Hydrochemical and geophysical survey of the Almyros aquifer system, East Central Greece

C. Myriounis[1], K. Voudouris[1], P. Tsourlos[2], G. Soulios[1], G. Dimopoulos[1]

Abstract **The Almyros plain is located in the central** eastern **part of Greece, covering an area of 110 km^2, with a mean altitude of 30 m. The plain is formed of recent unconsolidated materials consisting of sands, pebbles, and fine clay to silty sand deposits. The neogene formations are characterized by alternating coarse and fine materials. The main aquifer systems are developed in limestone (karst aquifer) and in coarse post alpine deposits.**

The results of chemical analyses from 63 samples, collected during the wet and dry period of the year 2005, were used. Seawater intrusion phenomena are mainly recorded in both, southern and northern part of the study area, due to overexploitation, low ability of refreshing and the presence of the brackish spring of Kefalosi. In the southern part the seawater intrusion phenomena are more intensive than the northern part, due to the hydraulic communication between alluvial and karstic aquifers. Two main groundwater types may be identified: Ca HCO_3 (freshwater) and Na Cl (water affected by seawater intrusion). Results of cluster analysis identified the existence of two aforementioned types of groundwater.

The geophysical investigations comprised of measurements along two profiles using the electrical resistivity technique (ERT) in an attempt to provide information about both the general geological and hydrogeological setting of the studied area with special focus into the mapping of the saline intrusion front. Results were processed with a 2D inversion algorithm and the produced subsurface images are jointly interpreted with the results of the hydrochemical surveying and the drill information in order to define the extension of the seawater intrusion front.

Finally, a set of recommendations are proposed, in order to improve the groundwater quality in study area.

Index Terms **coastal aquifer, seawater intrusion, electrical tomography, Almyros, Greece**

I. INTRODUCTION

Groundwater is vital resource for socio-economic development in coastal areas in all over the world. The water demands of these areas have increased during the last decades due to rapid urbanization, accelerated tourism development, agricultural activities and a continuous increase of population [11, 16, 18]. Water needs are mainly covered by groundwater abstracted from the aquifers via numerous wells and boreholes. As a result, a negative water balance is established in the coastal aquifer systems triggering seawater intrusion. In the last decades seawater intrusion phenomena are recorded, due to overexploitation [2, 4, 9, 17]. In recent years, many research projects using hydrochemical and geophysical methods have been carried out into seawater intrusion [1]. The aim of this work is to investigate the origin of the seawater intrusion in the coastal aquifer systems of the Almyros plain, central Greece, using hydrochemical and geophysical data. Firstly, the geological and hydrogeological regime was examined. Secondly, the areal extension of the seawater intrusion was determined. Finally, some recommendations are made to assist the rational management and improve the sustainability of the groundwater resources in the study area.

II. DESCRIPTION OF THE STUDY AREA

The Almyros plain (887 km^2) is located in the central part of the Magnesia prefecture, Thessaly region, East Greece (Fig. 1). The coastal zone of the basin is oriented N-S, covering an area about 110 km^2 with a mean altitude of 30 m. The topographic relief is controlled by the neotectonic action [3].

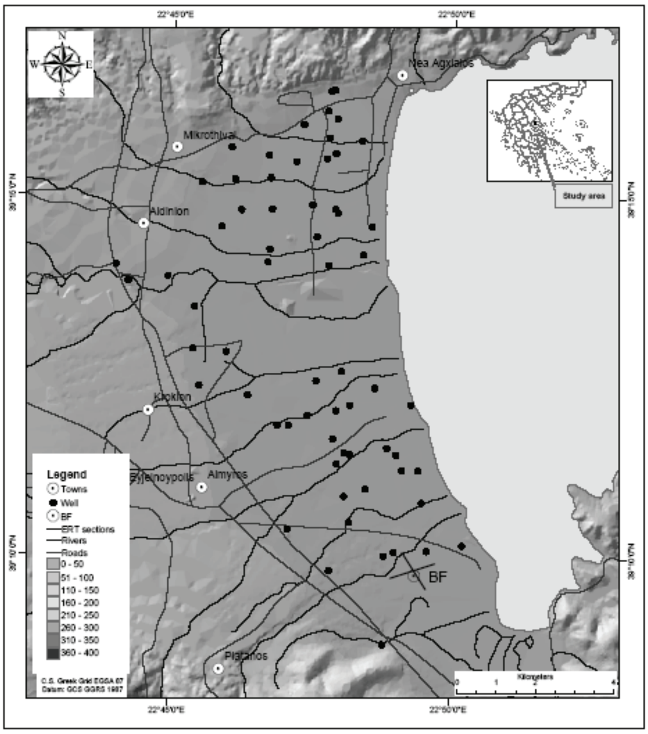

Fig. 1. Topographic map of the study area, showing the location of tomography sections and sampling sites.

Manuscript received September 2006

[1]Lab. of Eng. Geology & Hydrogeology, School of Geology, Aristotle University GR 51124, Thessaloniki, Greece. E-mail: kvoudour@geo.auth.gr
[2]Lab. of Applied Geophysics, School of Geology, Aristotle University, Greece

The mean annual rainfall is 478 mm at Nea Agxialos rain gauge station. The rainfall occurs mainly from late October to May (85% of annual rainfall) and the peak season is from November to December. The real evapotranspiration is estimated to be around 64% of the annual rainfall. The study area is drained by small torrents; flow in these torrents persist during the wet period, after heavy storms.

The area is characterized by intense agriculture, which consume the major sector of water demands. The aquifer system shows signs of depletion and quality deterioration during the last decades. The seawater intrusion is the clearest evidence that present exploitation of the aquifer is not sustainable.

III. GEOLOGICAL AND HYDROGEOLOGICAL SETTING

The geological formations which cover the highland in the border area can be identified: limestones (Jurassic or upper Cretaceous age), flysch, volcanic rocks and othiolitic rocks. These rocks have primary or secondary porosity, due to tectonism. Limestones appear in the northern (Nea Agxialos) and in the southern part (Soyrpi) of the plain and are karstified (Fig. 2).

The coastal zone is formed of recent unconsolidated material consisting of sands, pebbles, and fine clay to silty sand deposits. The neogene formations are characterized by alternating coarse (sandstones, gravel and conglomerate) and fine materials (clays and marls). As a result of their origin the deposits are characterized by high degree of heterogeneity and anisotropy [8].

The main aquifers are developed in the Quaternary and Neogene deposits (porous aquifers) and in the carbonate formations (karst aquifers) at the margins of the study area. Limestones which appear in the northern and in the southern part of the study area are faulted and karstified. They appear high permeability due to their well development of jointing and karstification. In the southern part, the carbonate aquifers are in direct hydraulic communication with the Quaternary deposits. The karstic system of southern part of the study area is discharged by the karstic spring of Kefalosi Almyrou, with a discharge of the order of 150-5000 m^3/h. The Kefalosi spring is discharged at an elevation of about 26 above sea level (ASL). The spring water is brackish due to tectonic regime of the area [3].

The sedimentary aquifers of the alternating coarse-grained alluvial beds may be regarded as unified aquifer system. The presence of silts implies the occurrence of artesian conditions in the coastal part of the area. In the last decades artesian phenomena are not appeared, due to overexploitation.

The general groundwater flow direction in alluvial aquifer, is West-East oriented. The mean hydraulic gradient of the alluvial aquifer ranges from 0.08% to 3%. The groundwater table was at depth 0-40 m ASL [8].

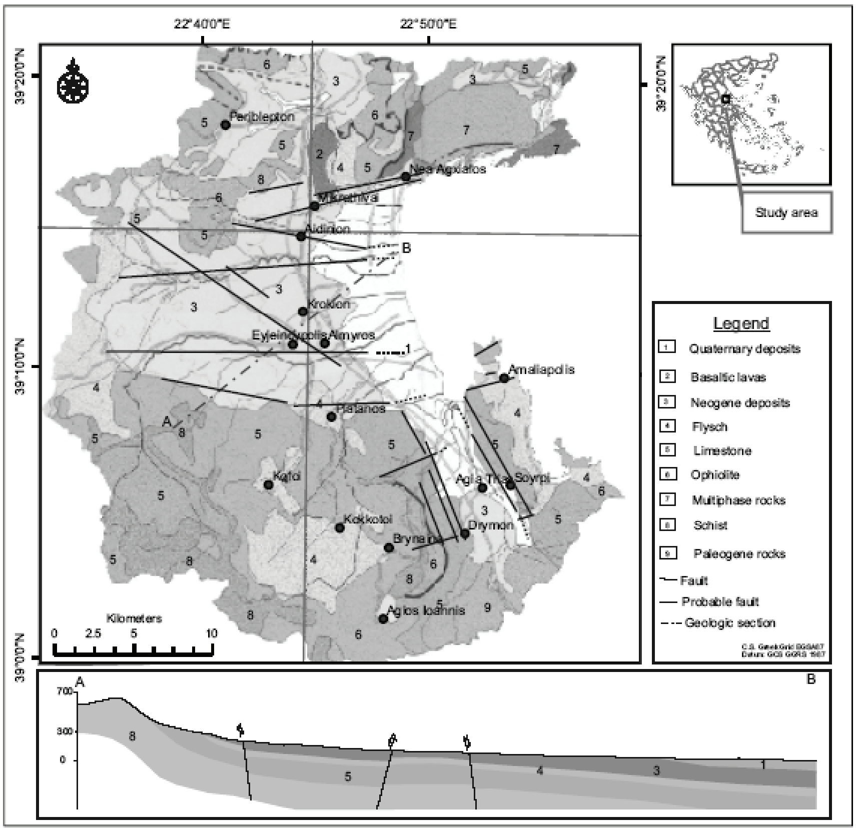

Fig. 2. Geological map of the study area.

Overexploitation has caused a decline of groundwater levels and changes in the direction and the velocity of groundwater flow, during the period 1985-2005. The water table is still below sea level during the dry period.

IV. DATA COLLECTION AND ANALYSIS

In order to examine the hydrochemical characteristics, 73 groundwater samples from boreholes were collected during the period May and September 2005, respectively. The samples were analyzed in the Laboratory of Engineering Geology & Hydrogeology of Aristotle University of Thessaloniki for major ions Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, NO_3^{-}, SO_4^{2-} and HCO_3^{-}. Electrical conductivity (Cond), temperature (^oC) and pH were also measured in situ. Statistical results of chemical analyses for period May 2005, are listed in Table 1.

The geophysical investigations comprised of measurements along several profiles using the electrical resistivity technique (ERT). Data-set were obtained using several known electrode arrays with variable interelectrode spacing in an attempt to provide information about both the general geological and hydrogeological setting of the studied area with special focus into the mapping of the saline intrusion front. Results were processed with a new 2D inversion algorithm which allows the combined weighted inversion of data arising from different electrode arrays [10].

TABLE I
STATISTICAL CHARACTERISTICS OF CHEMICAL ANALYSES

May 2005	MIN	MEAN	MAX	St. DEV.
pH	6.7	7.4	7.8	0.2
T	15.3	18.5	21.9	0.9
Cond	382.0	819.0	2880.0	354.3
Na	11.0	45.3	770.0	109.0
K	0.6	2.0	23.5	3.6
Mg	2.9	44.8	222.2	42.8
Ca	16.0	118.6	568.0	82.3
Cl	8.6	174.1	2750.0	460.9
SO_4	1.0	30.6	160.0	32.9
NO_3	8.5	49.0	105.6	28.6
HCO_3	190.0	317.3	475.0	66.1
Sept 2005	**MIN**	**MEAN**	**MAX**	**St. DEV.**
pH	6.91	7.3	7.7	0.2
T	15.5	18.5	21.0	0.8
Cond	435.0	846.8	4850.0	642.
Na	8.2	74.5	1680.0	248.6
K	0.3	1.4	10.8	1.8
Mg	2.4	40.0	130.4	25.7
Ca	30.3	104.7	582.0	72.2
Cl	8.0	149.9	2800.0	417.8
SO_4	2.0	34.8	230.0	45.1
NO_3	4.0	48.9	121.0	27.2
HCO_3	168.0	318.0	449.0	69.0

V. GROUNDWATER QUALITY

The statistical results of chemical analyses are listed in Table 1

The overall precision of the analyses is within ±5%, as indicated from the ionic balance.

The electrical conductivity (Cond) values range between 382 and 2880 μS/cm (May 2005). Relatively high values of electrical conductivity along the coastline are attributed to seawater intrusion.

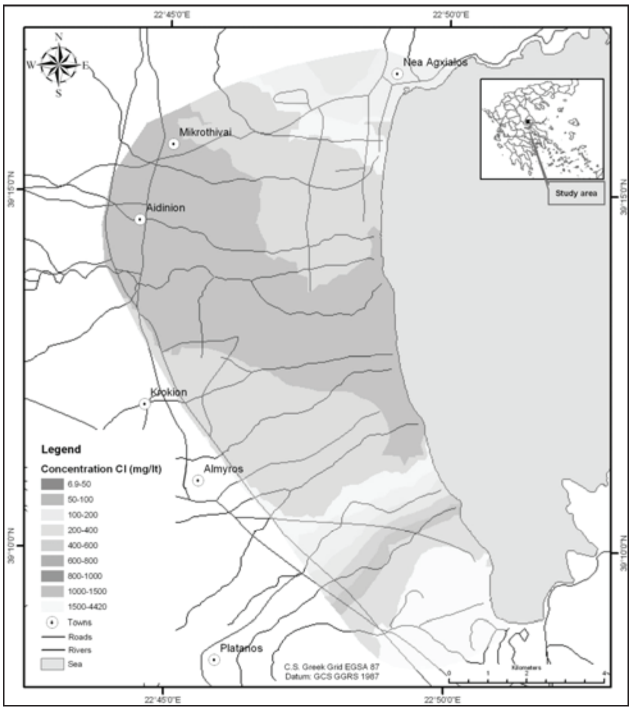

Fig. 3. Chloride distribution (May 2005).

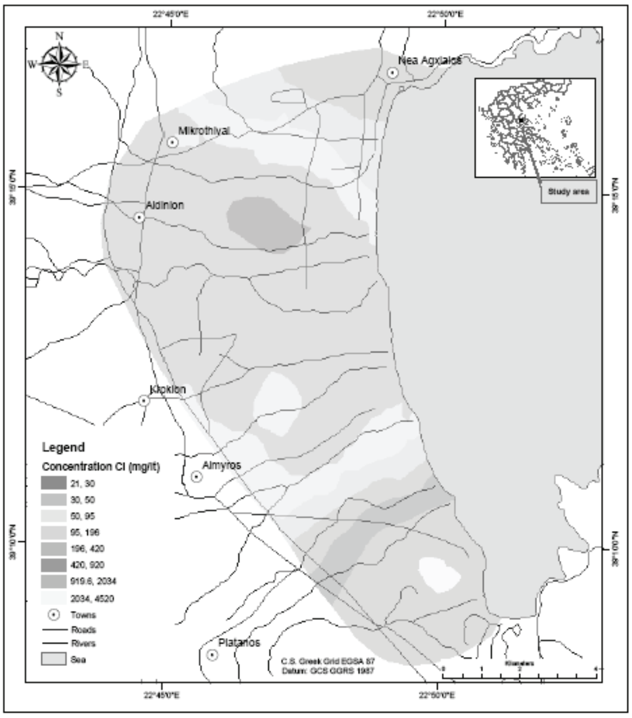

Fig 4 Chloride distribution (September 2005)

At the end of the dry period the values of Cond are higher than the wet period [7]. Most of the central area is characterized by Cond values between 400-850 μS/cm. It is pointed out that, in the central part there is the military airport and pumping boreholes not used for irrigation.

The Cl^- concentration ranges from 8.86 mg/L to 2750 mg/L; the high values are signs of seawater intrusion. The Cl^- distribution maps are shown in Figures 3 and 4. In the northern part, the high Cl^- concentration values are recorded in Nea Agxialos, due to seawater intrusion. In the southern part the seawater intrusion phenomena are more intensive than the northern part, due to the hydraulic communication between alluvial and karstic aquifers. The brackish spring of Kefalosi recharges the alluvial aquifer system in the southern part of the Almyros plain. Cl^- correlates strongly with Na^+, indicating the common origin (Fig. 5).

Nitrate range is 8.5-133 mg/L with a mean value of 50.8 mg/L (Fig. 6). Nitrate sources are agricultural activities and sewage effluent through seepage from septic tanks. It is pointed out that, fertilizers are applied at the cultivated crops of the study area. The applied fertilizers (NH_4NO_3, $(NH_4)_2SO_4$, mixed types Nitrogen Phosphate Potassium-NPK) in cultivated areas and the disposal of domestic and industrial wastewater through rivers are the most important sources of nitrates [15].

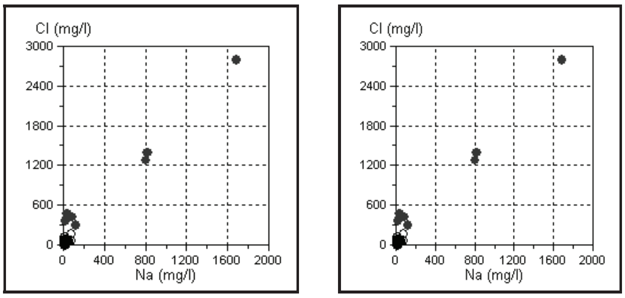

Fig. 5. Cl vs Na: period May 2005 (left), period September 2005 (right).

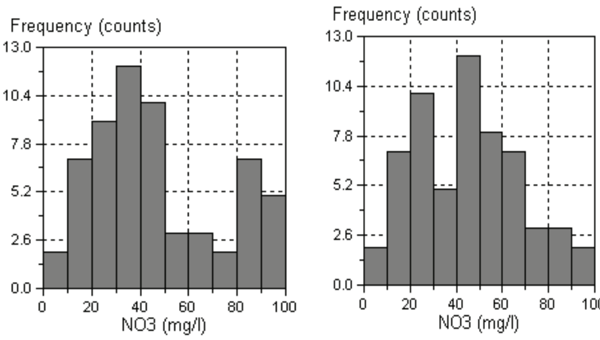

Fig. 6. Nitrate: period May 2005 (left), period September 2005 (right).

Figures 7 and 8 present the PIPER diagrams for period May and September 2005 respectively, indicating that regarding the hydrochemical facies, the groundwater can be classified in two types: Ca-HCO_3 (fresh water-plots in the left side of the central diamond) and Na-Cl (water affected by seawater intrusion-plots in the right side of the central diamond).

The box plot is a visually effective way to summarize graphically the distribution of the data [14]. Figures 9 and 10 show the box plot of major ions for each period. The upper and lower quartiles of the data define the top and the bottom of a rectangle (box). The line inside the box represents the median value and the size of the box the spread about the central value. As it can be seen from these Figures, the groundwater in both wet and dry period has similar quality characteristics.

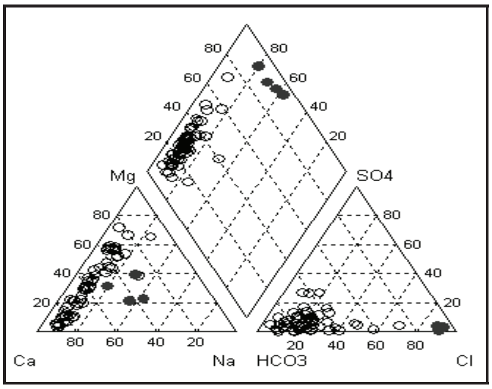

Fig. 7. Piper diagram: period May 2005.

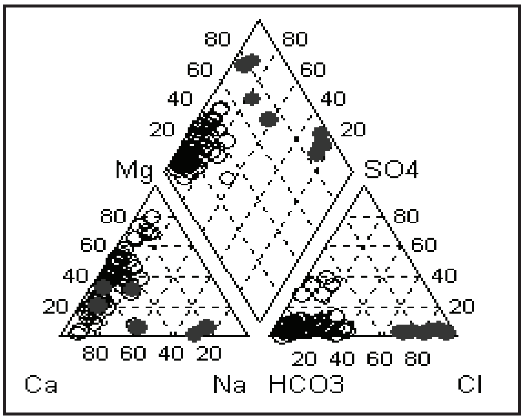

Fig. 8. Piper diagram: period September 2005.

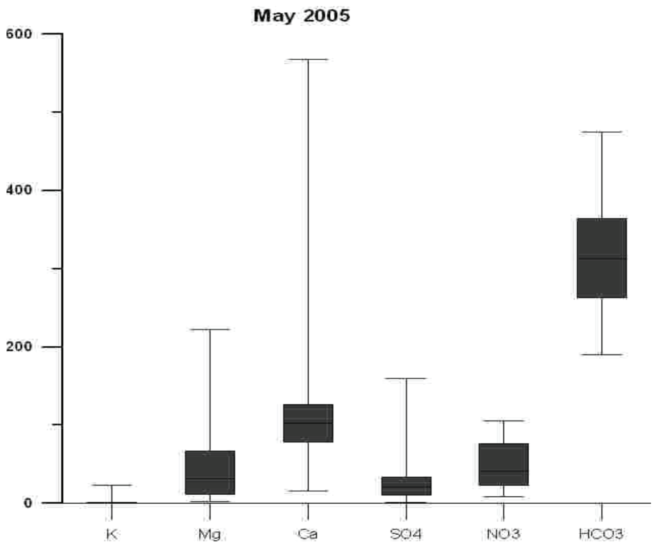

Fig. 9. Box plot of major ions (May 2005)

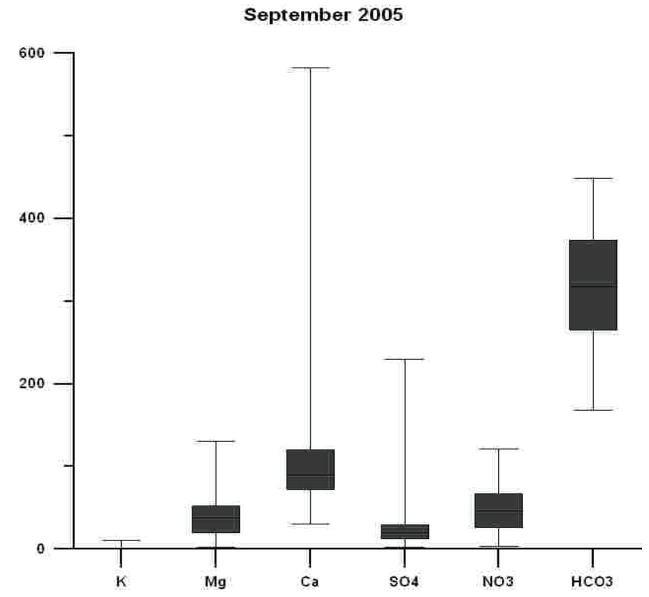

Fig. 10. Box plot of major ions (September 2005).

Table II indicates the correlation coefficients between major elements in groundwater. High correlation (>0.70) and significant at p-level 0.05 have been obtained between: Na^+-Cl^- (0.96), Na^+-Mg^{2+} (0.75), Na^+-Ca^{2+} (0.88), K^+-Cl^- (0.80), Ca^{2+}-Cl^- (0.92), Mg^{2+}-Cl^- (0.78).

The electrical conductivity (Cond) mainly depends upon the major ion concentrations. The correlation coefficients between E.C. and major ions are greater than 0.70, apart from nitrate (Fig. 11). The correlation matrix for dry period (September 2005) shows a similar behaviour.

TABLE II
CORRELATION MATRIX (PERIOD MAY 2005)

	Na	K	Ca	Mg	Cl	SO_4	NO_3	HCO_3
Na	**1**	0.67	0.88	0.75	0.96	0.43	-0.29	-0.16
K		**1**	0.69	0.63	0.80	0.29	-0.30	-0.23
Ca			**1**	0.53	0.92	0.46	-0.07	-0.44
Mg				**1**	0.78	0.40	-0.43	0.22
Cl					**1**	0.41	-0.31	-0.26
SO_4						**1**	0.13	0.05
NO_3							**1**	-0.18
HCO_3								**1**

VI. CLUSTER ANALYSIS

Cluster analysis is a simple approach of classifying groundwater quality. The Euclidean distance is used as a measure of similarity between every pair of groundwater samples [6]. Because the different parameters use different units (µS/cm, °C, mg/l) the initial data must be standardized with a mean value of 0 and a standard deviation of 1 [13].

The samples were grouped into distinct clusters, representing different hydrochemical groups. The distance between two samples (i, j) is given by [5, 12]:

$$d_{ij} = \left[\sum_{k=1}^{n} \left(X_{ik} - X_{jk} \right)^2 \right]^{1/2}$$

where X_{ik} denotes the k^{th} parameter measured on sample i and X_{jk} is the k^{th} parameter measured on sample j.

TABLE III
FINAL CLUSTER CENTERS

Parameter	Cluster 1	Cluster 2
pH	7.4	7.2
T	18.5	17.8
E.C.	742.1	1797.2
Na	21.5	393.7
K	1.1	15.2
Mg	36.0	167.3
Ca	99.0	389.1
Cl	60.3	1840.0
SO_4	26.9	77.8
NO_3	50.7	14.3
HCO_3	319.9	246.0

Based on the cluster analysis, the final cluster centers are listed in Table III. All the samples collected from the inland not affected by seawater intrusion were found to be in cluster 1; the samples collected from the coastal part affected by seawater intrusion were found to be in cluster 2.

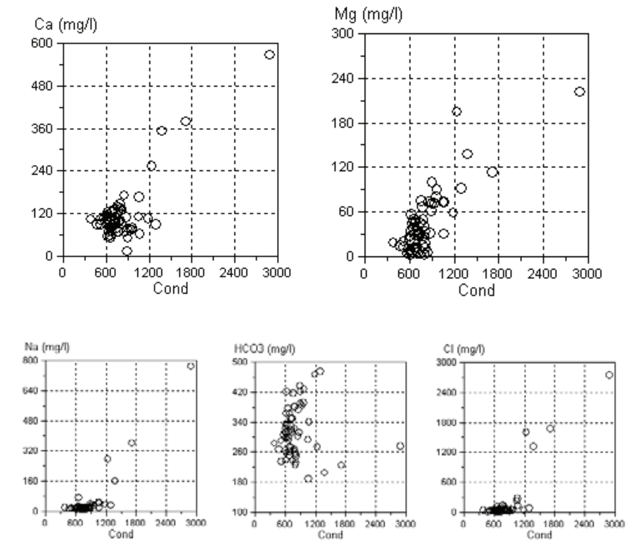

Fig. 11. Plot of major ions (mg/L) versus electrical conductivity (Cond) (µS/cm) for period May 2005. The plot shows that high values of Ca, Mg, Na and Cl correlate with conductivity values.

VII. GEOPHYSICAL INVESTIGATION

Two Electrical Resistivity Tomography (ERT) sections, located perpendicular to each other, were measured at the southern part of the studied area as shown in Fig 12.

Given that relatively low apparent resistivities were anticipated in the area the Wenner-Schlumberger array was used with inter-electrode spacing a=45 m and the maximum N separation was Nmax=7 (a, 2a). Each section has 21 electrodes and a length of 900 m.

Data were inverted with a standard iterative smoothness constrain scheme based on a finite element forward solver [10]. Inversions produced low RMS errors (<4%) between measured and predicted data indicative of good data quality and reliable reconstructions. The inverted results for sections 1, 2 are depicted in top and middle Fig. 13 respectively.

A similar stratigraphy of geoelectrical formations appears in both sections (Fig. 13):a relatively resistive (30-60 Ohm-m) top layer at a mean thickness of 20 m corresponding probably to the vadoze zone overlies a distinctive low resistivity layer (2-10 Ohm-m) at a mean depth of 20-80 m. A third distinctive bottom layer of relatively high resistivity (>80 Ohm-m) can be shown below the depth of 80-100 m.

The geophysical information is in very well agreement with the information acquired from private well BF located at 360 m of Section 1 (see Fig. 12). The water level at BF was measured to be at 20 m depth and the conductivity in-situ measurements of the well water samples obtained the same day with the ERT survey exhibited high water conductivity (5,000 μS/cm).

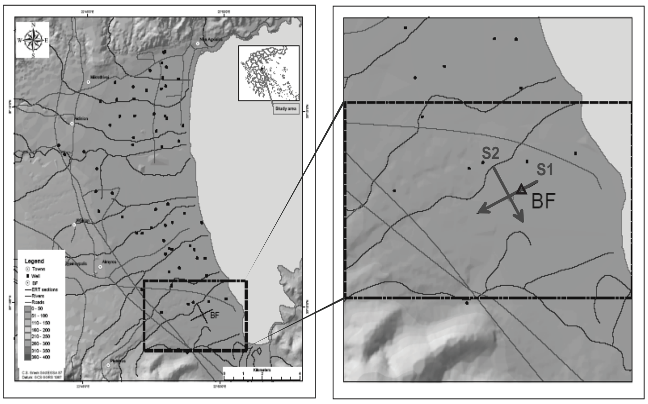

Fig. 12. Location of the ERT sections S1, S2.

Further information coming from the BF well suggest that water comes from the first 100 m since after that an impermeable formation was encountered which in full agreement of the bottom layer depth found in section 1 (Fig 13, top).

All indications from the surveyed area suggest that that the intermediate conductive layer clearly depicted in both sections 1, 2 found corresponds to a saline aquifer. The subsequent interpretation for Section 1 is depicted at the bottom of Fig. 13.

Ii s also worth mentioning that the saline water layer exhibits increased thickness towards the South part of the surveyed area but only limited thickness at the Northern part. This is generally in agreement with the ground water quality measurements which clearly suggest that seawater intrusion phenomena are more intensive at the southern part of the region that the northern part.

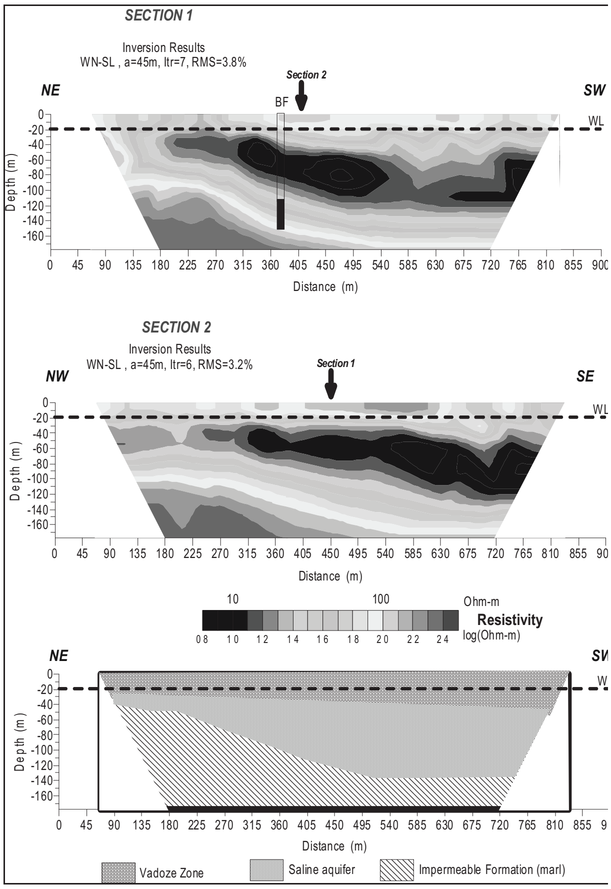

Fig. 13. Electrical Resistivity Tomography sections and subsequent interpretation.

VIII. CONCLUSIONS-RECOMMENDATIONS

The Almyros plain is located in the central eastern part of Greece and is formed of recent unconsolidated materials. The main aquifer systems are developed in coarse postalpine deposits.

The alluvial aquifer of Almyros plain shows signs of quality deterioration. The aquifer system is overexploited and has shown signs of depletion and quality contamination. The seawater intrusion is the clearest evidence that present exploitation of the aquifer is not sustainable.

Degradation of groundwater quality is mainly caused by seawater intrusion and nitrate pollution. Seawater intrusion phenomena are mainly recorded in both, southern and northern part of the study area, due to overexploitation, low ability of refreshing and the presence of the brackish spring of Kefalosi.

Based on Piper diagram, two main groundwater types may be identified: Ca-HCO_3 (freshwater) and Na-Cl (water affected by seawater intrusion). Results of cluster analysis identified the existence of two aforementioned types of groundwater.

The produced subsurface images from geophysical survey are jointly interpreted with the results of the hydrochemical surveying and the drill information in order to define the extension of the seawater intrusion front.

The increasing pumping has increased the risk of seawater intrusion and deterioration of groundwater quality. A rational management plan should be applied, in order to restore the negative water balance and to improve the groundwater quality of the aquifer systems.

This strategy could be based on the conjunctive use of groundwater, surface and spring water. Reduction of groundwater abstraction should be applied in the areas that are affected by seawater intrusion. Water-saving techniques such as spray irrigation and drip irrigation should be applied in order to decrease the groundwater quantities used for agriculture. Training courses should be organized in order to educate farmers in using methods to optimize water use.

Construction of small interception dams in the main torrents of the hilly region, aiming at the retardation of wintertime torrential flows and the increasing of the groundwater recharge.

The Directive 2000/60/EC and the harmonisation from Greek authorities provides new legislation and opportunities for the sustainable management of groundwater resources. the surface water.

Finally, a monitoring programme on groundwater quality should be established in selected boreholes, in order to avoid seawater intrusion phenomena and nitrate pollution on a large scale. Future investigations of the sustainable management of groundwater resources in the Almyros plain would benefit by isotopic analysis and computer modelling to simulate the groundwater flow.

REFERENCES

[1] Aracil, A., Maruri, B., Valles, I., Porres, B. et al. 2004. Electrical resistivity tomography as a technique for studying and modelling saline water intrusion. Selected papers from the 18th Salt Water Intrusion Meeting. Cartagena, Spain, 341-351.

[2] Custodio, E. 1987. Seawater intrusion in the Llobregat delta, near Barcelona (Spain). Groundwater problems in coastal areas. Studies and reports in hydrology, No 45 UNESCO, 436-463.

[3] Dimopoulos, G. (1983). Salzwasserführende Karstquellen oberhalb der Meeresoberfläche (Am Beispiel der Karstquelle Kefalosis von Almyros, SE-Thessalia, Griechenland, erläutert, Zeitschrift für angewandte Geologie, BD. 29, Heft 11, s. 565-569.

[4] El-Baruni S.S. 1995. Deterioration of quality of groundwater from Suani wellfield, Tripoli, Libya. Hydrogeology Journal 3(2):58-64.

[5] Hussein, M.T. 2004. Hydrochemical evaluation of groundwater in the Blue Nile Basin, eastern Sudan, using conventional and multivariate techniques. Hydrogeology Journal (2004) 12, 144-158.

[6] Güler, C., Thyne, G.D , McCray, J.E., Turner, A.K. 2002. Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeology Journal 10, 455-474.

[7] Lambrakis, N., Voudouris, K., Tiniakos, L., Kalergis, G. 1997. Impacts of drought and overpumping on the Quaternary aquifers of the Glafkos basin (Patras region, Greece). Environmental Geology, 29 (3/4) February 1977, pp. 209-216.

[8] Mentzafou, A., Koumantakis, J. (2005). Contribution to the hydrogeological study of Almyros basin, Magnesia. Proc. 7th Hellenic Hydrogeological Conference, 321-330.

[9] Stamatis, G., Voudouris, K. 2003. Marine and human activity influences on the groundwater quality of southern Korinthos area (Greece). Hydrological processes, 17, 2327-2345 (2003).

[10] Tsourlos, P (1995). Modelling, interpretation and inversion of multielectrode resistivity survey data. D.Phil. Thesis, University of York, U.K.

[11] Tulipano, L. 2003. Overexploitation consequences and management criteria in coastal karstic aquifers. Conf. TIAC'03, Alicante, Spain.

[12] Vasalakis, A , Voudouris, K., Fytikas, M., Dimopoulos, G. 2005. Groundwater quality in Naxos island, Cyclades, Greece. e-Proc. of the 9th Int. Conf. on Environmental Science & Technology. Rhodes.

[13] Voudouris, K., Panagopoulos, A., Koumantakis, J. 2000. Multivariate statistical analysis in the assessment of hydrochemistry of the northern Korinthia prefecture alluvial aquifer system (Peloponnese, Greece). Natural Resources Research, Vol. 9, No 2, 135-146.

[14] Voudouris, K , Mandilaras, D., Antonakos, A. 2004. Methods to define the seawater intrusion: examples from South Greece. Groundwater and saline intrusion. Selected papers from the 18th Salt Water Intrusion Meeting. Cartagena, Spain, 465-480.

[15] Voudouris, K., Panagopoulos, A., Koumantakis, J. 2004. Nitrate pollution in the coastal aquifer system of the Korinthos Prefecture (Greece). Global Nest: The International Journal, Vol. 6, No 1, pp. 31-38.

[16] Voudouris, K. 2005. The impacts of agricultural and touristic development groundwater sustainability: two examples from South Greece. Geographies, No 10, pp. 130-146 (in Greek).

[17] Voudouris, K. 2006. Groundwater Balance and Safe Yield of the coastal aquifer system in NEastern Korinthia, Greece. Applied Geography (ELSEVIER, In press).

[18] Xue, Y., Wu, J., Lui, P , Wang, J., Jiang, Q., Shi, H. 1993. Sea-water intrusion in the coastal area of the Laizhou Bay, China: 1. Distribution of seawater intrusion and its hydrochemical characteristics. Ground Water 31(4), 532-537.