Coastal aquifer assessment using geophysical methods (TEM, VES), case study: Northern Crete, Greece

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Abstract: - The Geropotamos aquifer on the north-central coast of Crete, Greece, is invaded in some places by salt water from the Aegean Sea, with impact on freshwater supplies for domestic and business uses, including agriculture. Investigation of the aquifer using electromagnetic (TEM) and electrical resistivity (VES) measurement techniques has resulted in 1D models and 2D imaging of geoelectric structure, depicting the zones of salination of groundwater in the aquifer. Comparisons with geological map and field-based observations, indicates that saline intrusion is likely to occur along fractures in a fault zone through otherwise low-permeability phyllite-quartzite bedrock, and emphasizes the critical role of fracture pathways in salination problems of coastal aquifers.

Key-Words: - Transient Electromagnetic (TEM) method, Vertical Electrical Sounding (VES) method, resistivity, Crete, coastal aquifer, sea-water intrusion, saline groundwater, 2D imaging, dolomitic limestones, phyllite/quartzite nappe, fracture zone

1 Introduction

The recent changes in climate patterns highlight the need to secure reliable water supplies especially in areas where water is scarce. A place where this problem is of importance is the island of Crete, Greece. In Crete, important aquifers are located in limestones in coastal locations, where salt water from the sea may intrude into the aquifer. This research investigates the extent of this problem for the Geropotamos aquifer, on the coast of central-northern Crete (Zarris, 2008). One part of the aquifer in the catchment of the Geropotamos River is of particular interest because of severe contamination of water in some places, from seawater intrusion. Suggestions that Miocene evaporates led to groundwater salination are unconfirmed, and seawater intrusion is the most probable cause, supported by the results of this research. The research also makes recommendations for action to ensure good water supplies. Due to the development of the area, many hydrowells have been constructed. The excessive extraction of groundwater is leading to a fall in the aquifer level and as a result the saltwater intrusion into the study areas. Consequently, there is an urgent need to monitor the changes taking place within the aquifer, and assess the threat to the drinking water supply. For that reason two complementary geophysical methods has been applied, Transient ElectroMagnetic (TEM) and Vertical Electrical

Soundings (VES). The results of these surveys were integrated with hydro-geological data from hydrowells, which were available and collected from the local authorities.

Geophysical techniques have been carried out many times in the past for aquifer study giving very good results (Chalikakis, 2006). The TEM method has was selected for our study since it has found increasing application in saline-freshwater interfaces mapping in coastal regions (Nielsen et al, 2007; Land et al., 2004; Descloitres et al, 2000; Goldman, M., and Kafri, U., 2006). The expected results from the application of TEM method are the recognition of the main tectonic structures that govern the hydrogeological status of the area. This information could be safely used as prior info for the masterplan of the water management of the area.

2 Study Area

The study area is situated along the northern coastline of Crete and it is lying before Geropotamos river to some km before Bali, viz from 35° 25΄N 24° 40΄19΄΄E west to 35° 24΄N 24° 44΄ 25΄΄E at East, i.e. it covers about 40Km^2 (Fig.1). It consists the northen part of the municipality of Geropotamos and comprises 9 villages: Achlades, Aggeliana, Exantis, Melidoni, Panormos, Perama, Roumeli, Siripidiana, and Skepasti.

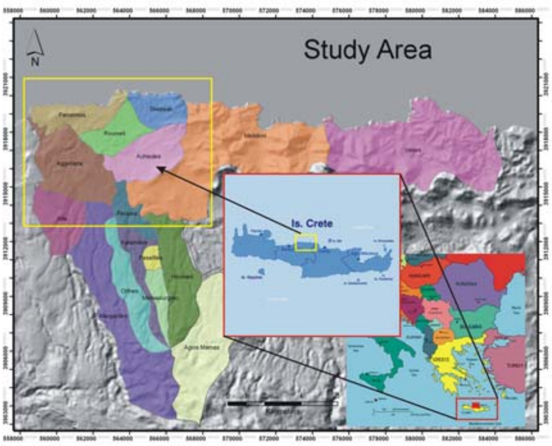

Fig. 1: Geographic overview

2.1 Geology and Tectonics

The surficial geology of the area is composed of Pliocene/Pleistocene marine deposits laid down on the older bedrock. Miocene biogenic limestones, marls, clays and conglomerates crop out in the central and the western part of the study area and clastic limestones and dolomites of the Tripolis and Ionion nappe (the bedrock) in the eastern part of the study area. The phyllite-quartzite nappe (which forms the oldest rock of the study area) lays on the northern part of Geropotamos basin (Fig. 2).

The local tectonic regime of the study area is characterized by faults of NW-SE and NE-SW directions, which define the boundaries between the existing geological formations (Mylonakis et al., 1991) as well as the groundwater flow direction and possible contamination from seawater intrusion. In some cases, these tectonic structures may act as underground barriers bounding the groundwater movement. The only worry, concerning the "contribution" of tectonic in the aforementioned water contamination, comes from the fact that the tectonic features start from the coastline and seems to continue for about 5Km.

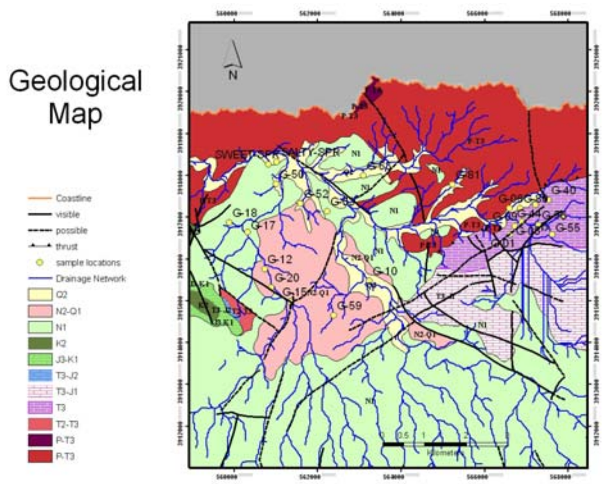

Fig. 2: Geological status of the study area (modified from Mylonakis et al, 1991). Note the prominent approximately North-South-orientated faults intersecting the coastline, that may permit pathways of saltwater intrusion, indicated in Fig. 9.

Table 1: The nappe pile of Crete (modified from Fassoulas et al, 1994)

Post-Alpine Rocks	**Quarternary sediments**		Q2, Q1-N2, N1
	Neogene sediments		
Alpine and Pre-Alpine Rocks	**Upper nappes**	Ophiolites	
		Asteroussia nappe	
		Tectonic melange	
		Pindos nappe	
		Tripolis nappe	K2, J3-K1, T3-J2, T2-T3
	Lower nappes	**Phyllite-Quartzite nappe**	P-T3
		Trypali nappe (western Crete)	
		Ionion nappe (Plattenkalk series)	T3-J1, T3

2.2 Hydrogeology

Figure 3 gives some information about the hydrogeological situation of the study area. The northern part (along the coastline) consists of impermeable formations, expecting to act as

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groundwater barrier for any possible seawater intrusion. The recharge of the study aquifer is expected to come from a) the eastern and southern part of the area which consists of high permeable formations (K1), and b) leakages from the dense river banks (network).

A priori hydro-geological data from hydrowells, which were available from the local authorities, were collected and were integrated in a GIS-based environment (Rockworks software) (Fig.4). In the study area data from 23 public drills were used and sorted based on their spatial distribution (Western and Eastern) [9 drills=potable water, 14= water only for irrigation, bad quality]. The groundwater of the drills, which are used only for irrigation, is characterized by high salinity and conductivity. Note that at the study area many exploratory drills have been constructed, especially at the central part, but then they were abandoned due to bad quality of the groundwater sample.

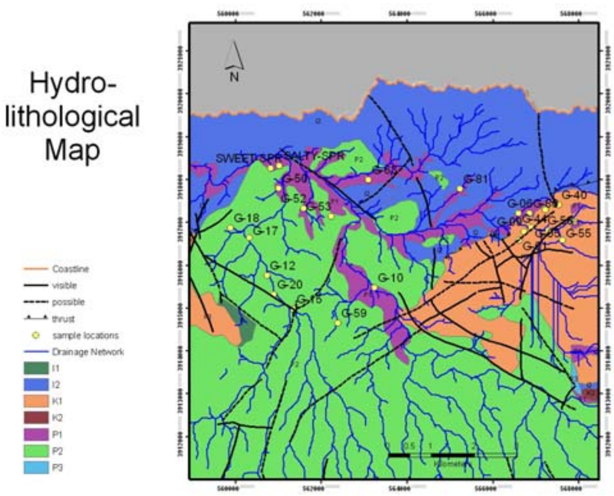

Fig. 3: Hydrolithological status of the study area. See Table 2 for explanation of key colours.

The increasing density of those drills (mostly the private ones) which influences adversely the environment (the quantitative and qualitative characteristics of the coastal aquifers) is also investigated. Finally, the logs from available boreholes are the only reliable geological information, so they are used for calibration and confirmation of the resulted geophysical modelling.
The two local springs, sweet and salty, are explicitly investigated as well, as they consist an unusual hydrological occurrence. They have less than 200m distance from each other but the quality differs greatly, demonstrating the complex nature of subterranean plumbing.

Table 2: The hydrolithological classification of the geological units based on permeability is presented.

I1	impermeable, low-vlow permeability
I2	impermeable or selective low-vlow permeability
K1	Karstic, high-medium permeability
K2	Karstic, medium-low permeability
P1	Granural deposits, fluctuating permeablility
P2	Deposits, medium-low permeability
P3	Granural, low-vlow permeability

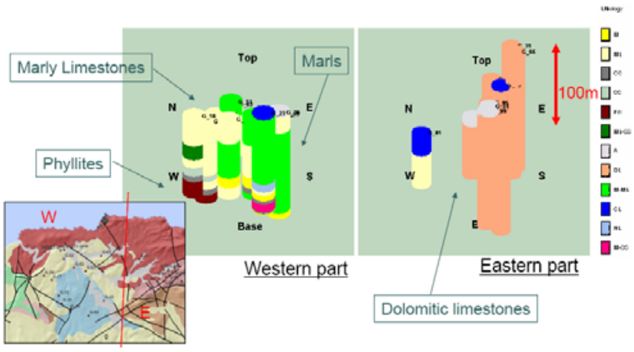

Fig. 4: 23 public drills were sorted in two parts (Western and Eastern)

2.3 Geomorphology

The overall area is characterized as lowland and semi-mountainous. The elevation range is 0-300m (Fig. 5).

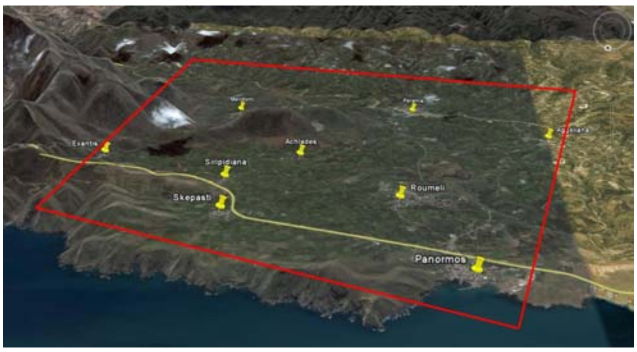

Fig. 5: Oblique satellite image defining the area of interest (Google Earth, 2009); view is from NNW.

3 Geophysical Methods

Two geophysical methods have been applied for this study, Transient ElectroMagnetic (TEM) and Vertical Electrical Sounding (VES) methods.

3.1 TEM

The TEM method is a controlled source electromagnetic (EM) method that uses large loops laid on the ground as a transmitter/receiver. For a comprehensive review of the TEM method and theory, see Nabighian and Macnae (1991) and McNeill (1994). The proposed method can be applied in many different configurations, no direct electrical contact with the ground is required, can be used to investigate the top few meters of ground till hundreds of meters in depth, it is a fast and cost effective method, but it does not work properly in high resistive region and is susceptible to interference from nearby (buried or not) metal pipes, cables, fences, vehicles and induced noise from power lines.

The processed raw data produce a 1D model of apparent resistivity vs. depth, similar to borehole logging. Resistivities greater than 10 Ohm-m usually result from the presence of fresh water in the subsurface and when resistivity is less than 10 Ohm-meters indicate the existence of salty/contaminated water.

The acquisition of the TEM data took place using the TEM-Fast 48 system from AEMR Ltd. It is a new portable, fast and robust geophysical instrument providing efficient operation in several environmental noisy conditions, giving solution in many environmental and mineral explorations.

A careful field procedure (site selection, receiver-transmitter installation, etc.) is crucial for obtaining good quality successful results.

The data processing and analysis started immediately after the acquisition of the first datasets (before the completion of raw data). The processing gives the estimation and presentation of 1D models of the conductivity structure of the study area. TEM-RESearcher, a Windows integrated software system, was the tool for data processing of TDEM data and inverse problem solution. The program reads the field data, makes the processing and presents the results in cross-sections in the class of gradient or layered structures (TEM-RESearcher manual, 2007).

3.2 VES

One dimensional (1D) surveying is carried out either as profiling or vertical electrical sounding (VES). VES involves increasing the electrode separations around a mid-point, usually with a logarithmic electrode separation distribution, in order to find the layering of strata. The basic procedure of this method is to measure at the surface the resulting potential due to a known current flowing into the ground (Kunetz, 1966). We should note that VES method is valid only in case of 1D structure (stratified homogeneous sedimentary basins). The usual procedure is to insert two electrodes (A,B) through which current is flowing into the ground, while the associated potential is measured between another two electrodes (M,N). For that survey Schlumberger array was used. VES with that array is carried out by keeping the electrode array centred over the field site while increasing the distance between current electrodes, thus increasing the depth of investigation. In our fieldwork, resistivity data were acquired with an IRIS SYSCAL R1 equipment and soundings were carried out with maximum AB/2 separations ranging from 3.2 to 400m.

IPI2Win, a Windows software system which is designed for automated and interactive semi-automated interpreting of VES and/or induced polarization (IP) data, was the tool for data processing of VES data (IPI2Win user's guide, 2001).

4 Results, Data processing, analysis & Modelling

4.1 TEM

Until now, 1179 soundings in 372 sites have been carried out in a detailed survey grid (about 200m in X and Y dimension) using single loop 50x50m, Stack 5 (65 complete cycles) and Time 5 or 6 (i.e. 32 or 36 time gates).

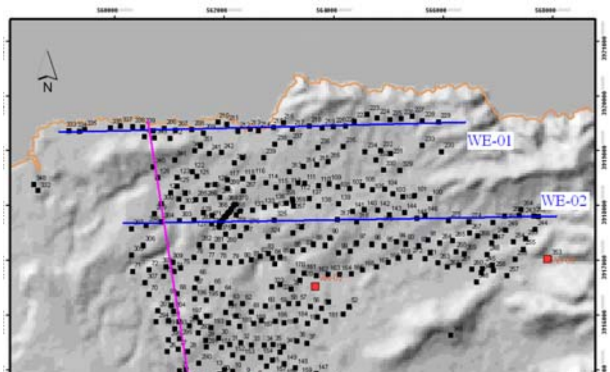

Fig. 6: The exact locations of the TEM and VES soundings are presented. The WE profiles are blue coloured and the NS profile is pink

4.1.1 1-D modelling

TEM soundings are often used to define aquifer properties and other subsurface characteristics. While these structures are inherently multidimensional, 1D inversion codes are commonly used to interpret the data. As interpretation of 1D inversions are used to determine geologic structure for groundwater flow models, an interpretation that is incorrect due to unrecognized 2D or 3D effects can have serious implications. A study was conducted to determine how well 2D geological structure could be imaged using 1D inversion and the errors associated with such an interpretation. Figures 6a & 6b show an example for 0071 sounding.

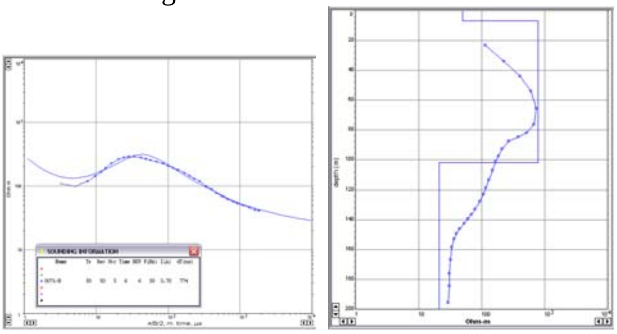

Fig. 6: a) Curve of apparent resistivity (example of sounding 0071), and b) transformation and inversion (example of sounding 0071)

4.1.2 TEM: 2D Imaging

Since the 1D modelling is inadequate to reconstruct and describe the subsurface, 2D imaging in comparison with geological sections is demanded (Fig.6).

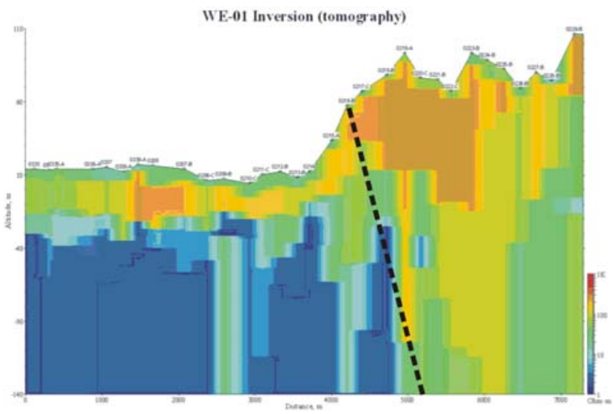

Fig. 7: 2D imaging of WE-01 profile after 1D inversion. Blue indicates lower resistivities and red the higher ones.

Figures 7, 8 and 9 show the validation of the resulted geophysical 2D models by the known geological information. A big fracture zone is determined throughout the geophysical survey in figure 7. Two tectonic features are already recorded by the local geologists (Fig. 2) and confirmed by WE-01 profile.

TEM method is also capable to image the geological contact (thrust zone) between the dolomitic limestones (plattenkalk) with phyllite/quartzite nappe. The geological and geophysical data for WE-02 profile are presented in figure 8. The geophysical inverted data are in good agreement with the logs from the boreholes in the study area. Resistivities more than 700 Ohm-m are directly correlated with the limestones (T3-J1, T3) appeared in the eastern part of the section. Resistivities which vary from 400-700 Ohm-m are correlated with the phyllites/quartzites. Resistivities ranging from 100-400 Ohm-m, depict the Neogene formations.

The same assumptions and comments can be safely made for the geological and geophysical section which shown in figure 9.

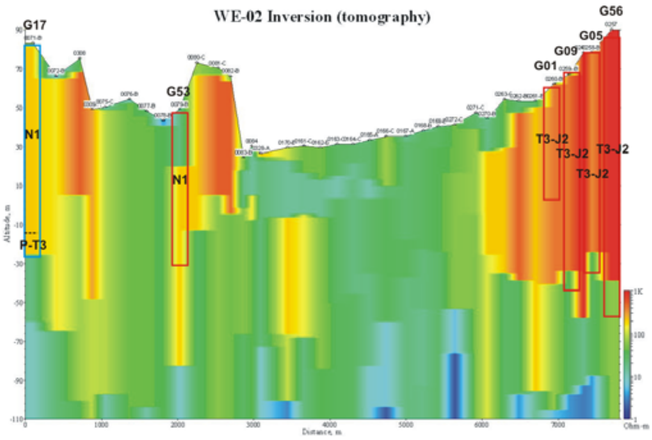

Fig. 8: 2D imaging of WE-02 profile after 1D inversion. The geophysical section and the lithostratigraphic columns from available boreholes are given for comparison. Blue indicates lower resistivities and red the higher ones.

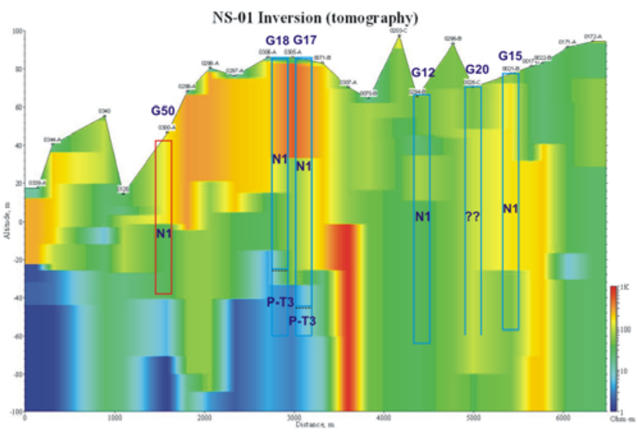

Fig. 9: 2D imaging of NS-01 profile after 1D inversion. The extracted section is presented in the form of tomography. Blue indicates lower resistivities and red the higher ones.

4.2 VES

Three soundings were acquired in three different sites (different geological conditions): VES-00 on dolomitic limestones (Plattenkalk series), VES-01 on neogene sediments, and VES-02 near the boundary between phyllite/quartzite nappe and neogene sediments. For VES-01 and VES-02, cross measurements were also acquired since the structure is expected to be more complex than a 1D model that VES is able to model.

4.2.1: 1D modelling

The 1D representation of the resistivity distribution in depth is presented in figure 10. The model shows 3 layers and the subspace and the extracted model is in agreement with the available geological data (borehole's logs, geological sections, etc.) for this site.

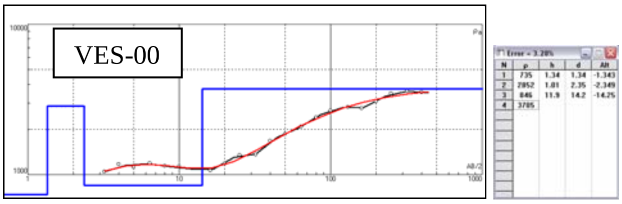

Fig. 10: Modelling of VES-00 sounding curve: measured apparent resistivities (dots), best fit layer model (tabulated and as a graph in the logarithmic diagram) and related model curve (full line) are shown. The thickness of the last layer is assumed to be infinite.

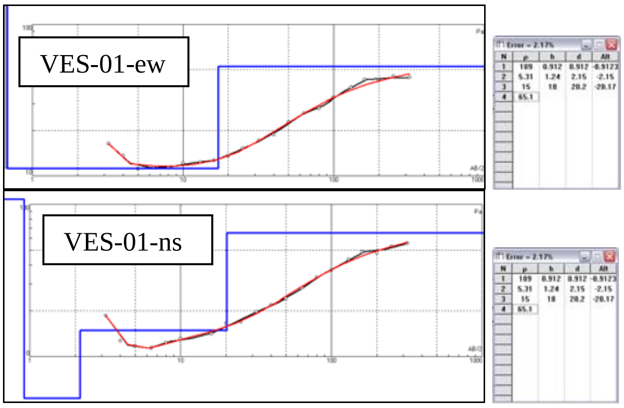

Fig. 11: Modelling of VES-01 sounding curve: experimental apparent resistivities (dots), best fit layer model and related model curve (full line) are shown. The measurements in different orientations are given for comparison.

As mentioned above, in two areas (VES-01 & 02) two crossed VES measurements were carried out to compare the result and extract possible inhomogeneities of the site under investigation. In figure 11, the resulted 1D models for the same location but different directions are shown. The 1D resistivity models were almost identical show us that the problem in this site is 1D and can be described by VES method with high accuracy. Usually, this sharp change in the experimental curve as it is shown (fig. 12) in the last 3 resistivity measurements, is correlated with tectonic features (faults or tectonic geological contacts).

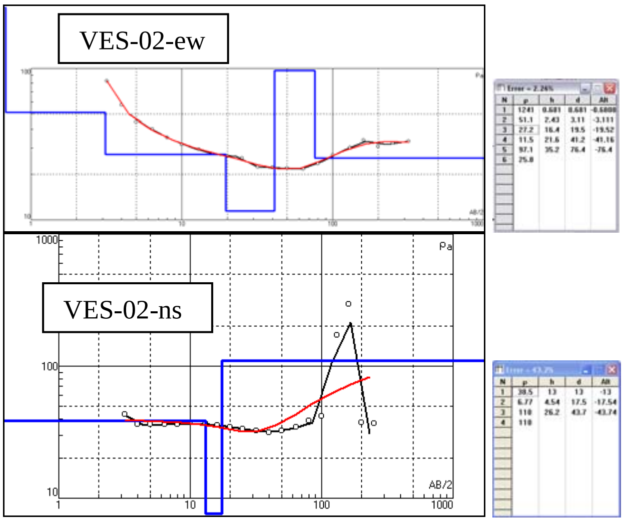

Fig. 12: Modelling of VES-02 sounding curve: measured apparent resistivities (dots), best fit layer model (tabulated and as a graph in the logarithmic diagram) and related model curve (full line) are shown. The measurements in different orientations are given for comparison.

5 Discussion

The value of TEM and VES geophysical methods in determining locations of low resistivity, that are linked to saltwater intrusion because of their position, are clearly shown by this work. Thus, the relationship between a major faulted area and the saline water in the aquifer is a valid interpretation. Thus aquifer problems may be addressed by a multiproxy approached adopted in this paper. However, this work may be enhanced by future work in the following areas:

1) Due to geological complexity, 3D imaging also is an essential point. It has to be applied combining by interpolation all the acquired 1D models of study area. The 3D imaging will be presented in depth slices covering the whole area.

2) By individual inversion of the data we showed that TEM and VES methods are well suited at our area. Now we should produce more tightly constrained interpretation models at three sites (VES-00, VES-01 and VES-02) with joint inversion

of vertical electrical and transient electromagnetic soundings.
3) Estimation and evaluation of geological and tectonic structures from the detailed 3D imaging of the subsurface till the depth of about 170m.
4) Possible scenarios that could be developed to explain the hydrogeological status of the area and the mechanism of contamination
5) Estimation of aquifer vulnerability based on point source contaminants (landfills, etc.)

6 Conclusions

By the quantitative interpretation of the TEM data, it has been possible to delineate the subsurface characteristics and to enhance areas of groundwater potential in the study area. With the additional information obtained from the available geological maps, boreholes and previous hydrogeological studies, the boundaries of the geological formations and a reliable hydrogeological model could be assumed. Most of the resulted geophysical images have already been confirmed by other geoenvironmental data (hydrochemical analyses).
Beyond the results concerning the main objectives of the study, the survey has shown that TEM method is a practical cost-effective technique for the geometry delineation of watersheds, and that high-quality TEM data could be recorded near complex geological areas, when the subsurface is conductive.

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