water supply wells, therefore a thick weathered zone may exist yielding fresh granite basement in a deeper position. CSAMT models show fresh granite basement from 80 m up to 120 m depth. Its morphology gives an idea of gentle slopes that might be produced by fault activity and weathering evolution.

Comparison with hydrogeological data

Hydrochemistry analyses are collected once a year in selected spots of the fluviodeltaic system by governmental water service ACA. In this section, we will compare the CSAMT models obtained in may 2004 with hydrogeological data collected in spring 2004.

Multitube Piezometers W-04 and W-06 are located close to PS1 and M-1 profiles respectively. They provide three independent lectures in depth that can be correlated with three geoelectrical zones. Figure 3 shows the comparison among lithology, water resistivity and bulk resistivity (CSAMT resistivity models). In W-04 well, the shallower zone (3-15 m), shows a water resistivity of 7.3 Ohm.m (fresh water) in coarse sands that agree with the bulk resistivity of 40 Ohm.m obtained in the 2D model. Between 20 to 45 m depth, the water resistivity is 7.6 Ohm.m in finer sand-clay interbeded layers. This is evidenced in the bulk resisitvity 10 Ohm.m. And finally in the deeper position, from 50 to 80 m depth, is recorded 16.000 ppm of Cl-, that corresponds to a water resistivity of 0.29 Ohm.m that together with the reported coarse sands agrees with the bulk resistivity of 1 Ohm.m. Therefore, the geoelectrical model expresses a sandy aquifer zone with high seawater content.

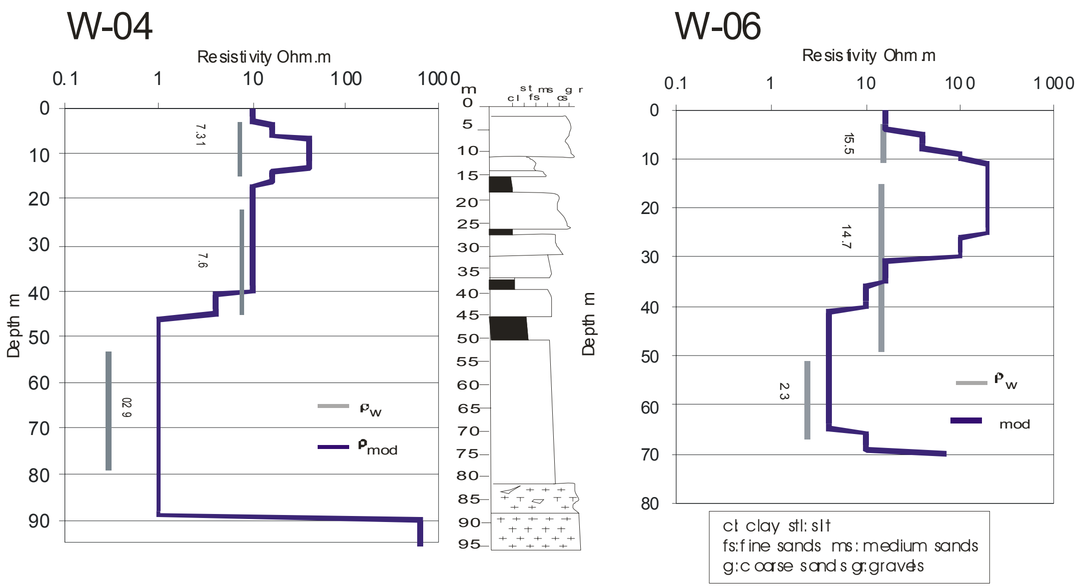

Figure 3. Water resistivity (ρ_w) and CSAMT bulk resistivity (ρ_{mod}) plots on wells W-06 and W-04. Resistivity data is correlated in depth with lithologies. See figure 1 for location.

W-06 is located 500 m to the north of PS1 close to M-1. Lithological description reveals coarse sands and coarse gravels composition that corresponds to the paleochannel. Resistivity values of the first and second levels (3-11 m and 15-48 m) are around 15 Ohm.m. The bulk resistivity show high resistive values (> 100 Ohm.m) that agree with coarse gravel bearing fresh water. Around 40 m depth it is seen a bulk resistivity decrease whereas neither lithologic nor hydrochemical evidence is observed. Below 52 meters water resistivity value is 2.3 Ohm.m. (1350 ppm Cl^-), bulk resistivity present low resistivity value (4 Ohm.m) and coarse sands are reported. Seawater influence reaches inland induced by the paleochannel on the western part of the delta in an oblique direction to the actual river line. This main preferential sweater flux path has been monitored every four month.

Time- lapse CSAMT profiles

Figure 4 presents the seawater monitoring models. The analysis of the 2D model sequence reveal tendencies of the seawater wedge associated with the deep low resistivity layer, specially on their northern part. From April 2004 model (first survey) to August 2004 seawater influence seems to move seawards. However, from December 2004 to August 2005 the conductive layer show a progression inland. August 2005 model achieve the maximum distance of seawater influence (Fig.4e). These results could be explained by two main factors. During fall of 2002, a seawater treatment plant has begun its activity. In addition, 2003 and most of 2004 have been quite rainy years. That had released hydrologic pressure over the aquifer system and thus seawater wedge was in regression. However, fall and winter of 2004 and all 2005 has been an extremely dry period, coming to an extreme hydrologic situation over the country. Additional information obtained from CSAMT time-lapse models, is the image of the main coastal fault (described above) due to the location of the southernmost sites near the shoreline. CSAMT modelled fault fits with PS4 seismic reflectors and velocity tomography model.

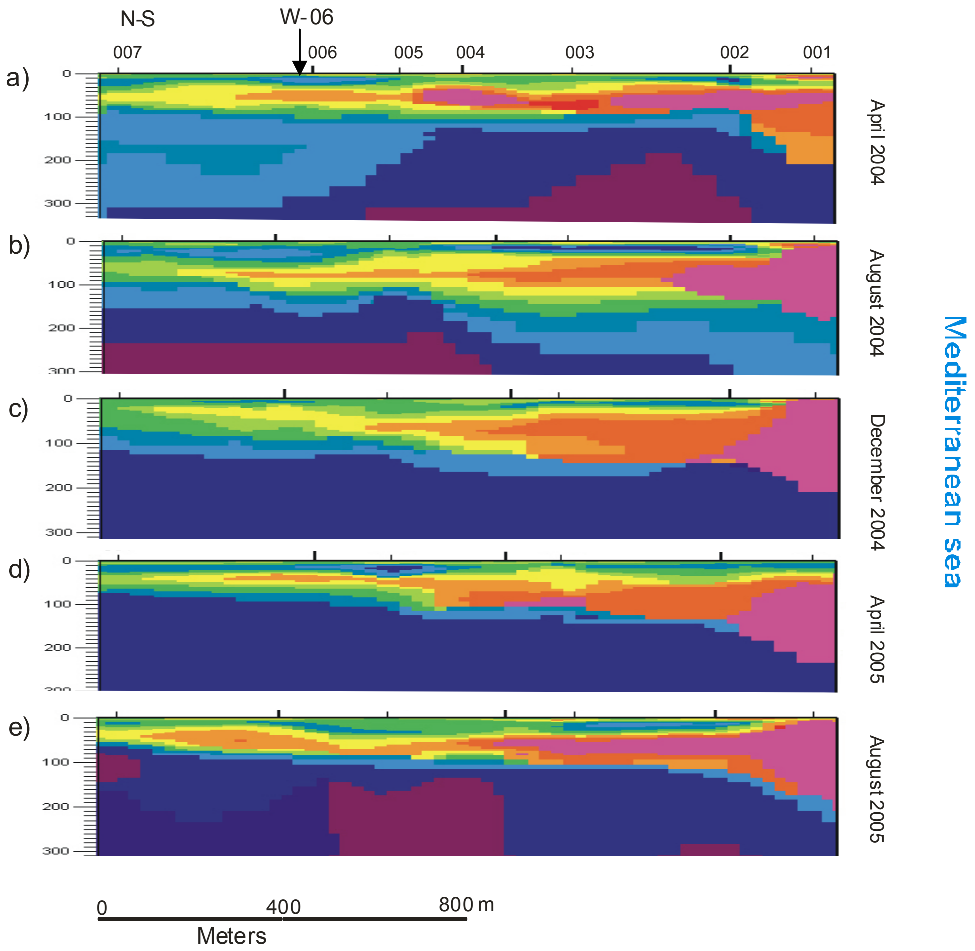

Figure 4. Time-lapse CSAMT modelling. Northern part of the models shows variations on the deep resistivity layer, associated to changes in water salinity content. Resistivity colour-scale same as in figure 2.

Conclusions

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

Aquifer units carrying fresh water presents high resistivity values ranging from 40 to 1000 Ohm.m, whereas zones of lower hydraulic conductivity present lower resistivity from 10 to 40 Ohm.m. Seawater bearing units have been identified clearly on the three CSAMT profiles PS1, PS4 and M-1. With them is possible to get a spatial image of the seawater intrusion state of the Tordera delta. The relations between chlorine concentration, water resistivity and bulk resistivity of the 2D CSAMT models have been observed for collocated data in W-04 and W-06. Results provide validation for the inversion models linking the material properties and water quality. CSAMT data analysis has evidenced the position of main intrusion paths of seawater flux flow. Along the riverbed, seawater intrusion is restricted from 500 m towards the shoreline whereas on the western part of the delta seawater intrudes through an ancient paleochannel. In hydrogeological terms, that behavior seen in the southern part of PS4 has to be explained with a main change in facies distribution, from more sandy seawater wearing sediments towards a dominated clayey sediments what blocks seawater progression in land in this direction (actual riverbed).

The CSAMT method has been proved as a sensitive method that can reflect changes in the electrical resistivity as a consequence of groundwater salinity changes. It has been clearly observed in the monitoring profile with the different far-reaching seawater influence over the time. CSAMT resistivity is well correlated with the hydrologic state of the system.

Acknowledgements

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