Salt Water intrusion characterisation in the Coastal Aquifer of Nabeul Hammamet Using Geophysical Methods


Abstract— A Time Domain Electromagnetic (TDEM) survey was carried out on the Mediterranean coast of Tunisia (Nabeul Hammamet), in order to delineate salt water intrusion into coastal fresh water aquifer detected by drilling wells. The survey was also carried out to determine the geometry of the fresh water aquifer and to identify the continuity between the aquifer system of Nabeul Hammamet and the contiguous aquifer system on the northern side (coastal aquifer of Korba). One dimensional interpretation of the TDEM data was correlated to existing data from borehole logs (Gamma Ray, Spontaneous Potential, Resistivity). The results indicate that TDEM survey was able to map the interface between fresh and salt water and estimate depth to basement when siting new monitoring wells.

Index Terms Coastal aquifer, Salt water intrusion, TDEM, Tunisia.

I. INTRODUCTION

Located in the North-Eastern part of Tunisia in Cap Bon peninsula, the largely populated Nabeul-Hammamet area (Figure 1) is considered an interesting agricultural sector with important urban, tourist and industrial activities. The steady increase in water consumption has severely depleted the shallow aquifer resulting in declining water levels, salt water encroachment, and dewatering in some areas of this coastal plain.

The resistivity of a water bearing formation is highly dependent upon porosity, degree of saturation, and water salinity [19]. Electrical surveys may be used to map aquifers and water quality zones. The inherent capabilities of the electrical geophysical methods to detect changes in water resistivity make them highly sensitive to the fresh-saline water interface found in coastal regions. Several authors have described the subject in detail [11, 13, 15]. In the survey area, the Time Domain Electro Magnetic (TDEM) method was employed to determine electrical resistivity stratification with depth. The main aim of this work was to detect, identify and delineate aquifers by exploiting the expected large contrasts in resistivity between fresh water saturated rocks (high and intermediate resistivity) and salt water contaminated or clayey materials (low resistivity). Other aims were to verify the continuity between the aquifer of Nabeul- Hammamet and the contiguous aquifer on the northern side: the coastal aquifer of Korba. For this survey, TDEM soundings enabled to verify the presence of path-ways for migration of contaminated groundwater by salt water intrusion.

Fig. 1. Location Map of Nabeul Hammamet area
I. GEOLOGICAL & HYDROGEOLOGICAL BACKGROUND

A. Geological Background

Northeastern Tunisia is characterised by NE-SW to NNE-SSW folds and by faults of various directions, forming shear corridors. These faults delimit compartments with different deformation geometries [3]. In the Nabeul Hammamet catchment area, is a NW-SE trending structure corresponding to the Grombalia trough covered by the Quaternary series [5]. Beneath these series, several authors have proposed a graben structure limited by two major faults to explain the thickening of the Mio-Pli-Quaternary series in this trough [2, 6, 26]. In the southern part of the trough, the Hammamet Fault extends over a length of 5 km. In the subsurface, this fault represents a major deep polyphased strike-slip fault represented by a flower structure [2, 4, 6, 8, 14]. This structure gives the zone a form of syncline bordered NW-wards by major faults.

![Structural map of Nabeul Hammamet area](image1)

**Fig. 2.** Structural map of Nabeul Hammamet area

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![Geological map of study area](image2)

**Fig. 3.** Geological map of study area

B. Hydrogeological Background

The Nabeul-Hammamet area (Figure 1) covers a surface area of about 308 km², a length of 34 km and a width ranging from 8 to 16 km. The climate is semi-arid with mean annual precipitation at Nabeul city of 400 mm and mean temperature of 19°C. Surface water resources are very limited. The area was supplied by two main temporary rivers (wadi) with extended catchment areas, serving to ensure natural recharge of the aquifer systems. Groundwater resources constitute the main source of water supply for agricultural, tourist and industrial activities. Former studies of the basin provided other hydrogeological information. Essentially composed of Plio-Quaternary deposits, the shallow aquifer displays several lithologies: sands, sandstones, limestones, and sandy clays. These deposits rest on the Pliocene Nabeul clay. The deeper aquifers are embedded in detritus formations of Oligo-Mio-Pliocene age. Aquifers are presumably hosted in the sedimentary formations of the Quaternary of Nabeul and in the Plio-Quaternary and Upper Oligocene of Hammamet.

II. METHODS

A. TDEM soundings

TDEM method has been utilized successfully in hydrogeological surveys, delineating aquifers structures and contamination [13, 16, 28]. The earth is energized by abruptly shutting off the current in the transmitter. According to Faraday’s Law, currents are induced in the subsurface, decaying with time and producing secondary magnetic field that creates a measurable voltage in the receiver [27]. In the coincident loop configuration, only one loop serves as transmitter and receiver during the time-on and time-off period of the current, respectively. Unlike other geophysical sounding methods where the receiver-transmitter array must be expanded to explore deeper parts of the geoelectric section, the depth of investigation for the TDEM method depends on length of recording window [24]. Measurement of the signal at later times provides information at greater depths. The intensity of the eddy currents at specific times and depths is determined by the bulk conductivity of subsurface rock units and the fluids contained therein. Depth of investigation depends on the time interval after shutoff of the primary current, because later the receiver subsequently senses eddy currents at progressively greater depths [13, 21, 22]. The method is insensitive to inhomogeneities in the surface layers; most common reason for poor quality data sets in all electromagnetic methods. Among the EM methods, this method has the best lateral and vertical resolution with regards to highly conductive targets [17]. A variety of data interpretation techniques have been proposed. These include the imaging techniques [20, 30], conductive finite plate models [18, 25] and inversion methods that use 1D horizontal layered earth model [7, 9, 12, 29]. A TDEM survey consists of TEM FAST 48 battery powered transmitter (4 μs–16 ms), connected to a single-turn,
ungrounded, insulated cable in the form of a square loop with sides of between 25 and 300m. In the present work, we conducted a large scale TDEM survey involving 55 soundings (Figure 4) with the coincident loop configuration (50×50m and 100×100m square loops at respectively 50m and 100m spacing) aligned on a rectangular grid. We performed 1D interpretation scheme [10] and the interpreted results have been correlated with available geological and geophysical data, providing useful information about the local hydrogeological conditions.

![Fig. 4. Location of TDEM stations in the study area](image)

**III. RESULTS**

**A. TDEM Results**

Time Domain Electromagnetic (TDEM) soundings were interpreted using one-dimensional (1-D) inversion. The initial model for each inversion was obtained by first applying Occam’s inversion [9] and then reducing to the minimum possible the number of layers in the recovered smooth model. Most of the sites yield sounding curves with a monotonic decrease in apparent resistivity with time. Such curve behavior undoubtedly proves the presence of a low resistivity layer in the base of the section. At some sites it was necessary to include a thin layer of very low resistivity within the top resistive layer to be consistent with the data. Figure 5 shows some typical examples of TDEM sounding curves from locations close to the coast (sites F16 and F15) and farther inland (sites F12, F13, F7, F6, F3, F8 and F9). The quantitative interpretation of the TDEM measurements is, however, hampered by the equivalence problem, which means that several different layered models may give practically the same resistivity curve.

![Fig. 5. Examples of model of resistivity vs. depth generated by TEM-FAST smooth modelling procedure corrected to sea level](image)

1) Comparison of borehole Log and TDEM resistivity

Both TDEM soundings from the surface and borehole resistivity logs measure vertical geoelectrical sections. Comparison of the two provides important information (i) to define the position of the transition zones within individual coastal plain aquifers, (ii) to interpret the geoelectrical section derived from TDEM data. We present results of TDEM, which are correlated to borehole logs (SP, GR, and Resistivity). TDEM soundings were conducted at existing drilled wells wherever possible, or at a maximum distance of 1km from wells allowing correlation of apparent resistivity with borehole geophysical logs. TDEM survey can then be extrapolated to other parts of the coastal plain between research stations. The TDEM resistivity soundings show good correlation with the borehole resistivity, SP and GR Logs. The sequence and thickness of layers, however, and the relative values of high and low resistivity, are consistent between two records.

Field example 1

The presence of dispersed or interbedded clay will suppress the bulk resistivity of an aquifer, as shown by the example in Figure 6 where the relatively high Gamma Ray count in the borehole log reflects the clay-rich nature of the aquifer in this area. Low resistivity measurements on both the TDEM sounding and borehole resistivity log represent the combined effects of clay content and high salinity conditions within the aquifer.
In this example (Figure 7), the TDEM sounding shows good correlation with the borehole log. The depth of the low resistivity layer coincides with a water level of the borehole (-9.5m) which is considered as the fresh water aquifer. The second low resistivity zone is apparent below the depth of (-6m) with very low resistivity. This layer consists of sandstone with clay and is attributed to the saline water infiltration. Additional TDEM surveys in the study area indicate that up coning of salt water may be occurring due to excessive withdrawals from local supply wells.

2) Geoelectrical sections 2D
On the basis of the geological and geophysical data of hydrogeological drillings and oil wells, and the results of correlation between borehole logs and TDEM resistivity soundings, the aquifer system of Nabeul Hammamet is considered as a multi-layer aquifer. In order to understand the distribution of the permeable area, the geoelectrical sections have been constructed.
The section contributes (i) to defining the geometry of the aquifer, in particular in the northeastern part of Nabeul, (ii) to identifying the structures and (iii) a salt water wedge. Geoelectrical models plotted in pseudo 2-D sections, using interpolation to acquire a better presentation of the subsurface of the area, shows the presence of three aquifers formation. In Figure 8, the geoelectrical section (1) obtained, shows a very low resistivity layer between 1-5 Ohm-m attributed to aquifer formation at greater depths, primarily due to salt water encroachment.

In the near surface down to depths of over 20m, exists a layer formation with a resistivity between 7-20 Ohm-m, indicative of fresh water. It coincides with a thick high resistivity zone on the borehole record. But in some geoelectrical sections, a high resistivity layer with 25-55 Ohm-m indicative of fresh water in the shallower aquifers, is readily apparent near the surface. It coincides with a thick high -resistivity zone on the borehole record. This high resistivity zone just appears in the TDEM sounding in fault zones. This variation of resistivity correlated to structural data gives good agreement for the presence of these faults and graben boundary definition. TDEM sounding within the graben shows continuity of the aquifer formation overlain by thin sediments.

On the other hand hydrostratigraphic details are almost completely masked by a low resistivity contrast between fresh water aquifers and clays and by the lateral effect of fault displacements in this areas. Consequently, this fresh aquifer cannot be detected due to lack of resolution.

Fig. 8. Geoelectrical section (1)

Fresh water, salt water transition zones and the geometry of the salt wedge in the aquifer are shown in the geoelectrical sections by vertical and lateral variations in resistivity within individual aquifers. The geoelectrical section of lateral profile (Figure 9) parallel to the coast shows a very low resistivity layer, according to the well log. The top layer consists of an aquifer formation, hence, the low resistivity is attributed to the saline water infiltration.

Fig. 9. Geoelectrical section (2)

The question always asked by hydrogeologists about the Nabeul Hammamet aquifer, is whether continuity and communication exists within this aquifer and the contiguous aquifer on the northern-eastern side (coastal aquifer of Korba). A cross section (Figure 10), shows continuity of the two aquifers and probably the presence of fault detected in sounding b5, interpreted as the limit of this aquifer.

Fig. 10. Geoelectrical Section (3)

3) 3D geoelectrical section
A 3D model was constructed using EVS (Environmental Visualisation Software) data representation. The program is able to extract data from the entire volume investigated (i.e. resistivities higher, lower than fixed value) and reconstruct by a 3D interpolation, the plume or the extension of a layer in the volume.
Figure 11 shows the plume of a resistivity layer ranging from 1-5 Ohm-m. Comparison between the results of TDEM soundings, borehole logs and 2-D geoelectrical sections, shows that for the TDEM soundings near the coast, this layer can be attributed to salt water intrusion. For the TDEM soundings carried out in inland areas this low resistivity can be attributed to salt clay deposits and it can be due to intensive pumping from wells in the area.

Figure 12 shows the continuity of resistivity layer ranging between 7 and 25 Ohm-m versus elevation. This layer is attributed to the second aquifer formation, and confirms results of the geoelectrical section (3).

In general, these interpretation results are a good agreement with the expected resistivity values for the layers appearing in the well log, and the 2-D sections.

IV. CONCLUSION
TDEM surveys provide an efficient, and semi-quantitative method of evaluating ground water resources in coastal aquifers, at fairly high vertical resolution, to a depth down to few hundred meters, on both local and regional scales.

Comparison between TDEM soundings and borehole logs provides more information about fresh water formation and the structural configuration of the aquifer.

In our work, we delineate the salt water intrusion areas, identify a subsurface aquifer formation and determine the hydrogeological limit between the Korba and Nabeul-Hammamet aquifers.

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