HYDRAULIC PARAMETERS FROM SURFACE GEOPHYSICAL METHODS : KERITIS BASIN IN CHANIA-CRETE

P.M. Soupios(1), M. Kouli(1), F. Vallianatos(1), A. Vafidis(3) and G. Stavroulakis(2)
(1) Technological Educational Institute of Crete, Department of Natural Resources and Environment, Laboratory of Geophysics & Seismology
(2) Technological Educational Institute of Crete, Department of Natural Resources and Environment, Laboratory of Water and Soil Quality Control
(3) Technical University of Crete, Department of Mineral Resources Engineering, Laboratory of Applied Geophysics

ABSTRACT
Knowledge of aquifer parameters is essential for the assessment and management of groundwater resources. Conventionally, these parameters are estimated through pumping tests carried out on bore wells. Few bore wells may be available and carrying out pumping tests at a number of sites may be costly and time consuming. The application of surface geophysical methods in combination with pumping tests at a few sites provides a cost-effective and efficient alternative to estimate aquifer parameters. This study has been carried out in the Keritis basin (Chania-Crete Island), where the aquifer characteristics are required for the management of groundwater in the region.

1. INTRODUCTION

During the last decades, the imperious need of accurate global groundwater resources assessment has led to a rapidly growing awareness in the field of groundwater management. Therefore, quantitative description of aquifers has become vital in order to face several hydrogeological problems. Hydraulic conductivity and aquifer depth are fundamental properties describing subsurface hydrology. As a result, many investigation techniques are commonly employed with the aim of the estimation of spatial distribution of hydraulic parameters such as hydraulic conductivity, transmissivity and aquifer depth. Field estimations of the above parameters are not always available and usually the estimation appears to be problematic [20,14].

Traditionally, one of the more effective ways of hydraulic conductivity calculation are the pumping tests that are carried out on certain boreholes sites. Nevertheless, a probable sparse spatial distribution of the available boreholes gives rise to significant problems in modeling the hydrogeological systems. In such cases, drilling new boreholes has proved to be rather expensive as well as time-consuming.

In the other hand, the integration of aquifer parameters calculated from the existed boreholes locations and surface resistivity parameters extracted from surface electrical measurements can be highly effective not only for aquifer hydraulic conductivity estimation but also for a group of hydraulic parameters.

The aim of our study is the estimation of the aquifer parameters and the possible use of them in the assessment and management of groundwater resources of Keritis Basin, which is located in the eastern part of Chania Municipality, Crete Island, Greece. Keritis Basin is the main source of irrigation water for the whole plain land of Chania Basin, one of the most developed agricultural areas in Crete. For this purpose, surface geophysical methods have been used for aquifer zones delineation and evaluation of the geophysical character of the aquifer zone in several locations.

The inadequate number of boreholes has been overcome with the use of calculated correlation coefficients between geophysical parameters extracted from surface electrical measurements interpretation and aquifer hydraulic parameters extracted from pumping tests carried out on the existed boreholes. Correlation coefficients method has been utilized in order to estimate aquifer parameters in numerous locations providing effective and inexpensive characterization of the study area aquifer system.

2. STUDY AREA

The study area is situated from 35°24΄50΄΄N to 35°30΄00΄΄N, and 23°49΄50΄΄E to 23°58΄00΄΄E (Fig. 1). The total county area is 137 km^2 and is located in the central part of Keritis river drainage basin, 3.5 km west of the city of Chania. It is bordered by the villages Vryses and Galatas to the north, Skines and Fournes to the south, Psathogiannos to the west and Varypetron to the east (Fig. 1).

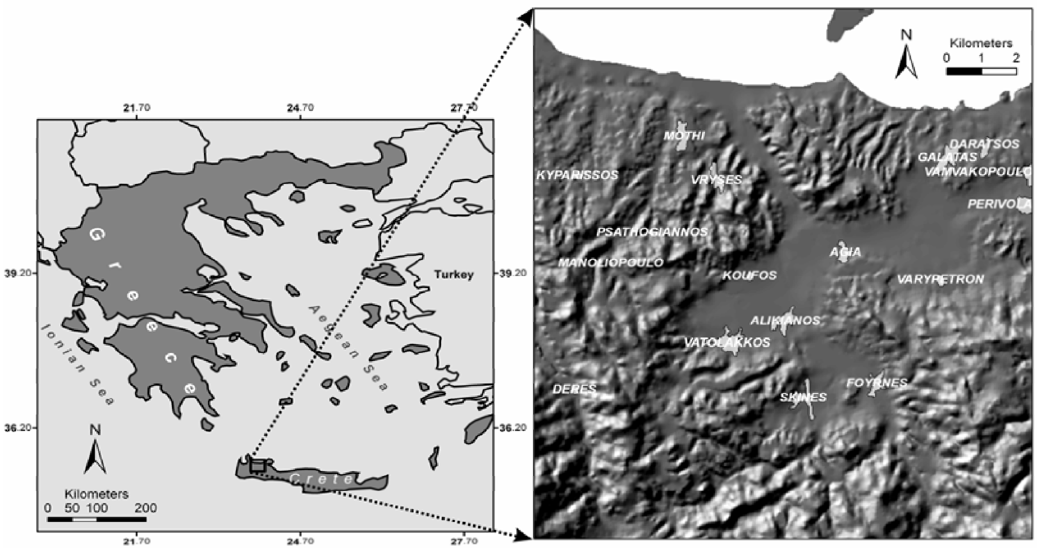

Figure 1. Location map of the Keritis Basin, Chania, Crete Island, Greece

The area is drained by the Keritis river which is considered to be the main river of the area. The water resources availability is limited due to spatio-temporal variations of precipitation [16]. The growing water demands make the water resources management extremely important for sustainable development.

3. GEO-TECTONIC AND HYDROLITHOLOGICAL CONTEXT

The surficial geology is composed of Quaternary deposits that form depositional plains. Miocene to Pliocene sediments crop out in the central and the northwestern part of the study area and carbonates in the northeastern part. Dissected hills of phyllites and quartzites and a package of sedimentary rocks composed mostly of quartz-rich siliciclastic sediments with minor limestone and gypsum [11] are observed mainly in the southwestern and southeastern part of the study area.

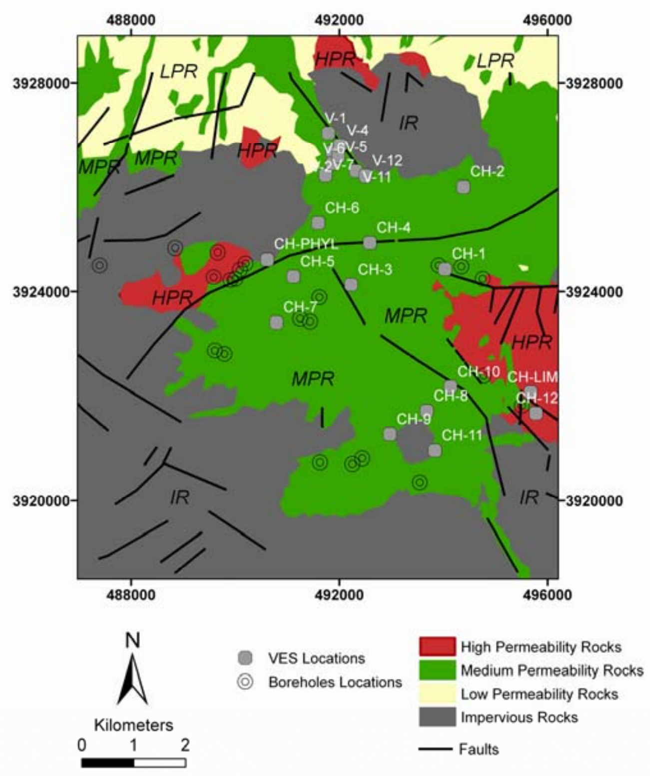

Figure 2. Hydrolithological map of the study area with tectonic faults overlay. The locations of boreholes as well as Vertical Electrical Sounding (VES) are also shown.

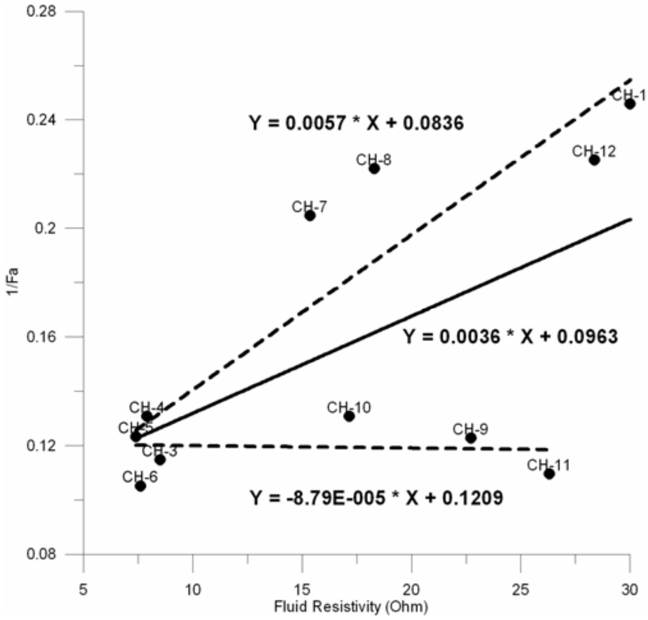

Figure 3. Determination of the intrinsic formation factor, F_i, plotting $1/F_a$ versus fluid resistivity.

In the present work the geological units have been classified in the sense of permeability into four hydrolithological units (Fig. 2): high permeability rocks which comprise the karstic limestones of Tripolis and Trypalion nappes, medium permeability rocks which consist of the Quaternary deposits as well as the Miocene to Pliocene conglomerates and marly limestones, low permeability rocks which consists of the Pliocene to Miocene marles and impervious rocks which mainly consist of the phyllites–quartzites unit.

The local tectonic regime of the study area is characterizing by faults of NW-SE and E-W directions, which define the boundaries between the existing hydrolithological units (Fig. 2) as well as the groundwater flow direction. Thus, these tectonic structures probable act as underground dams bounding the underground water movement.

4. GEOELECTRICAL INVESTIGATION

Resistivity techniques are well-established and widely used to solve a variety of geotechnical, geological and environmental subsurface detection problems [18]. The primary purpose of the resistivity method is to measure the potential differences on the surface due to the current flow within the ground and therefore to have a relative estimation of the area's hydraulic parameters (porosity, water distribution, etc.).

During the current work, twenty one (21) geoelectrical soundings (CH# and V#) (Figure 2) with a maximum half current electrode separation of 500 m have been carried out. The measurements were planned having in mind to cover the whole area extent while at the same time to be as close to the existing boreholes as possible in order to use them for calibration.

TABLE 1. Estimation of Formation Factor and other hydraulic parameters from the geophysical data obtained from locations CH-#. (Grain size = 0.01m)

Location	Bulk Resistivity (Ωhm-m)	Aquifer Resistivity (Ωhm-m)	Aquifer Thickness (m)	Formation Factor (Fa)	1/Fa	Longitudinal Unit Conductance (S)	Transverse Resistance (TR)	Transmissivity (m^2/s)
CH-1	122	30	50.2	4.0667	0.2459	1.673	1506	1.34E-02
CH-3	74	8.5	48	8.7059	0.1149	5.647	408	1.28E-02
CH-4	60.4	7.9	27.6	7.6456	0.1308	3.494	218.04	7.37E-03
CH-5	60	7.4	115.6	8.1081	0.1233	15.622	855.44	3.09E-02
CH-6	72.2	7.6	79.8	9.5000	0.1053	10.500	606.48	2.13E-02
CH-7	75	15.35	48.3	4.8860	0.2047	3.147	741.405	1.29E-02
CH-8	82.4	18.3	88.2	4.5027	0.2221	4.820	1614.06	2.35E-02
CH-9	185	22.72	61.3	8.1426	0.1228	2.698	1392.736	1.64E-02
CH-10	131	17.15	113	7.6385	0.1309	6.589	1937.95	3.02E-02
CH-11	240	26.31	111.2	9.1220	0.1096	4.227	2925.672	2.97E-02
CH-12	126	28.38	90	4.4397	0.2252	3.171	2554.2	2.40E-02

a	m	low bound porosity	porosity	upper bound porosity	average porosity	hydraulic conductivity (m/sec)	hydraulic conductivity (m/day)
1.04	2.3	0.406	0.368	0.346	0.373	5.15E-04	4.45E+01
0.5	2.31	0.297	0.269	0.253	0.273	1.50E-04	1.29E+01
1.1	1.61	0.286	0.248	0.227	0.254	1.14E-04	9.84E+00
1	1.3	0.197	0.165	0.148	0.170	2.78E-05	2.40E+00
1	1.5	0.245	0.210	0.191	0.215	6.31E-05	5.45E+00
1	1.7	0.289	0.252	0.232	0.258	1.21E-04	1.05E+01
1	1.9	0.329	0.292	0.271	0.297	2.07E-04	1.79E+01
1	2.1	0.366	0.328	0.307	0.333	3.25E-04	2.81E+01
1	2.3	0.399	0.361	0.340	0.367	4.79E-04	4.14E+01
1	2.5	0.430	0.392	0.371	0.397	6.73E-04	5.81E+01
		0.324	**0.289**	**0.269**		**2.67E-04**	**2.31E+01**
diameter	**0.01**						
d2	**0.0001**						

All measured resistivity soundings were processed using the IPI2Win software. This package performs an automated approximation of initial resistivity model using the observed data [2]. All resulting models produced a low RMS relative error of the order of 3%.

For eleven (11) of the total twenty one (21) VES measurements, valuable information such as, insitu aquifer conductivity measurement and knowledge of the aquifer thickness (derived from the existing boreholes), were available for the accurate estimation of the formation factor as well as for the extraction of all the hydraulic parameters as is shown in Table 1.

5. DETERMINATION OF AQUIFER PROPERTIES

In order to obtain quantitative information in groundwater flow and contaminant transport modelling, it is essential to estimate the hydraulic properties of any given aquifer system. Such aquifer hydraulic properties (hydraulic conductivity and transmissivity) are usually obtained either from pumping tests or laboratory experiments when core samples exist.

However, an alternative approach can be applied utilising non-invasive geophysical information. Geophysicists have realised that a correlation between hydraulic and electrical aquifer properties can be possible, as both properties are related to the pore space structure and heterogeneity [10,13,8,12,3,4,15].

Concerning our work, since bulk and fluid resistivities were available at several locations, it was desirable to examine the possibility to obtain hydraulic conductivity values using the Kozeny–Carman–Bear equation [6]. The porosity φ required in this equation has to be estimated using Archie's law, with its empirical nature and dependence on Archie's parameters. Moreover, we calculated the range of hydraulic conductivities produced by the plausible values of these porosities.

5.1 Determination of porosity through the intrinsic formation factor Fi

Archie's law [1] relates the bulk resistivity of a fully saturated granular medium to its porosity and the resistivity of the fluid within the pores according to Equation (1):

$$\rho_o = \alpha \cdot \rho_w \cdot \phi^{-m} \tag{1}$$

where ρ_o is the bulk resistivity, ρ_w is the fluid resistivity, φ is the porosity of the medium, *m* is known as the cementation factor and the coefficient *a* is associated with the medium and its value in many cases departs from the commonly assumed value of one.

For a clay-free medium, the ρ_o / ρ_w ratio is known as the intrinsic formation factor, F_i. Thus, Eq. (1) could be easily reformulated in the following form, Eq. (2),

$$\phi = e^{\frac{1}{m}\cdot\ln(\alpha)+\frac{1}{m}\cdot\ln\left(\frac{1}{F_i}\right)} \tag{2}$$

The values of the coefficients *a* and *m* should, ideally, be determined for each site under investigation. Three different expressions for the intrinsic formation factor in relation to the porosity of samples from different locations was suggested by Worthington [19]. A fourth expression in which the coefficient *a* has the value of one while *m* is allowed to vary from 1.3 to 2.5 was suggested by de Lima and Sharma [5].

However, for field data a complication arises due to the fact that Archie's formula (Eq. (1 and 2)) is valid only for clay-free, clean, consolidated sediments. Any deviations from these assumptions make the equation invalid as discussed by Worthington [19]. In the case of unclean, clayey sands and a mixture of sand/rubble/gravels, the ratio of bulk resistivity to fluid resistivity is known as the apparent formation factor, F_a. As our aquifer system consists of clayey/silty sand material enhanced with rubbles and gravels, a modification of the Archie's equation was required. For this reason, the Waxman–Smits model was considered [17] as it relates the apparent and intrinsic formation factors, F_a and F_i, after taking into account the shale effects. According to Worthington [19],

$$F_a = F_i \cdot \left(1 + BQ_v\rho_w\right)^{-1} \tag{3}$$

where the BQ_v term is related to the effects of surface conduction, mainly due to clay particles. In case surface conduction effects are non-existent, the apparent formation factor becomes equal to the intrinsic one.

Re-arranging the terms of Eq. (3), we obtained a linear relationship between $1/F_a$ and ρ_w,

$$\frac{1}{F_\alpha} = \frac{1}{F_i} + \left(\frac{BQ_v}{F_i}\right)\rho_w \tag{4}$$

where $1/F_i$ is the intercept of the straight line and BQ_v/F_i represents the gradient [8,19]. Thus, by plotting $1/F_a$ vs. fluid resistivity ρ_w, we should, in principle, obtain a value for the intrinsic formation factor, which will subsequently enable us to estimate porosity using Eq. (2) as is shown in Table 1.

To follow the above approach, we used bulk resistivities ρ_o, as resulted from 1D resistivity inversion coupled with the measured fluid electrical resistivities, ρ_w, obtained from the nearest to the VES locations, boreholes. These values were used to calculate the apparent formation factor

($F_a = \rho_o / \rho_w$) of the saturated top aquifer. The resistivity values obtained from the inversions and the estimated apparent formation factors are shown in Table 1.

Figure (3) shows $1/F_a$ plotted versus the fluid resistivity ρ_w. Three straight lines were used to fit the data. The data could be easily separated in two individual groups with common characteristics as is shown by the dashed fitted lines. These best fit linear approach of the data, gives the range of the inverse of the intrinsic formation factor F_i which for our data set varies between 0.0836 and 0.1209 as is shown in figure 4. The porosities could now be determined through Eq. 2 for reported values of *a* and *m* as shown in Table 1.

5.2 Determination of hydraulic conductivity and transmissivity

The hydraulic conductivity calculation was achieved through the use of the Kozeny–Carman–Bear equation, given by [6] as:

$$k = \left(\frac{\delta_\omega g}{\mu}\right) \cdot \left(\frac{d^2}{180}\right) \cdot \left[\frac{\phi^3}{(1-\phi)^2}\right] \quad (5)$$

where *d* is the grain size, δ_ω is the fluid density (taken to be 1000 kgr/m^3), and μ is the dynamic viscosity taken to be 0.0014 kg/ms [7]. The estimated hydraulic conductivity values (in m/sec and in m/day) using Eq. 5 are shown in Table 1. The average geometrical hydraulic conductivity value for the aquifer under investigation is $2.67 * 10^{-4}$ m/s or 23.1 m/day.

The transmissivity, using the estimated hydraulic conductivity ($k = 2.67 * 10^{-4}$ m/s), was also calculated using the equation (6),

$$T = k \cdot h \quad (6)$$

where T = transmissivity (m^2/sec), k = hydraulic conductivity (m/sec) and h = aquifer thickness (m). The extracted parameters for each VES locations are shown in Table 1.

The calculated hydraulic parameters were interpolated with geostatistical and deterministic techniques.

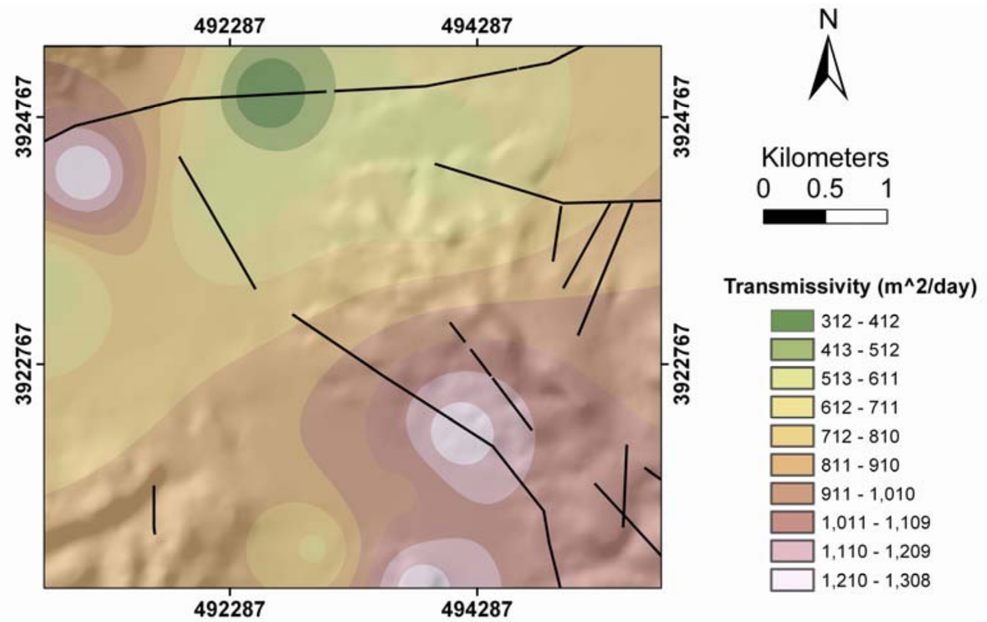

Figure 4. Transmissivity (m^2 per day) map for the Keritis Basin area with tectonic faults overlay. Transmissivity values tend to decrease with the transition from permeable to impervious rocks. (fig.2).

The spatial map that was derived from the interpolation of the calculated hydraulic parameters show that the transmissivity seems to be spatially related with the high permeability formations. Furthermore, a relationship between the estimated and presented hydraulic parameters as shown in figure 4 and tectonic structures seems to exist with faults acting as boundary even between the same hydrolithological unit and define the place where aquifer parameters varies.

6. CORRELATION OF THE OBSERVED AND ESTIMATED HYDRAULIC PARAMETERS

The most common in-situ test for the calculation of real water supply and the indirect estimation of hydraulic conductivity in a borehole, is the pumping test performed on wells, and involves the measurement of the rise and fall of water level with respect to time. The water level fluctuations with time, is then interpreted to arrive at aquifer parameters. The availability of pre-existing wells makes the pumping test cost-effective.

More than twenty hydrowells were operated throughout the study area and one of them was selected as the most representative for the indirect estimation of the hydraulic conductivity through the use of pumping test.

Using the estimated water supply (Q=100 m^3/h), the diameter (d) of the fenced tubing as well as the thickness (h) of the aquifer we estimated the hydraulic conductivity using the following formula,

$$Q(m^3/h) = E(m^2)\cdot k(m/h) \quad (7)$$

Applying the above equation, the hydraulic conductivity k, is estimated equal to $6.8*10^{-4}$ m/s (coarse grained sand). This indirect observed value of hydraulic conductivity, is in agreement with the estimated aquifer parameter ($k=2.67*10^{-4}$ m/s, medium grained sand) as calculated from the superricial geophysical measurements. Both values are within the range of 10^{-5}-10^{-2} which is the characteristic range of a pure sands and gravel aquifer [9].

7. CONCLUSIONS

Since well-drilling for the hydraulic parameters calculation is often prohibitively expensive, determining the aquifer parameters from VES is a cost effective alternative. Based on our results, the contribution of VES coupled with the available pumping test data except from its apparent use to groundwater exploitation and aquifer geometry delineation was proved to be rather significant to the quantitative estimation of aquifer parameters.

The calculated hydraulic parameters of the shallow aquifer in Keritis basin are very useful for further studies of the groundwater regime in the area. The estimated aquifer parameters could also be used to derive input parameters for contaminant migration modeling and to improve the quality of model. Finally, we should mentioned tha the calculated aquifer parameters are well defined within the range of observed aquifer parameters.

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