CHAPTER 15

STUDY AND MONITORING OF SALT WATER INTRUSION IN THE COASTAL AREA BETWEEN MAZARA DEL VALLO AND MARSALA (SOUTH–WESTERN SICILY)

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Abstract: In this chapter the study of a coastal aquifer located in South-Western Sicily (between the towns of Marsala and Mazara del Vallo) is presented, carried out using geochemical, hydro-geological and geophysical techniques. The aquifer has been over-exploited to the point of being subject to intense and worrisome salt-water intrusion.

A preliminary chemical and physical characterization of the waters was carried out; this included measuring their conductivity and their chloride content. This allowed to detect the marine intrusion wedge in the coastal aquifer. A series of electromagnetic soundings, suitably calibrated by well logs, were effected in the whole area and allowed to create a 3D interpretative model of the resistivity distribution in the aquifer, thereby enabling to recognize the main intrusion directions and the pattern of the aquifer bed.

Furthermore an integrated geophysical 2D section was carried out along a line roughly perpendicular to the coast, in one of the zones that is particularly involved in the intrusion phenomenon. Field measures included ERT, IP, TDEM and seismic soundings, all of which were aimed at reconstructing a highly detailed geophysical section. The seismic soundings clearly show the lateral variation between the fresh and salt water, such as the overburden and the clayey bed of the aquifer.

The final target of this research is to propose an optimized management-model of underground resources. The lessons drawn from the use of different techniques for defining geophysical profiles suggest an integrated methodology to identify in detail the sea intrusion zone in aquifers. Therefore, the methodology used can be suitably extended and exported for studing and monitoring many similar Mediterranean coastal areas

Keywords: Salt water intrusion, groundwater, geophysical surveys

1. INTRODUCTION

Knowledge of groundwater quality, mainly referred to coastal aquifers with salt water intrusions, can be improved by defining standard monitoring and study procedures. These should be aimed at obtaining a detailed model of the aquifer, especially regarding

G. Rossi et al. (eds.), Methods and Tools for Drought Analysis and Management, 303–321.

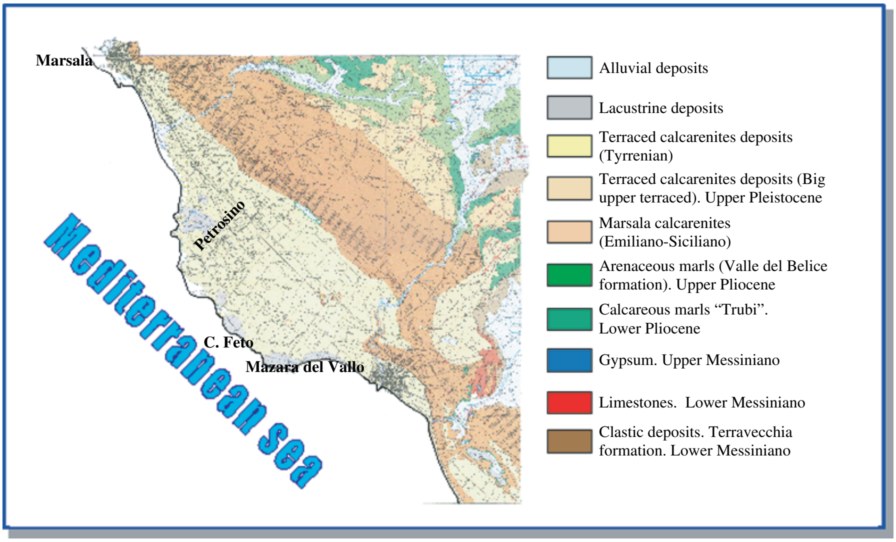

Figure 1. Geological sketch of the coastal area between Marsala and Mazara del Vallo (D'Angelo and Vernuccio, 1992; 1994)

salt water intrusion wedges. For this purpose a pilot project, which included a series of integrated studies using geophysical monitoring techniques (i.e. electrical, electromagnetic and seismic tomography, multi-parametric logs) was developed to define guidelines for the management of coastal aquifers in critical conditions.

The test-site is the coastal area between Mazara del Vallo and Marsala in South-Western Sicily (Figure 1). Here the coastal aquifer has been affected by sea water intrusion, caused by the over-exploitation of the local groundwater. Because of this harmful practice, the coastal aquifer has undergone a modification of the underground water flows which have in turn modified the natural equilibrium causing a serious intrusion of sea water. *Margi,* which were the most humid coastal areas, have disappeared. They are characterized by their unusual fauna and flora.

2. GEOLOGICAL, HYDROGEOLOGICAL AND GEOCHEMICAL SURVEYS

Preliminary surveys carried out in the zone (Cosentino et al., 2003), allowed us to define the hydrogeological characteristics of the aquifer and to characterize the preferential directions of the salt water intrusion. Further geochemical surveys allowed us to characterize the groundwaters according to the distribution of their chloride and carbonate contents.

The aquifer, which extends for approximately 150 km^2, is composed of pleistocenic sand and calcarenite deposits that overhang a clay-sand substratum. The hydrodynamic model (Figure 2) characterizes a strongly over-exploited aquifer with large zones affected by salt water intrusion.

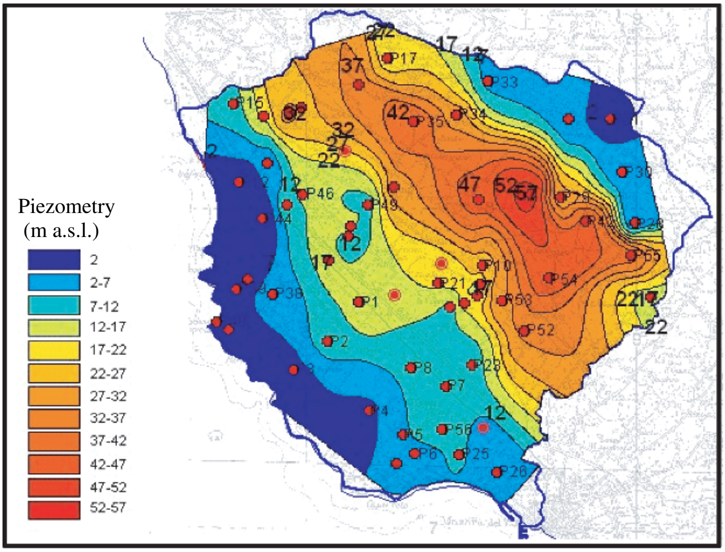

Figure 2. Piezometry map of the aquifer of Marsala – Mazara del Vallo

In natural conditions the near-surface groundwater heads towards the sea, coming up to the surface near the coast locally forming humid areas, the so-called *margi*. The pool water, substantially evaporated in the *margi*, and the sea water intrusion were limited to the contact areas between the *margi* and the sea. Part of the underground flow was drained off by small streams, today almost completely dry, whereas the

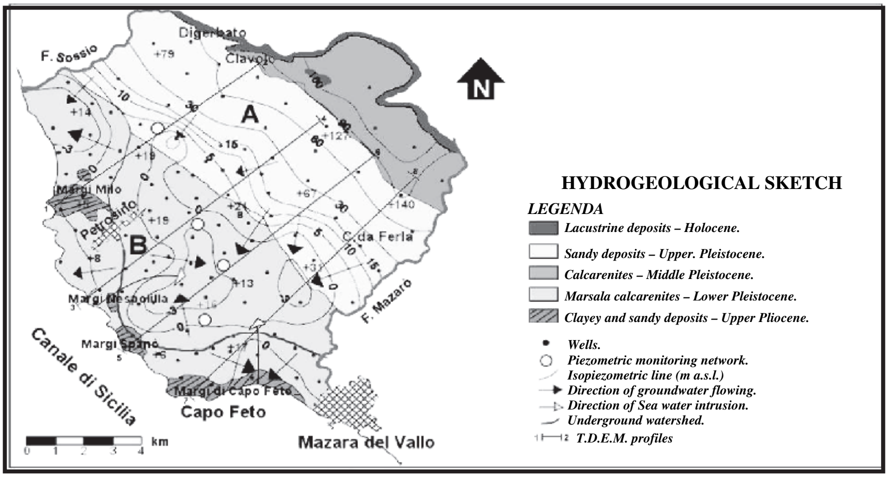

Figure 3. Hydrogeological sketch of the aquifer of Marsala – Mazara del Vallo

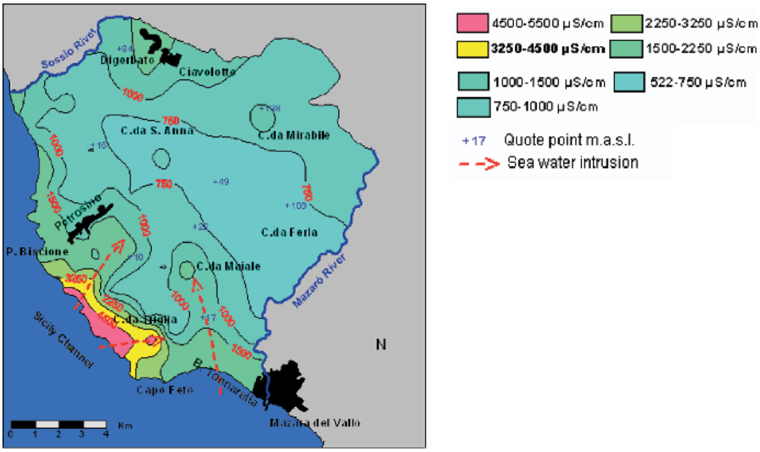

Figure 4. Map of conductivity of groundwater of the aquifer of Marsala – Mazara del Vallo

remaining flow recharged the superficial aquifer thereby feeding the *margi* and preventing the advance of the sea water wedge. The presence of the *margi* created a natural landscape with a delicate equilibrium: the superficial fresh water contrasted the sea water intrusion, so the expansion area of the *margi* was determined by the budget between evaporation and underground water contribution.

Hydrogeological surveys carried out in wells located in the zone allowed us to reconstruct the groundwater piezometry, shown in Figure 3.

Geochemical analyses of the water samples allowed us to elaborate a series of thematic geochemical maps. In particular, the groundwater conductivity map (Figure 4) allowed us to ascertain the main directions of the sea water intrusion.

3. 3D MODEL OF AQUIFER RESISTIVITY BY INTEGRATED GEOPHYSICAL SURVEYS

In order to obtain a three-dimensional interpretative model of the main structures of the aquifer and, in particular, to reconstruct the shape of the sea intrusion wedge, a series of integrated geophysical surveys, three-dimensional geophysical modelling of the aquifer and the localization of the main zones of sea water intrusion were carried out. Fifty electromagnetic TDEM surveys were also carried out, calibrated by four well-logs and two 2D electrical tomographies. Figure 5 shows the locations of the surveys.

TDEM surveys were located following some preferential directions (SSW-NNE) so as to make electro-stratigraphic sections that enhanced the zones with sea water intrusion (Fitterman and Stewart, 1986). The TEM-FAST 48 instrument (Figure 6) was used because of the following characteristics: precision, ease of handling and rapidity of acquisition. In the TEM-FAST 48 instrument a coil (transmitter loop) placed on the soil generates a series of electromagnetic impulses that are diffused

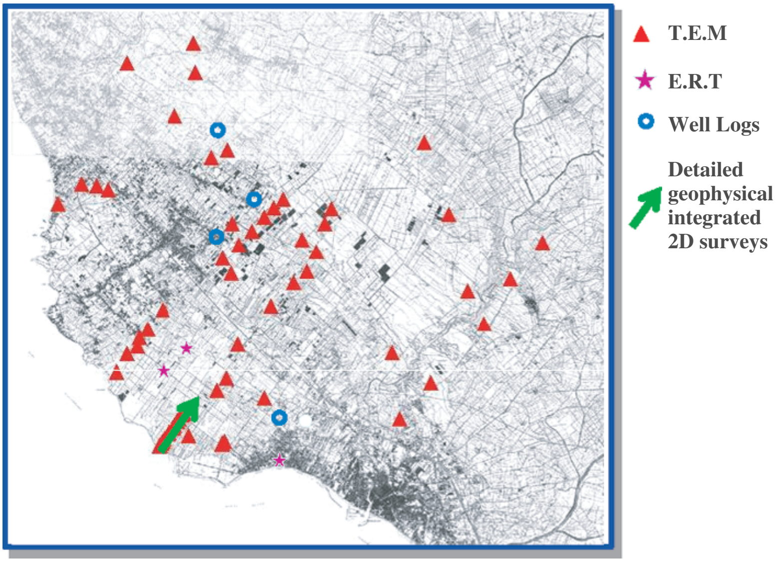

Figure 5. Location of the geophysical surveys carried out in the coastal area of Marsala – Mazara del Vallo

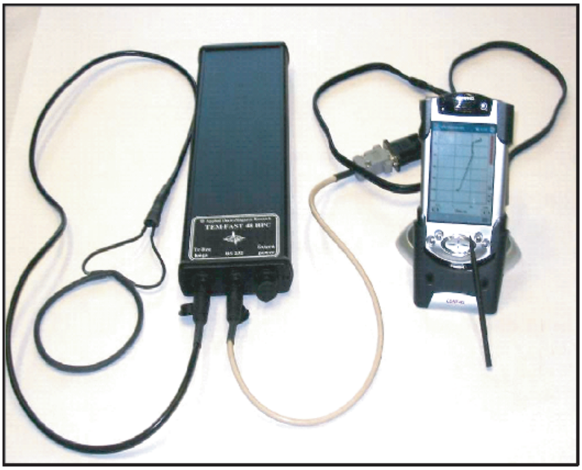

Figure 6. TEM-FAST 48 HPC instrument

in the subsoil inducing electrical eddy currents at different depths. These generate secondary electromagnetic fields. The analysis and the interpretation of induced signals, acquired by a receiver loop, allow us to recognize the electro-stratigraphic column of resistivity of the subsoil.

TDEM surveys were carried out by using the coincident loop configuration, with different coil lengths (12,5 m, 25 m and 50 m) in order to guarantee, case by case, a suitable penetration depth (Nabighian and Macnae, 1991). The data acquisition was made with a transmitting current of 3A. A time range varying from 2048 μs to 4096 μs was set.

TDEM measures were interpreted using TEM-RESEARCHER software, designed for the resolution of inverse problems in time domain electromagnetic soundings. Every sounding was interpreted based on a mono-dimensional model of subsoil with horizontal layers. At first, the data obtained from each sounding was interpreted in terms of a 1D model of depth varying resistivity (Figure 7). The analysis of the aforesaid models allowed us to estimate the height of the marly-clayey basement of the aquifer, corresponding to the roof of the "Marnoso-Arenacea della Valle del Belice" formation.

Subsequently electro-stratigraphic columns, obtained from the monodimensional interpretation of the TDEM soundings, were correlated (Figure 8) to obtain the assemblage of 8 resistivity sections (5 perpendicular to the coast line and 3 parallel). In order to obtain this assemblage, the re-interpretation of some of the curves of the apparent resistivity often had to be affected.

The resistivity sections (Figure 9) show a very irregular substrate and a large depression that coincides with the central zone of the investigated area. In this area,

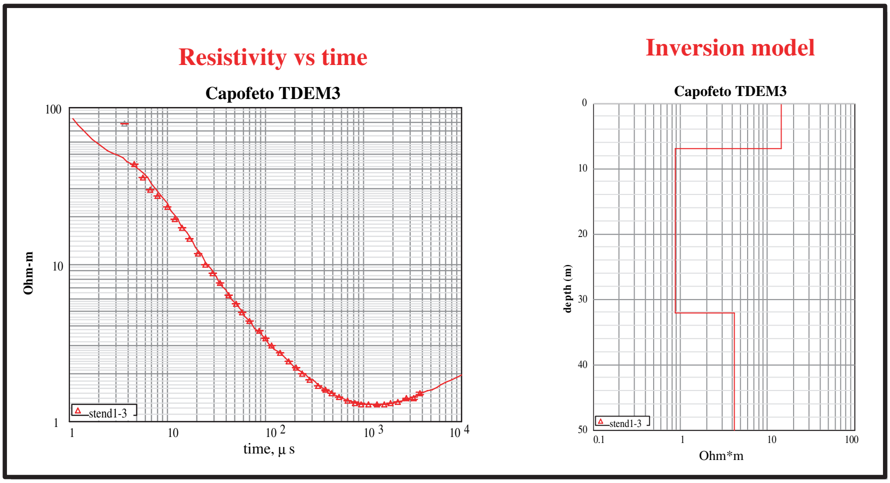

Figure 7. On the left, plot of the apparent resistivity versus time for a TDEM survey. On the right, interpretative electrostratigraphic model, showing pattern of resistivity versus depth

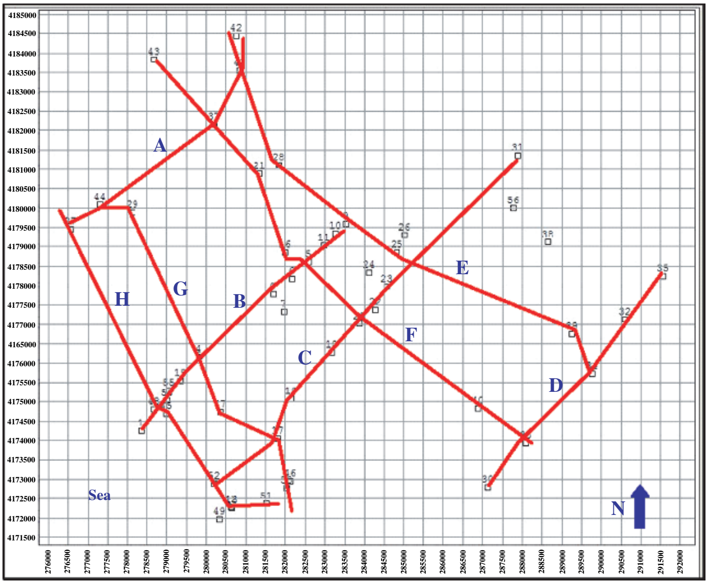

Figure 8. Location of TDEM surveys carried out in the area between Marsala and Mazara del Vallo. Red lines indicate the traces of the electro-stratigraphic sections, shown in Fig. 9

in correspondence with *Borgata Adragna*, the depression reaches a depth of – 30 m whereas near *Baglio Barberi* it reaches a depth of – 40 m.

From the locality called *Case Campanella*, and proceeding inland, the substrate reaches heights greater than 100 m near the northern side of the investigated area.

Finally the entire set of 1D TDEM inverting data was elaborated again to obtain a three-dimensional model of the aquifer resistivity (Fitterman and Hoekstra, 1984). This graphical 3D-plotting (Figure 10) allowed us to reveal and define the main directions of the sea water intrusion with more accuracy, by comparing these results with those shown by the isopiezometric lines of the hydrogeological map.

The analysis of the results highlighted the presence of extremely low values of resistivity along a strip of coast one kilometer wide. Evidently in this zone the sea intrusion is more intense than in the more internal areas. Moreover, the substantial agreement between the TDEM and the hydrogeological results was ascertained. In Figure 11 a perspective representation of an aerial photo of the zone is shown. In it, the resistivity map and the main lines of the sea water intrusion overlap in the coastal zones called margi. Considerations on the geometry of the aquifer obtained from electromagnetic surveys were strengthened by the data obtained from well logs. Moreover, they allowed us to identify some narrow layers having a high sand and clay content. These layers can limit vertical water flows by partially confining the aquifer in some areas.

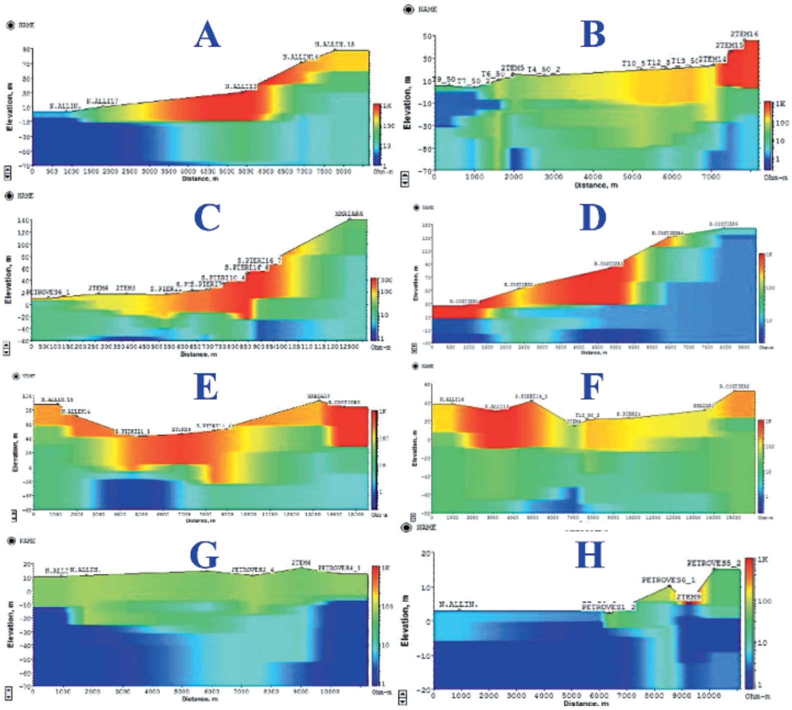

Figure 9. Electro-stratigraphic sections obtained from the profiles indicated in Figure 8

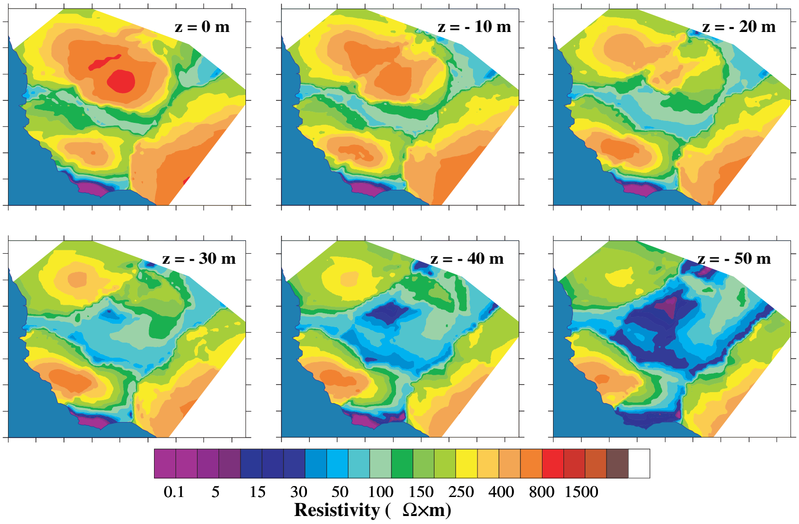

Figure 10. Electro-stratigraphic horizontal slices obtained by means of the combined interpretation of TEM-FAST surveys and their 3D interpolation

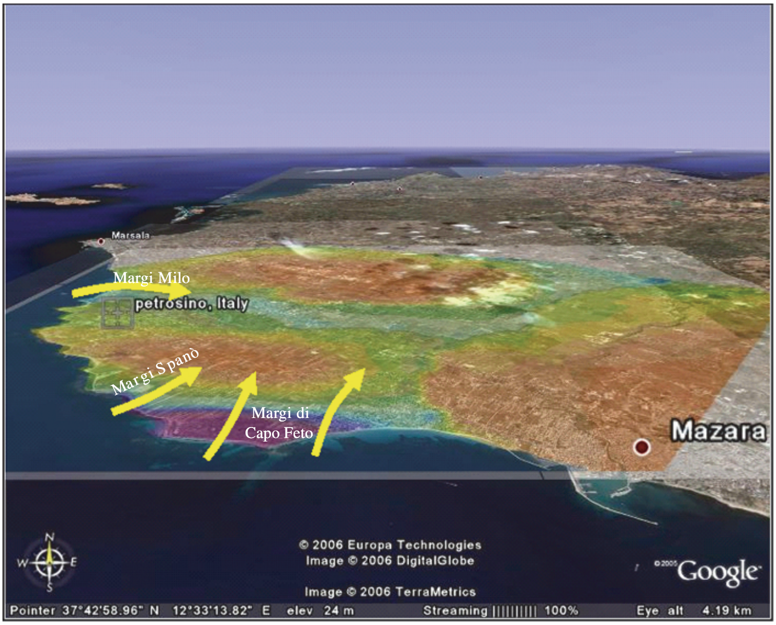

Figure 11. Overlapping of a resistivity horizontal slice on the aerial photo. The yellow arrows show the main directions of sea water intrusion (from Google ©)

4. METHODOLOGICAL STUDIES OF ELECTRIC RESISTIVITY TOMOGRAPHY (ERT)

Previous considerations on the general pattern of the sea intrusion wedge convinced us of the necessity to effect further surveys aimed at detailing the reconstruction of the aquifer in those zones affected by the intrusion. In fact, a geo-electrical investigation of the resistivity distribution in the subsoil would be useful to obtain a detailed reconstruction of the underwater structures. Then a geoelectrical methodology of data acquisition can be useful if optimized for the study of coastal aquifers interested by sea intrusion phenomena. Therefore a geoelectrical methodological study was carried out, by simulating synthetic models with electric parameters compatible with sea intrusion cases (Figure 12). In the chosen models the lateral and vertical resistivity variations in the subsoil were essentially determined by the pattern of the zones on the border between the fresh and salt water. Models simulate a sea intrusion (resistivity equal to $0.2\ \Omega \times \mathrm{m}$) in coastal aquifers ($80\ \Omega \times \mathrm{m}$) limited at the bottom by a clay basement ($2\ \Omega \times \mathrm{m}$) and at the top by a resistive overburden ($150\ \Omega \times \mathrm{m}$). The lateral passage between the fresh and salt water can be sharp or smooth, depending on the considered model.

The theoretical answers in terms of apparent resistivity values were evaluated assuming the execution of pseudosections using classic arrays (Wenner, Wenner-Schlumberger and dipole-dipole) and multielectrodic arrays (Linear Grid). This

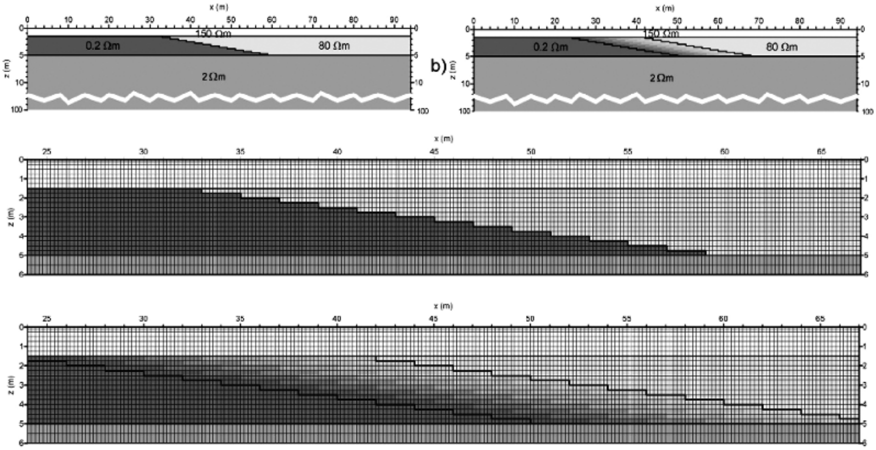

Figure 12. a) Model of an aquifer characterized by a sea intrusion wedge, with a lateral passage from the salt water intrusion zone to the fresh water zone. The aquifer is delimited at the bottom by a conductive basement and it is covered by a resistive superficial layer. b) the model is similar to the previous one, but with a transition zone between salt and fresh water. c) and d) Zooming of respectively a) and b) that show the choice of geometry and size of the model blocks

latter array (Fiandaca et al., 2005) allowed us to carry out a high number of measures for every current dipole, thereby reducing the acquisition time. The optimization of the number and the position of the current dipoles, allowed us to obtain results that were comparable, if not better, to classic arrays.

The linear Grid array is a 2D derivation of the resistivity grid array (Cosentino et al., 1999; Cosentino and Martorana, 2001) that concerns the use of a high number of potential dipoles for every current dipole considered. In fact a limited number of current dipoles was used in the same profile in contrast with the high number of potential dipoles. The array (Figure 13) was optimized to allow us to use it with a multichannel resistivity-meter.

Simulations on synthetic models were carried out considering 48 aligned and equal spaced electrodes and 21 different current dipoles, using two current electrodes every time and the remaining 46 for potential measures. The choice of the number and the positions of the current electrodes was finalized to obtain a good sampling density in the investigated zone.

Synthetic apparent resistivity data, with an added noise of different percentages (2% and 5%), were inverted with RES2DINV software (Loke and Barker, 1996), using the same optimized set of inversion parameters. In this way the inverted models, obtained from the theoretical pseudosections, were compared with the initial synthetic models using several comparison parameters to estimate the compatibility between these latter and the interpretative model. A quantitative evaluation of the resolution of each tested array was therefore obtained when applied to these hydrogeological problems. From a comparison of the results (Figure 14) it can be deduced that the best results were obtained using dipole-dipole and linear grid arrays.

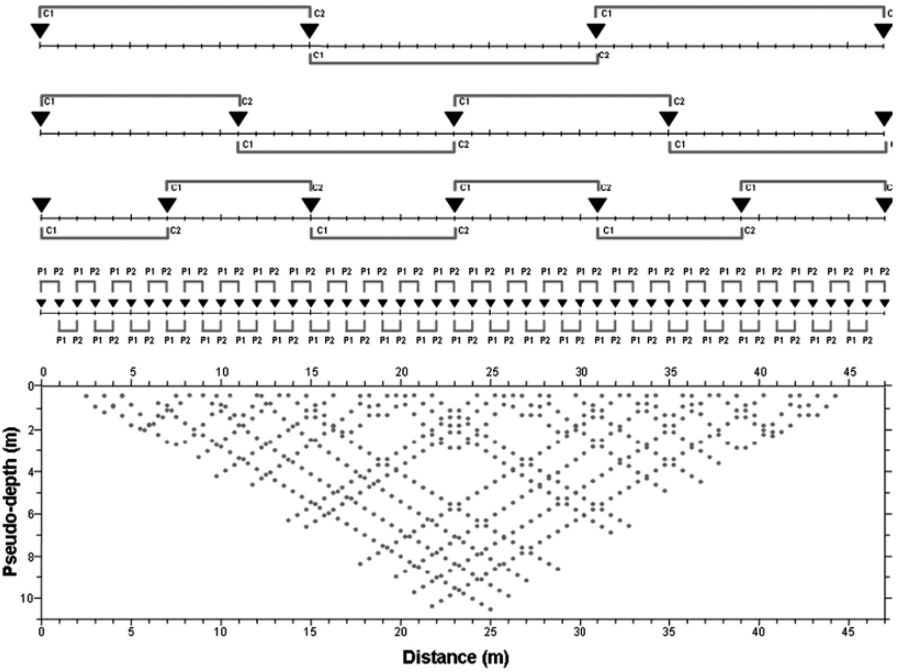

Figure 13. Top: outline of the Linear Grid array. For every current dipole C1-C2, potential measures for each adjacent electrode dipoles P1-P2 are carried out. Bottom: reference points for measures in the resulting pseudosection

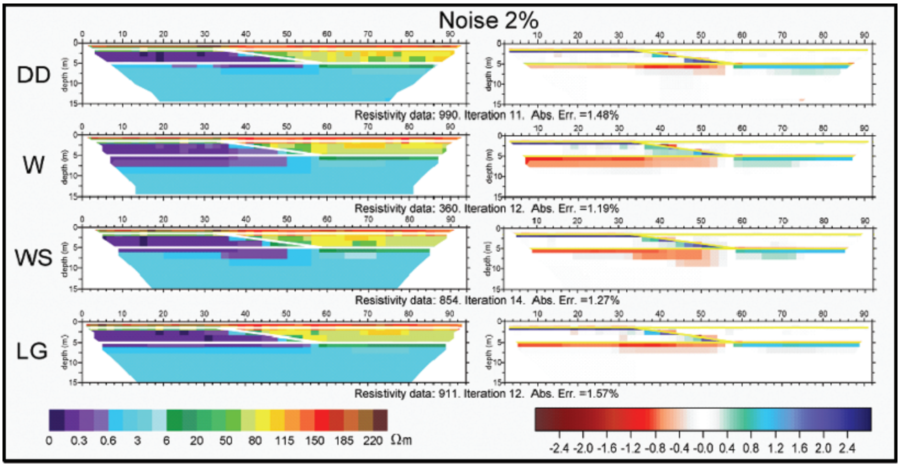

Figure 14. Inversion models (on the left) and correspondent patterns of the correlation parameters (on the right) of the model of sea intrusion shown in Figure 13. Simulations were executed with dipole-dipole (DD), Wenner (W), Wenner-Schlumberger (WS) and Linear Grid (RG) arrays. Results are referred to data with 2% noise

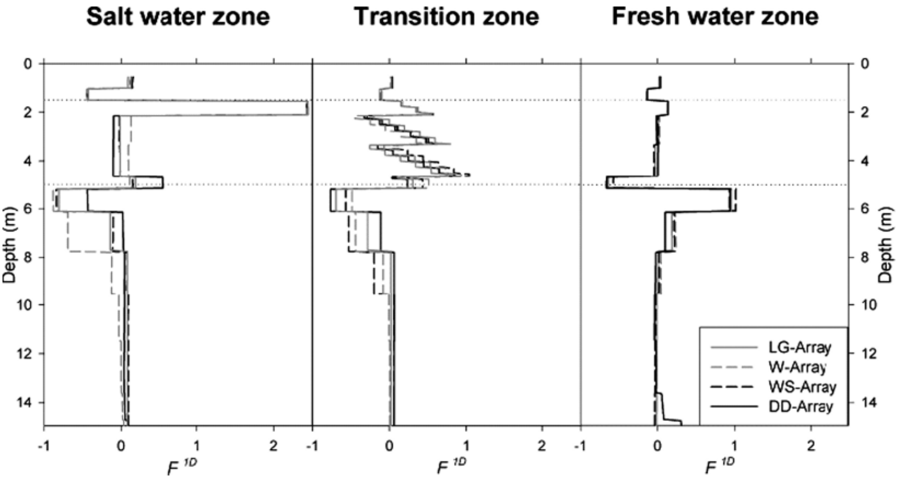

Figure 15. 1D misfit parameter relative to three different zones of the inversion model: salt water intrusion (on the left), to transition zone (at middle) and fresh water (on the right)

In order to estimate the approximation degree a 1D misfit parameter was used. In Figure 15 its patterns in simulations with errors of 2% are presented, the interpretative models are subdivided into three sections corresponding to three different zones of the profile: salt water intrusion, transition and fresh water. In the intrusion zone the worst results were obtained when using the Wenner array that wasn't able to locate the exact depth of the basement. On the contrary both the dipole-dipole and the linear grid recognized the contact between the clay basement and the aquifer well.

5. GEOPHYSICAL SECTION BY USING INTEGRATED METHODOLOGIES

A phase subsequent to the three-dimensional geophysical modelling of the aquifer and to the location of the main zones of salt water intrusion, was that of effecting a detailed characterization of these zones by means of high resolution geophysical surveys, aimed at the geometric reconstruction of the sea water intrusion wedge. The zone chosen for the soundings was the coast between Capo Feto and Margi Spanò, where the survey profile was approximately 1300 m long (Figure 16). The purpose of this was to reconstruct the 2D geometry of the aquifer and the sea water intrusion wedge with high precision, while trying to delineate the piezometric surface, the passage from salt to fresh water and the silt-clay substrate.

Along the chosen line AB, a series of integrated geophysical profiles were executed, using the following methodologies:

1. TEM-FAST electromagnetic surveys;
2. 2D resistivity tomographies;
3. 2D induced polarization tomographies;

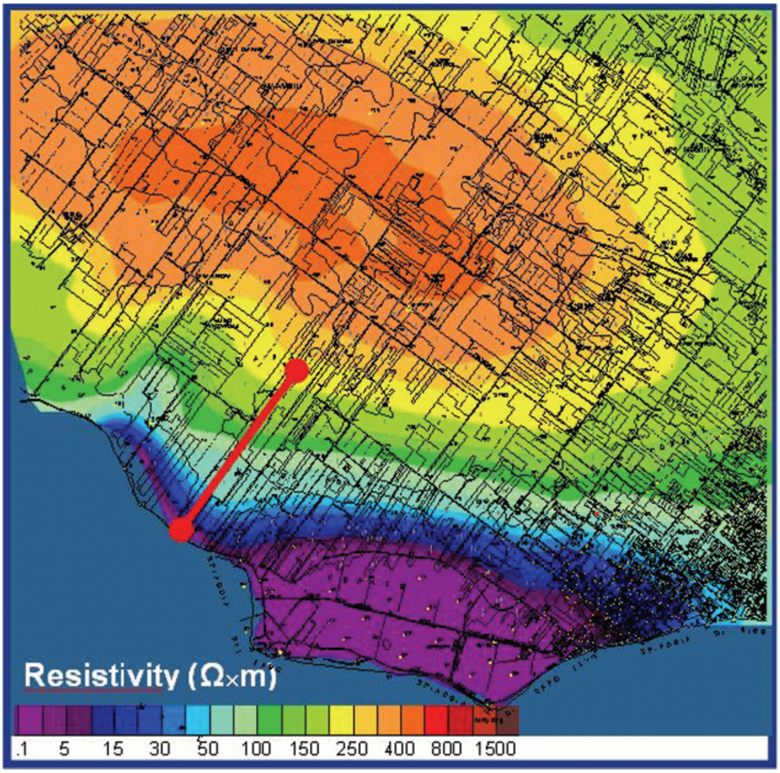

Figure 16. Slice of resistivity of aquifer at depth $z = -10\,m$ in the area of Capo Feto. The red line indicates the trace of detailed geophysical sections

4. refraction seismic profiles.

The interpretation of the acquired data with the aforesaid techniques was effected in a combined way, with the aim of linking together the interpretative models concerning different but specific parameters of the subsoil (i.e. electrical resistivity, chargeability, seismic wave velocity) as best as possible.

Along profile AB a series of TEM-FAST surveys was carried out with a *coincident loop* configuration and a square coil with side equal to 50 m, with the aim of obtaining an investigation depth greater than 40 m. The plot of the pseudo-section, from the apparent resistivity data, supplied a qualitative pattern of the subsoil conductivity. However the near-surface zone wasn't well detailed because of the limits imposed by the size of the coil.

The results of the surveys were interpreted with monodimensional layered models, whereas the results of the inversion models were interpolated to obtain a two-dimensional vertical electromagnetic section of resistivity (Figure 17). The section showed a resistive overburden over a lateral passage from very low resistivities (blue zone) to higher values (green zone). This variation was clearly interpretable as the transition zone from salt to fresh water.

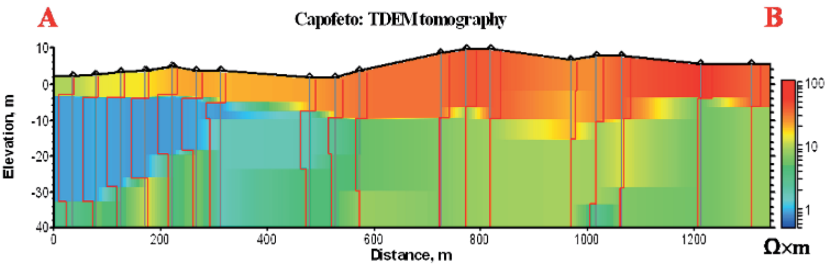

Figure 17. Capo Feto. Tomographic 2D section obtained from TEM-FAST surveys

The resistivity and induced polarization measures were carried out by placing a series of aligned electrodes in the ground spaced 2 m apart, and by connecting them to a Syscal Pro resistivity-meter, that allowed for the automatic injection of the current into the ground and the measurement of the electric potential at the surface. Measures of apparent resistivity or induced polarization were carried out using the same arrays, the interpretation of which enabled us to obtain vertical sections of resistivity and induced polarization.

Five resistivity tomographies were carried out along the AB line using the previously optimized linear grid array, for a total of 336 electrodes, spaced 2 m apart. The resulting vertical electrical section is shown in Figure 18. Furthermore, these

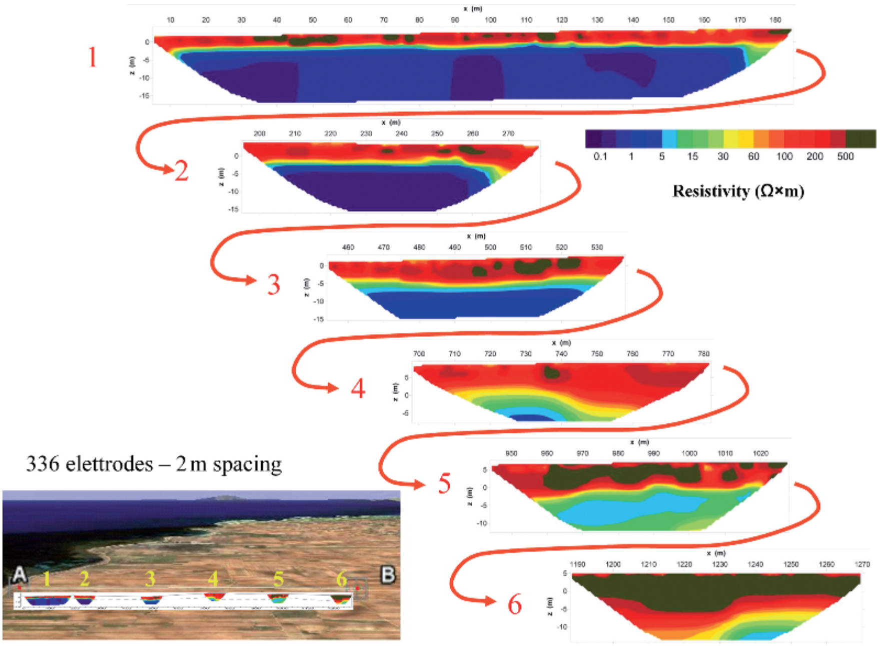

Figure 18. Capo Feto. Tomographic 2D sections obtained from resistivity surveys

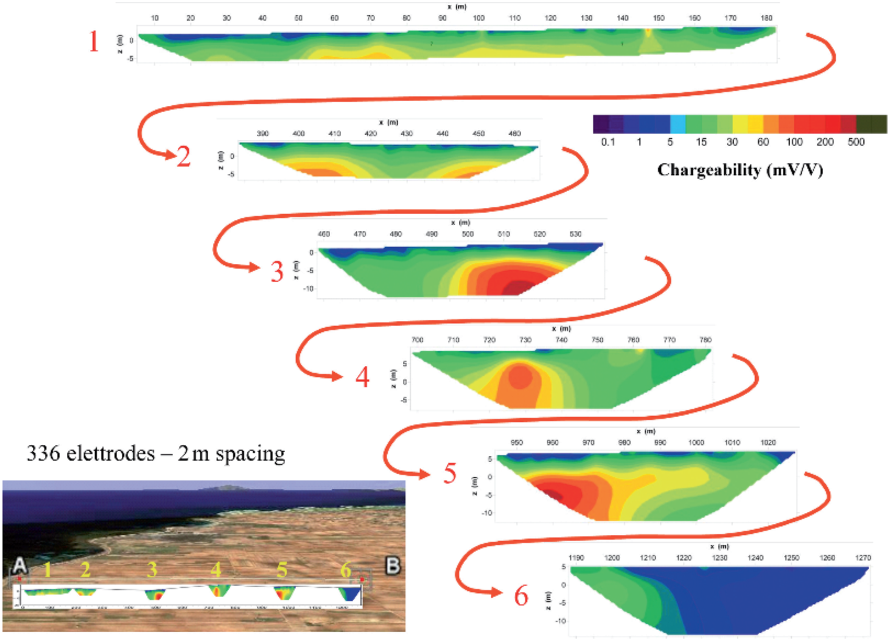

Figure 19. Capo Feto. Tomographic 2D sections obtained from I.P. surveys

sections also show a resistive cover overhanging a conductive zone in which a lateral increase of resistivity occurs when the distance from the coastal zone increases.

Measures of induced polarization were carried out with the same arrays. The obtained chargeability sections are shown in Figure 19. These are more difficult to interpret, since chargeability is not directly comparable with the presence of water, but is more linked to the clayey content. Unfortunately the obtained investigation depth didn’t allow us to obtain information on the clayey basement.

Lastly, seismic measures were carried out using a series of aligned geophones, spaced 3 m apart, connected to an ABEM Terraloc MK6 seismograph by a multi-channel cable. Every section was obtained using 48 geophones and carrying out lateral and intermediate shots at different offsets for a total number of 7 shots for each profile. In this way several dromocrones were obtained, i.e. graphic times of arrival of waves / source-geophone distances (Figure 20), while the velocity of the seismic waves in the ground were deduced from these values . The interpretative seismic sections show an irregular cover, characterized by low values of seismic velocity (1000–1300 m/s) that cover a formation characterized by higher velocity (1950–2150 m/s).

The integrated analysis of the geophysical data regarding the same area but carried out using several methodologies, allowed us to correlate different inversion models. The result is the correct location and delimitation of the water table, the salt/fresh water transition zone, the lythological structures of the aquifer and the substrate.

The overlap and the comparison of the interpreted models obtained using different techniques (Figure 21) allowed us to highlight substantial analogies in the results

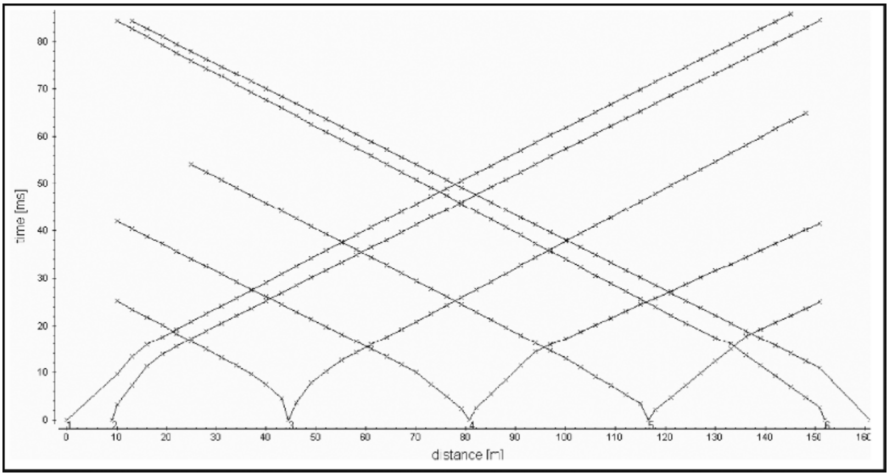

Figure 20. Seismic data are represented as a travel-time plotting, from which seismic velocities of the subsoil are deduced. For every seismic section seven shot points at different offsets were used

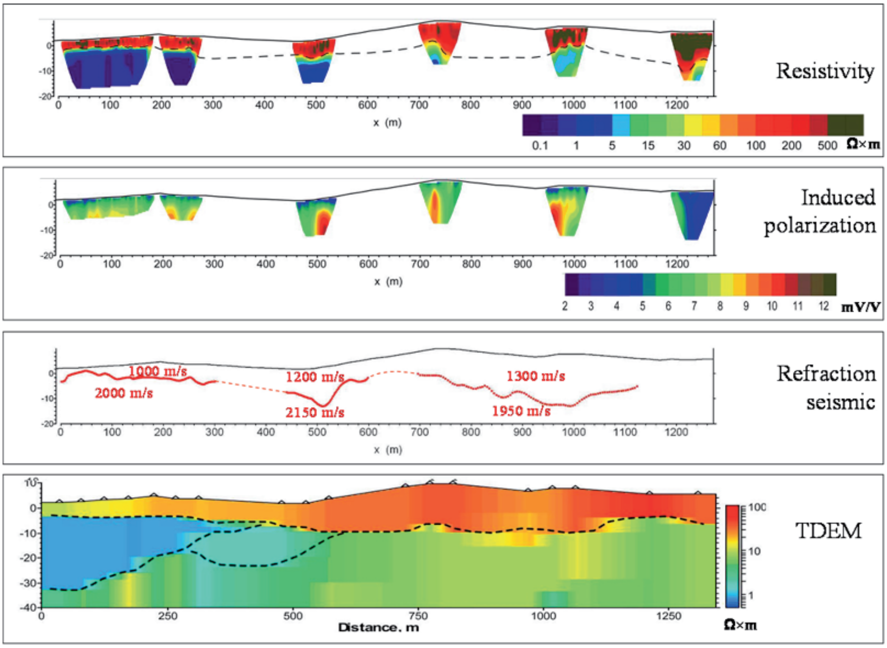

Figure 21. Capo Feto. Comparison of interpretative 2D models obtained from different geophysical methodologies

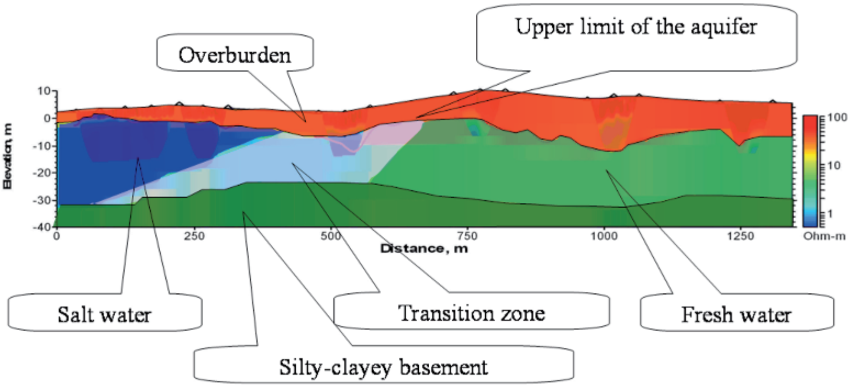

Figure 22. Capo Feto. Interpretative section obtained from integrated geophysical inversions

but also to underline some differences to be referred both to the analysis of the various parameters (i.e. resistivity, chargeability or seismic velocity) and to the different resolutions and depths of investigation of these techniques.

The combined interpretation of the different kinds of geophysical surveys allowed us to elaborate an interpretative section (Figure 22) in which the aquifer cover and the water table are characterized in good detail, while the sea intrusion zone, the transition zone and the fresh water zone are delimited with great precision. Finally upper limit of the siltous-clayey substrate is clearly evident.

6. CONCLUSIONS

The results of the geophysical surveys, together with the implementation of the geophysical monitoring techniques, allowed us to check, implement and partially support the previous hydrological balances of the coastal aquifer of Marsala-Mazara Del Vallo (Cosentino et al., 2003).

The integration of the selected geophysical methodologies (Geoelectrics, low-frequency electromagnetics – TDEM, Refraction Seismics and geophysical Logs) allowed decreasing the uncertainty limits of the various inversions, by means of a superposition of the various geometrical models obtained. However, TDEM and Geoelectrical investigations would be the basic tools for such kind of studies.

Some uncertainties do still remain, related to the real exploitation of the area and to the comparison of such utilisation with that both officially and unofficially declared. Furthermore, although the uncertainties regarding the exploitation heavily influence the balance, the geophysical methodology implemented and used allowed us to acquire fundamental information, the utility of which will be complete when the input/output data from the aquifer is more reliable and certain.

The methodological results obtained will allow us to draw some guidelines that could be applied to the study of coastal aquifers subject to intrusion risks. In particular, the proposed new geoelectrical array, which involves a remarkable reduction of the acquisition time without any qualitative loss, will be suggested not only in the phase of the preliminary study but also for the time-lapse monitoring periodical controls.

The mentioned guidelines, that will include methodologies to be used as well as technological suggestions, could be exported to other similar, hydrogeological cases typical of many coastal regions of the Mediterranean.

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REFERENCES

Cosentino, P.L., Deiana, R., Martorana, R., Pellerito, S. and Vega T. (2003) Geochemical and geophysical study of salt intrusion in the South-Western coast of Sicily. *Tecnología De La Intrusión de agua de mar en acuíferos costeros: Países Mediterráneos. IGME. Madrid 2003. ISBN. 84-7840-470-8*, 187–195.

Cosentino, P. and Martorana, R. (2001) The resistivity grid applied to wall structures: first results. *Proceedings of the 7th Meeting of EEGS, European Section*, Birmingham, ARCH02.

Cosentino, P., Martorana, R. and Terranova, L.M. (1999) The resistivity grid to optimize tomographic 3D imaging. *5th Meeting of EAEG, European Section*, Budapest, Hungary, Em12.

D'Angelo, U. and Vernuccio, S. (1992) Carta geologica del Foglio 617 "Marsala" scala 1:50.000. *Bollettino Società Geologica Italiana*, Vol. 113, Roma.

D'Angelo, U. and Vernuccio, S. (1994) Note illustrative della carta geologica Marsala (F°. 617 scala 1:50.000). *Bollettino Società Geologica Italiana*, Vol. 113, Roma, 55–67.

Fiandaca, G., Martorana, R. and Cosentino, P.L. (2005) Use of the linear grid array in 2D resistivity tomography. *Near Surface 2005 - 11th European Meeting of of Environmental and Engineering Geophysics*, Palermo, ISBN 90-737-8191-4, A023.

Fitterman, D.V. and Hoekstra, P. (1984) Mapping of saltwater intrusion with transient electromagnetic soundings, In:Nielsen, D.M. and Curl, M. (Eds.) *Proceedings of the National Water Well Assn. Conference on surface and borehole geophysical methods in subsurface investigations*, San Antonio: National Water Well Assn., 429–454.

Fitterman, D.V. and Stewart, M.T. (1986) Transient electromagnetic sounding for groundwater. *Geophysics* 51, 995–1005.

Loke, M.H. and Barker, R.D. (1996) Practical techniques for 3D resistivity surveys and data inversion. *Geophysical Prospecting*, 44, 499–523.

Nabighian, M.N. and Macnae, J.C. 1991 Time domain electromagnetic prospecting methods. *Electromagnetic methods in Applied Geophysics*, Vol. 2A, Tulsa, pp. 427–520.