The contribution of geophysical methods in the determination of aquifer parameters: the case of Mornos River delta, Greece ⊗

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Abstract: *Knowledge of hydraulic conductivity and transmissivity is essential for the determination of natural water flow through an aquifer. Although these characteristics are mainly deduced from pumping test analysis, attempts have been made to employ geophysical methods in order to reduce the amount of hydrogeological observations and the resulting cost. Use of layer thickness, as derived from the interpretation of resistivity soundings data and hydraulic conductivity calculated on the basis of both hydrogeological and geophysical data led to the calculation of aquifer transmissivity. This technique was used for the determination of aquifer parameters in Mornos River Valley at central Greece. Maps of the basement relief, resistivity, transmissivity and Transverse Resistance provided the means to identify areas where the aquiferous zone is prolific. The good agreement between aquifer hydraulic conductivities obtained from the resistivity soundings interpretation and those deduced from pumping test analysis emphasizes the potential of the methodology.*

Key Words*: Resistivity investigations, aquifer parameters*

INTRODUCTION

Relationships between aquifer characteristics and electrical parameters of the geoelectrical layers have been studied and reviewed by many authors (Kelly, 1977; Niwas and Singhal, 1981; Onuoha and Mbazi, 1988; Mazac et al., 1985; Mbonu et al., 1991; Huntley, 1986). Some researchers assume that the geology and ground water quality remains fairly constant within the area of interest and the relationships between aquifer and geophysical parameters deduced, are based on this assumption (Niwas and Singhal, 1981; Mbonu et al., 1991). Mazac et al. (1985) analysed the correlation between aquifer and geoelectrical parameters in both the saturated and unsaturated zones of the aquifers.

Geophysical methods can now contribute substantially towards this initiative and can greatly reduce the number of necessary pumping tests, which are both, expensive and time consuming. The locality of Mornos valley was selected as a test area to provide information on the aquifers hydrodynamic characteristics, by means of correlation tests performed between electrical parameters measured by surface geoelectrical soundings and aquifer characteristics obtained from a certain number of boreholes in which measurements of these properties were carried out.

In the present study the determination of aquifer's transmissivity was attempted on the basis of monitoring the variations of the ground water resistivity within the area of investigation. Aquifer depths, instead of Dar Zarrouk parameters, resulting from multilayer resistivity models (Zohdy, 1989), were also used in the determination of aquifer characteristics.

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The study area lies within the alluvial plain area of Mornos river valley (Fig. 1). The perceptible change of the river granting in the delta plains, due to a dam construction in the upper river course for water supply purposes, initiated the execution of a proper water resources exploration program in the plains of the lower river course.

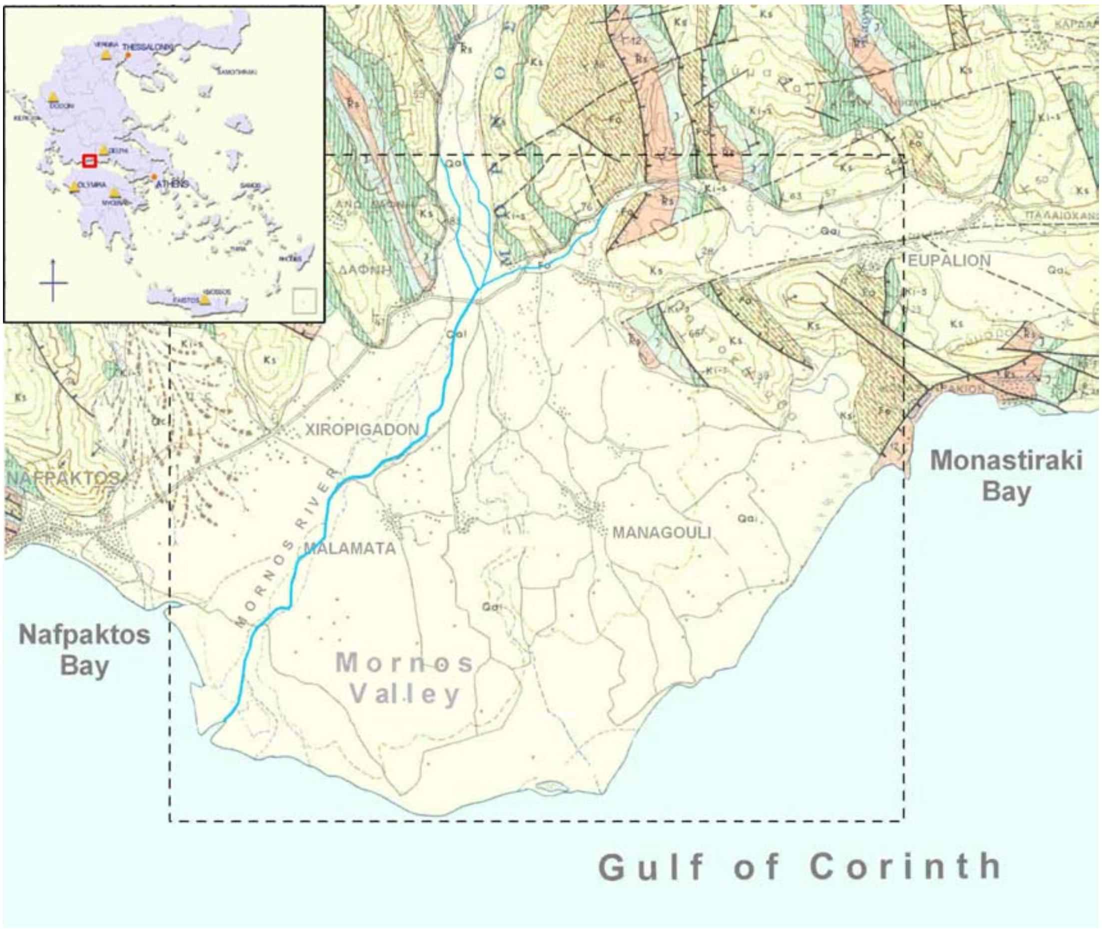

Figure 1. Location and geologic map of Mornos delta (IGME, 1978). Rectangle implies the investigated area.

The realization of such a program requires data from hydrological, hydrogeological, geological and geophysical surveys and drilling and pumping tests as well. Knowledge of aquifer characteristics, namely the hydraulic conductivity (permeability) and transmissivity is important for determining the natural flow of water through an aquifer and modelling pollution processes. This information was available from pumping test data.

GEOLOGIC SETTING

The river delta, extending to an area of 25km^2 with gentle slopes (4%), is situated at the northern coast of the Gulf of Corinth, which forms a significant graben and is considered as the main provider of the inner part of gulf with sediments. The riverbed is determined by two directing systems. A dam at the upper part provides large quantities of potable water to the capital city of Athens. In delta area, the course of the river is well established and is directed to the western coast of the delta. The area of interest is located at the boundary between the tectonic zones of Pindos and Gavrovo, where the over-thrusting of the first zone over the second is encountered. The carbonates of the Pindos zone have moved at low angles westwards and are put over the flysch of the Gavrovo zone.

The Pindos zone carbonates which are thin bedded and not very robust are highly deformed and folded, forming recumbent and overturned folds. The basement of the basin under consideration is constructed by these two geological formations, namely the flysch and the limestone. The existence of three main folds of the rocks forming the basin basement was detected-both-by geophysical investigations and test drilling. The axes of these antiforms have an almost N-S trend and they divide the subsurface waters in three different parts. The basin is filled by a series of fluvial deltaic sediments, with a thickness ranging from 60 to 150 m. The sedimentation pattern is typical for a delta, with the coarse material close to the exit of the river at the valley.

Thinner sediments occupy the area close to the coast, with a gradual transition from thin clays to mud. The deposition of sediments is continued in the gulf by means of turbidites that show very high mobility and form an almost vertical sedimentary body, in the see that is relatively deep at the northern part of the gulf. Within the basin three distinct aquifers can be distinguished, the Quaternary, the flysch and the karstic limestone aquifers. A number of submarine and coastal springs exist in the area and mainly close to Nafpaktos city and along the western margin of the basin. Some less important springs are also encountered close to the mountain boundary of the basin.

THE METHOD

When doing resistivity sounding surveys electrodes are distributed along a line, centred about a midpoint that is considered the location of the sounding. The electrode arrangement used in data acquisition was the Schlumberger array of electrodes since it is the most time effective in terms of field work. For a Schlumberger survey, the two current electrodes A and B and the two potential electrodes M and N are still, placed in line with one another and centred on some location, but the potential and current electrodes are not placed equidistant from one another. To acquire the resistivity data in the field, current is introduced into the ground through current electrodes and the potential electrodes are then used to quantitatively measure the voltage pattern on the surface resulting from the current flow pattern of the first set of electrodes. The geometry scheme for this array is shown in Fig. 2.

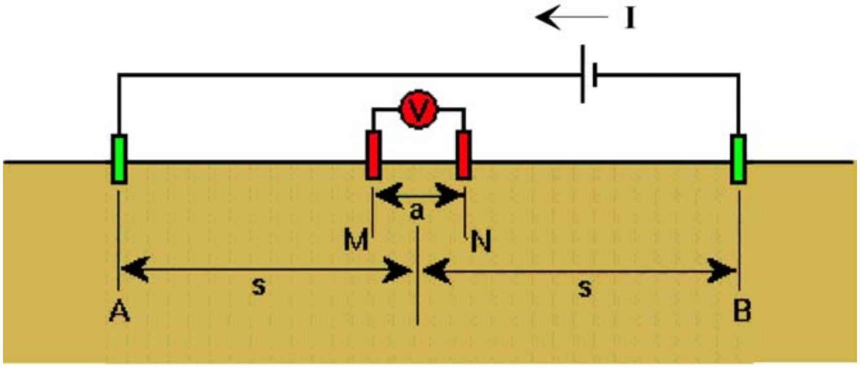

Figure 2. Sketch diagram of Schlumberger array.

All electrodes are placed in a line, a uniform distance apart. The Schlumberger array is widely used in geophysical exploration because it is an efficient means of collecting a large number of data points and these observations are sensitive to the lateral position and depth characteristics of the resistivity distribution.

The observational apparent resistivity data are presented on maps at various levels and pseudo-sections and they are useful in the first stage of interpretation to estimate approximately the anomalous zones. More realistic sections of the earth can be obtained only after interpretation of the data in terms of true variations of the resistivity distribution. This is a very important step because it allows the estimation of the true position and depth of an anomalous region. Moreover, it is possible to estimate the actual electrical resistivity of the region and relate it to its physical state.

DATA ACQUISITION AND INTERPRETATION

Thirty four resistivity soundings were carried out with maximum separation of current electrodes ranging between 150 and 630 meters. Thirteen of them were conducted nearby existing boreholes for correlation purposes (calibration boreholes). The location of soundings and the calibration boreholes are shown in Figure 3. Forty seven measurements of ground water resistivity were also conducted in an equal number of shallow boreholes or wells. Data were collected with an ABEM resistivity meter. Survey lines were located along existing roads and paths avoiding physical obstacles like buildings and fences.

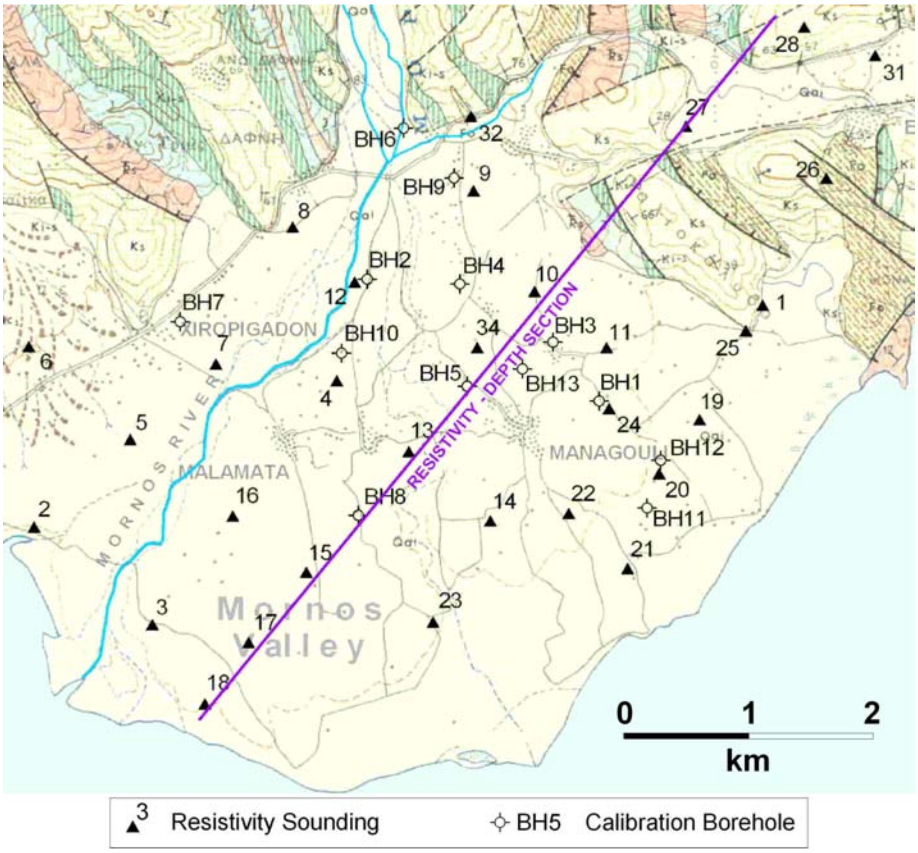

Figure 3. Location map of soundings and calibration boreholes.

Sounding data were interpreted using Zohdy's method for the automatic interpretation of sounding curves (Zohdy, 1989), which leads to geologically reasonable layer structured models that may be accepted or modified in order to agree with available geological information. The resulting multilayer final models are always well behaved with no thin layers or unusually extreme values of resistivity.

CONTRIBUTION TO THE KNOWLEDGE OF AQUIFER'S CHARACTERISTICS

The fundamental principle of the application of the geoelectrical methods in hydrogeology is the utilization of the dependence of rocks resistivity on the lithology of them and the mineralization of the water filling the pores. According to equation (1) the resistivity of the saturated rock, ρ_{ws} is directly proportional to the resistivity of the water, ρ_w filling the pores (Archie, 1942):

$$\rho_{ws} = F\rho_w \qquad (1)$$

where F is known as the formation factor, which is constant for pure sands. In the case of ground water with increased mineralization, an apparent formation factor F_a, instead of F, is introduced in relation (1) (Pirson, 1970). Thus, knowing the resistivity of ground water, we can calculate F or F_a.

Ground water resistivities in Mornos valley were determined from 47 insitu measurements at wells or boreholes well distributed in the investigation area. Figure 4 shows the variations of ground water resistivity.

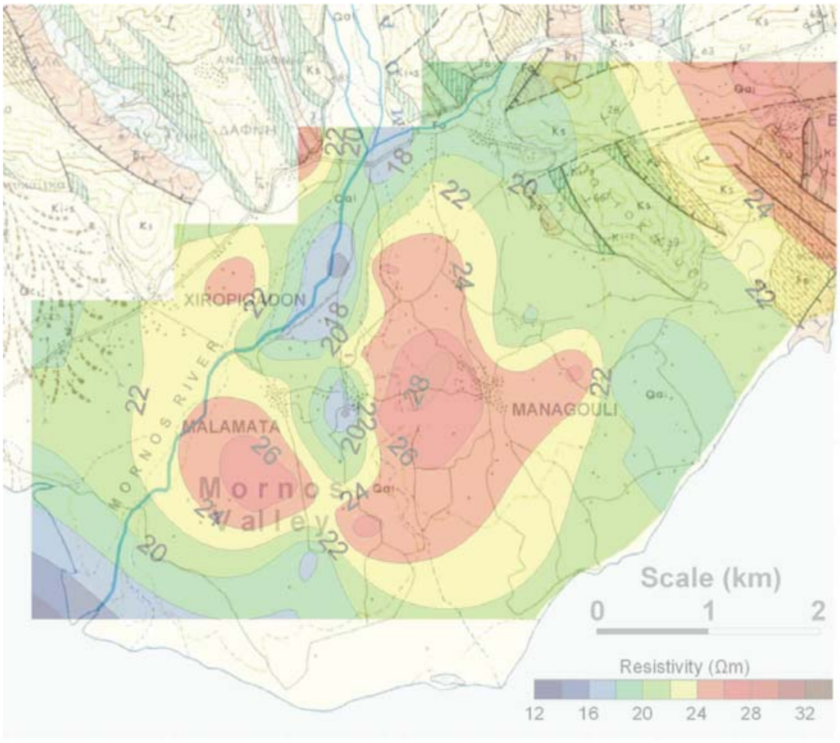

Figure 4. Ground water resistivity map of Mornos valley.

Measurements of the hydraulic conductivity K were also made from pumping test analysis at each calibration borehole. Figure 5 shows the plot of $F\ (=\rho_{ws}/\rho_{w}\ )$ versus K for the particular formation.

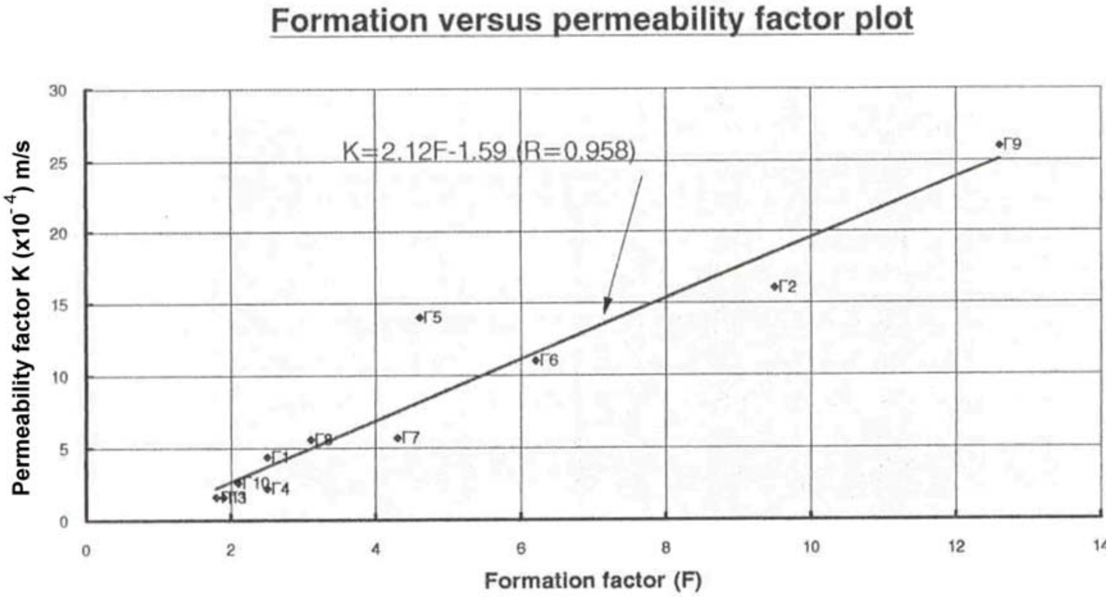

Figure 5. Formation versus Permeability Factor plot.

Equation (2) is the empirical relation between F and K obtained by using linear regression techniques.

$$K\left(10^{-4}\,m/s\right)=2.12F-1.59 \qquad (2)$$

Equation (3) is an analytical relationship between the aquifer transmissivity T_r and Transverse Resistance R or longitudinal conductance S determined by Niwas and Singhal (1981). They showed that

$$T_r = K\sigma R = KS/\sigma \qquad (3)$$

where σ is the aquifer conductivity and K the hydraulic conductivity of the aquifer. In equation (3) the quantities $(K\sigma)$ or K/σ are assumed to remain fairly constant within the investigated area (Niwas and Singhal, 1981; Mbomi et al, 1991).

Aquifer transmissivity T_r in ground water hydrology is given by:

$$T_r = Kh \qquad (4)$$

where h is the aquifer thickness. Hydraulic conductivity K, obtained from equation (2) at each sounding position and the aquifer thickness h, resulting from multilayer resistivity models, were used to derive the transmissivity T_r, according to equation (4). The variation of T_r across the aquiferous zone of the investigated area is shown in Figure 6.

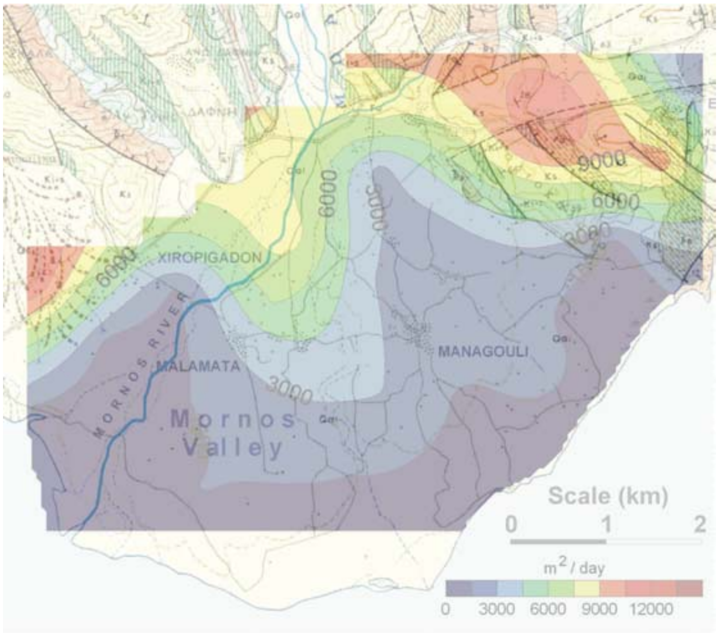

Figure 6. Transmissivity map of Mornos valley.

RESULTS

Two maps of true resistivity distribution were constructed using the results of the resistivity soundings interpretation. The distribution of resistivity values at elevation -50m (Fig. 7) indicates that two distinct zones can be identified within the area. The northern half of the map reveals the existence of relatively medium resistive material (70 to 250 Ωm), while the southern half corresponds to relatively conductive material (15 to 70 Ωm).

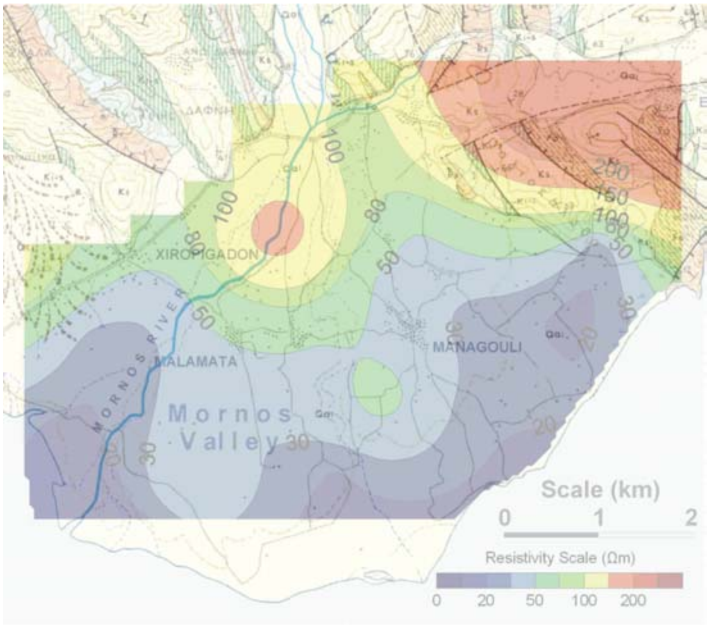

Figure 7. True resistivity distribution at the elevation of -50m.

This resistivity pattern is probably attributed to the variation of flysch basement relief as it is clearly shown in the resistivity-depth section of Figure 8, which crosses the valley in a SW-NE direction (Fig. 3).

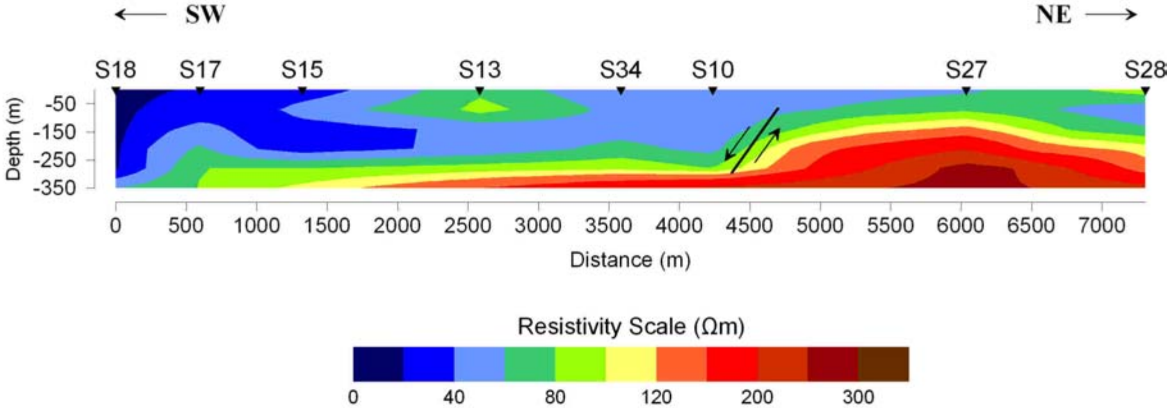

Figure 8. Resistivity-depth section showing the flysch basement relief (resistivity contours > 100 Ωm).

At the elevation of -80m (Fig. 9) the resistive material associated with flysch basement is extended to the south, occupying now a greater part of the investigated area.

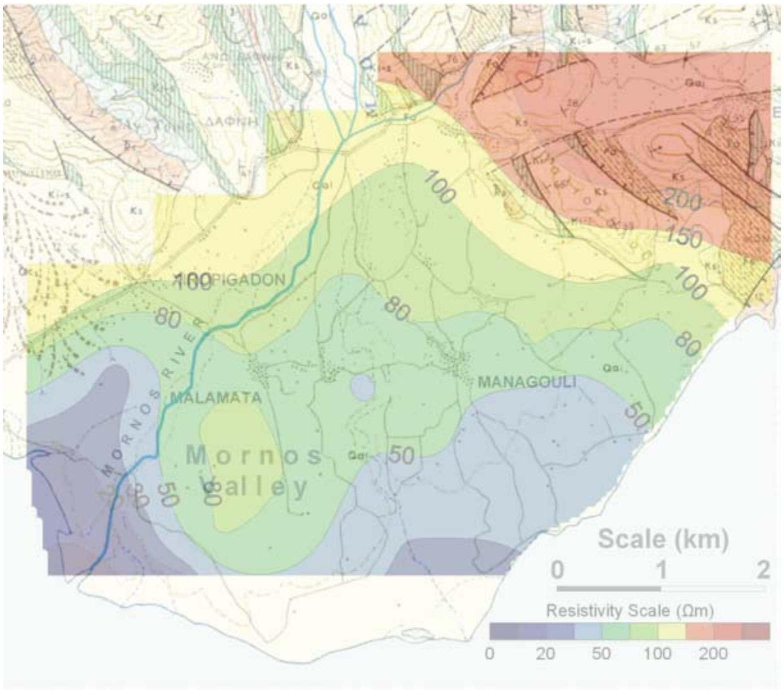

Figure 9. True resistivity distribution at the elevation of -80m.

Figure 10 shows the relief of flysch formation, which constitutes the aquifer alluviums basement.

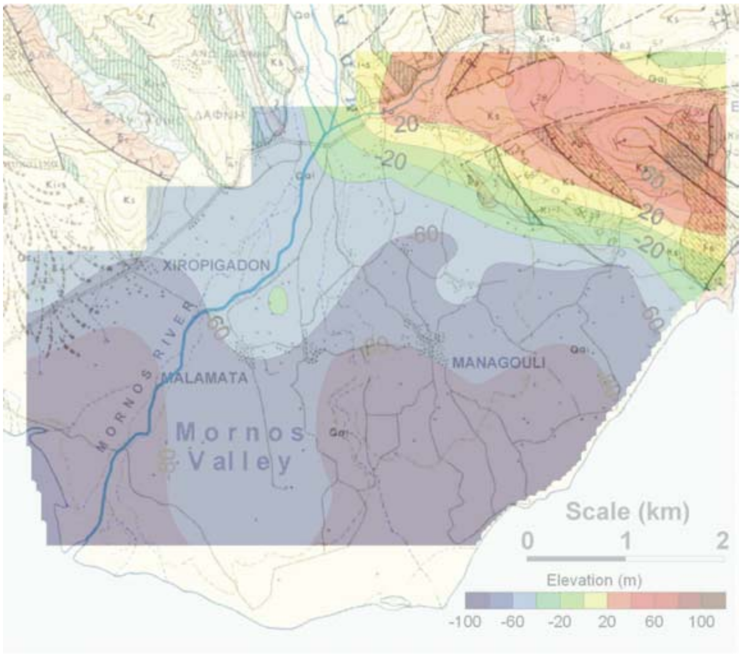

Figure 10. Basement map relief

A folding of the flysch basement is observed in Figure 10, which is associated with the existence of three synclines with axes trending NS. The anticlines axes divide the investigation area in three zones of different ground water courses.

Figure 11 shows the distribution of the aquifer raw Transverse Resistance computed from the resistivity soundings interpretation. Maximum Transverse Resistance values are observed in the central portion of the valley, along the old river course (Stournaras, 1990).

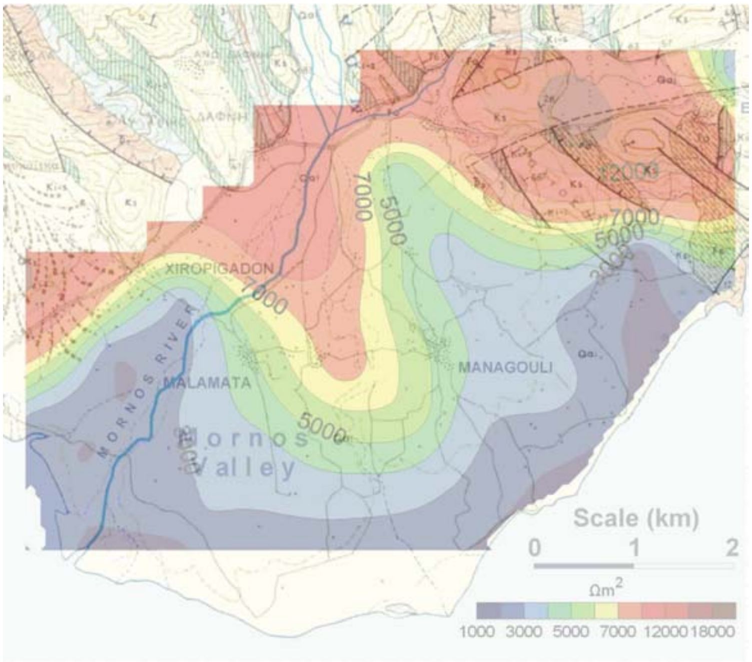

Figure 11. Transverse Resistance map of Mornos valley.

The area is characterized by a thick and prolific aquiferous zone, tapped by many productive boreholes and wells. This is due to the composition of the aquifer zone, consisted of unconsolidated medium to coarse grained sands and gravel.

Calibration resistivity soundings, performed at wells where pumping tests were carried out, allowed the determination of Transmissivity values. Figure 12 shows the Transmissivity T_r, versus Transverse Resistance TR, plot.

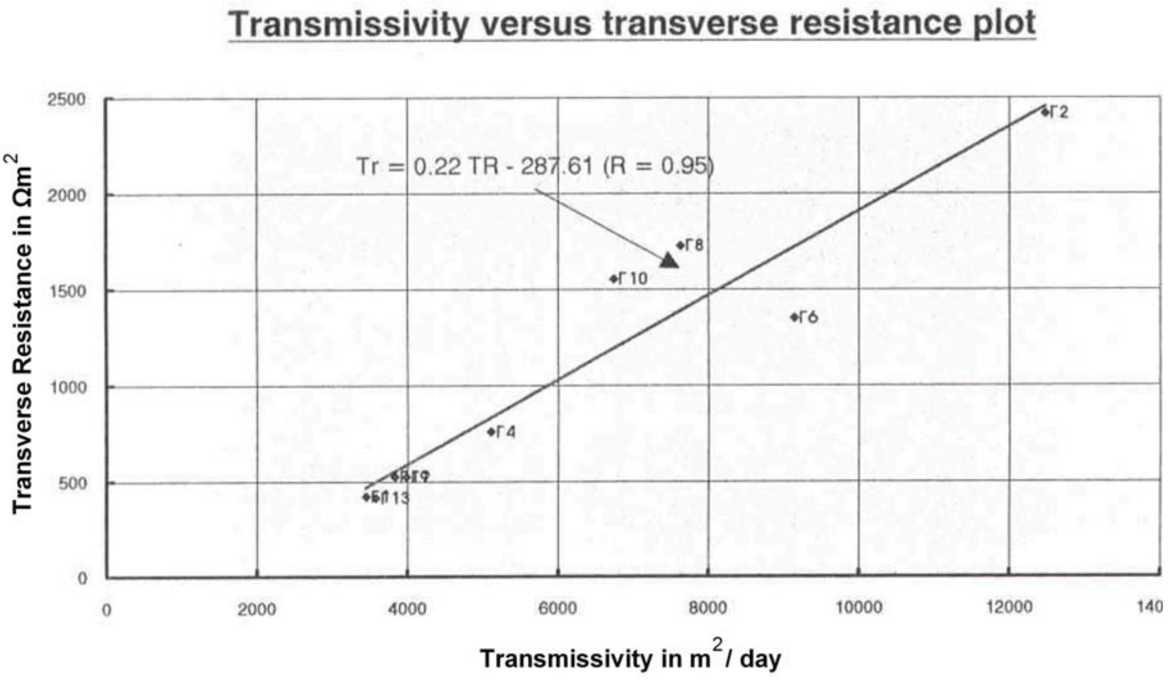

Figure 12. Transmissivity versus Transverse Resistance plot.

Equation (5) is an empirical relation between T_r and TR obtained by using linear regression techniques.

$$T_r\left(m^2/day\right) = 0.22TR - 287.61 \qquad (5)$$

this is practically a straight line, within the range of values used. A similar relation is expected if we try to relate Transmissivity and Transverse Resistance maps of Figures 6 and 11. Transmissivity values in Figure 6 vary between 2×10^{-2} to more than 1×10^{-1} m^2/s, suggesting thus a high quality reservoir. The knowledge of T_r distribution is a fundamental source of information for establishing a hydrogeological model.

Relating the transmissivity distribution (Fig. 6) and the valley basement relief (Fig. 10) it is evident that in deltaic areas, where the recent deposits are underlying by gradually varying size unconsolidated material, the higher transmissivities are expected close to the initiation of delta, as the coarse grained materials with higher hydraulic conductivities predominate.

CONCLUSIONS

The application of the resistivity exploration technique permitted the extrapolation of the data obtained by drilling tests within the study area. Measurements of the ground water resistivity in monitoring boreholes led to the division of the investigated area in zones where the water quality remains fairly constant. The aquifer thickness calculated from the interpreted resistivity soundings led to the construction of a well-controlled transmissivity map being in a good agreement with that obtained from Dar Zarrouk parameters. The good agreement between aquifer hydraulic conductivities calculated from the interpreted resistivity soundings and those deduced from pumping test analysis emphasizes the contribution of the geophysical methods in the determination of the aquifer parameters.

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