THE SALINISATION OF COASTAL AQUIFERS IN GREECE; A GENERAL REVIEW

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ABSTRACT

The most significant coastal aquifers in Greece are primarily those developed in carbonate formations and, secondly, those developed in deposits of Neogene and Quaternary sediments. Carbonate formations are extensive and cover 35-40% of the country. They are distributed mainly in the central, western and southern parts of Greece and have been fractured by intense tectonic activity. These formations are karstified and hold major aquifers in most cases open to the sea. Due to physical mechanisms and anthropogenic interventions in the environment, large quantities of groundwater have deteriorated in quality due to seawater encroachment, depending on the hydrogeological and hydraulic characteristics of the aquifers. Long dry periods also contribute to the reduction of groundwater quality. The coastal aquifers most sensitive to water regime changes are karstic ones. Although this type of aquifer may provide important quantities of groundwater, as for example in mainland Greece, Peloponnesus and Crete, groundwater already degraded by physical mechanisms, encroaches inland for long distances when overexploited. If the groundwater regime is restored, groundwater quality also restores quickly. Porous aquifers are more resistant to change but in conditions of remediation, the restoration period is much longer.

INTRODUCTION

During the last decade, increased water demands for industrial, agricultural and domestic purposes have made us acknowledge that water resources of a given quality are limited. Especially in highly populated lowland and coastal areas, this problem is more evident because aquifer salinisation, due to the defective surveillance of the aquifers and appropriate management strategy has seriously limited the available water resources. Natural processes affect the groundwater quality in one large group of aquifers in Greece - the coastal karstic aquifers but lowering of the water table due to intensive pumping, in combination with prolonged dry periods have caused further deterioration in groundwater quality. It is well-known that precipitation amounts are closely related to the discharge of karstic springs and their water quality. Overexploitation and human activities have also resulted in the reduction of groundwater quantity and quality in another group of aquifers, the porous aquifers. In Crete (Messara plain), the water level decreased from 0 m to -45 m b.s.l. between 1976-1992 (Lambrakis & Daskalaki, 2000). In Thessalia, Marinos et al. (1997) found the decrease in water level to be 25 m from 1974-1994. Under these conditions, porous aquifers in coastal areas suffer from severe seawater intrusion. Seawater encroachment not only affects groundwater quality but also causes chemical changes in the aquifer matrix. Ion exchange phenomena take place as follows: Na^{+}+1/2Ca-I_2xNa-I+1/2Ca^{2+} (Appelo & Postma, 1994). According to this equation, calcium from the aquifer matrix is replaced by sodium from seawater. In cases where the aquifer is refreshened, using for example the artificial recharge method, the inverse phenomenon, the replacement of sodium with calcium of the recharge water, requires multiple and successive "rinses" of the aquifer for a very long period, relative to that needed for salinisation (Lambrakis & Kallergis, 2001).

This paper aims to contribute to a review of the seawater intrusion problem in coastal aquifers of Greece. The text starts with an introduction to the geological evolution of Greece, which explains the distribution of carbonate rocks and coarse clastic sediments. It continues with some details on the hydrogeological characteristics of karstic and porous aquifers focusing on coastal aquifers. The text ends with the presentation of four characteristic cases of coastal aquifers and conclusions.

GEOLOGICAL EVOLUTION OF GREECE: A GENERIC FRAME

The Hellenides are separated traditionally into In-ternal (Eastern Greece and Macedonia) and External zones (the rest of the country) and are interpreted as representing discrete tectonic zones, varying in age from the Palaeozoic to Tertiary periods. The zones resulted from collisions that involved subduction of the oceanic continental crust during the Africa-Eurasia convergence (e.g. Burchfiel 1980; Mountrakis 1986, 2002; Koukouvelas & Doutsos 1990; Doutsos *et al.* 1993). Some of the zones correlated with Eurasia in terms of lithology and represent micro-continental fragments. These continental fragments, prevalent in the Internal Hellenides (e.g. Rhodope zone), are separated by oceans (e.g. Vadar zone) (see also Koukouvelas & Aydin 2002). Lithologies within the Internal Hellenides are predominantly gneisses with minor marbles and post-Maastrichtian sedimentary and volcanic cover (e.g. Pelagonian zones). To the west, the External Hellenides developed on the Apulian margin. The Apulian microcontinent constituted a carbonate platform during the early Mesozoic period, which was subdivided by rifting in the late Jurassic, into deep basins and shallow ridges forming the classic isopic zones of the External Hellenides. In all isopic zones, the accumulation of carbonates is prevalent, ranging from shallow to deep-water environments in shallow ridges or deep basins respectively. To the east, the rim of the Apulian microcontinent passed through a passive continental margin known as "the Pindos zones" into the Pindos ocean which separated the External Hellenides in the west from the Internal Hellenides in the east.

The external Hellinides, having mainly carbonate composition, are extensive in western (Epirus), central (Mainland, Attic and island of Euboea) and southern Greece (Peloponnesus and island of Crete), in NW to SE orientations which is the principal stress axis of Greek orogeny. The main fault systems also follow the same trend, as do riverbeds and boundaries of larger lowland areas that were later filled with post-alpine clastics. The major coastal aquifers of Greece developed in these areas are composed of limestones and dolomites and are of Triassic to Eocene age. They are in direct hydraulic relation with the seawaters, (see figure 1) aquifers of 1) "Pantokrator", 2) "Parga", 3) "Akarnanika", 4) "Arakinthos" 5) "Ghiona", 6) "Parnassos", 7) "Eli-kon", 8) "Hymitos", 9) "Parnitha-Ag. Apostoloi", 10) "Karla", 11) "Filiatra-Gargalianoi", 12) "Tripoli-Argos", 13) "Argolis", 14) "Parnon", 15) "Leuka Ori", 16) "Psiloritis", 17) "Dikti".

Other than karstic aquifers, porous aquifers that developed in porous Neogene and Quaternary sediments also contribute to the groundwater resources of Greece. This kind of aquifer occurs in lowlands and deltas (figure 1), aquifers of: A) Delta of Evros river, B) Delta of Lissos river, C) Delta of Nestos river, D) Kessani area, E) Orfanos area, F) Axios coastal plain, G) Sperchios basin, H) Glafkos river coastal area, I) Argos palin, J) Messara plain.

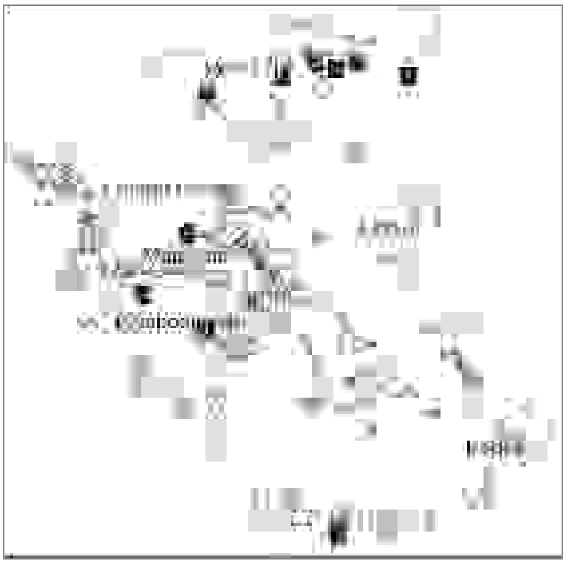

Figure 1. The main coastal aquifers of Greece (1,2,… karstic; A,B,… porous).

THE KARSTIC AQUIFERS OF GREECE

The distribution of carbonate formations is estimated to surpass 35-40% of the Greek territory. Due to the intense tectonics of these formations, the erosion process of the water has lead to the development of major karstic aquifers that constitute promising groundwater resources. For example, the estimated karstic groundwater resources are about 1000 Mm^3/y in the region of "Central Greece" which covers 25,293 km^2 (Marinos et al. 1997). Most of the karstic springs in continental Greece have a mean yield between 30 and 500 m^3/h of good water quality, while for a small number of springs the yield varies between 500 and 1000 m^3/h. There are also springs with yields of 10,000 m^3/h or more (see also Ompetsanof *et al.* 2002). These springs are encountered mainly in coastal areas where the karstic aquifer is open to the sea and the groundwater is frequently affected by seawater intrusion. Non-carbonate rocks as schists or flysch, that in many cases separate aquifer beds or play the role of the impermeable substratum, may belong to the karstic system rocks of limestone and dolomites.

The potential of storage and the possibilities of reregulation of spring depends on the base level of the karstic aquifers. In areas close to the sea, the base level due to the neotectonic and palaeogeographic evolution is below the present sea level of the area and this fact complicates the salinisation dynamic processes. Inland this evolution may impose an irregular position of the karstic base level which is ascending as the elevation of the mountains grows. Precipitation accounts for about 50% of the infiltration through these carbonate rocks. Transmissivity values range in the class of 10^{-3} and 10^{-2} m^2/s, while storativity is around 1%. However, in some cases extreme values may be encountered.

Under conditions described by Kuscer's model (1950), seawater encroachment in coastal karstic aquifers is a very common phenomenon due to the presence of deep conduits of seawater that are connected to shallower, inland, fresh water conduits at a distance from the coast. In almost all cases, brackish water springs at positive levels on the coast, coexist with brackish water springs at negative levels in the sea. In many areas coastal aquifers, such as Almyros aquifer (Crete) and Kalamos aquifer (Attica), deep conduits are localized for several meters in the sea at negative levels. Morfis (1995) refers the existence of such conduits at depths of 150 m below sea level. Monopolis (1971), Mastoris (1972) and Morfis (1995), describe that in the past in both the Parnassos-Giona and Kalamos Attica areas, brackish water springs discharged at sea level or below sea level. However, in later times, upward movements caused springs that were very close to the coast to emerge on the coast. The relatively limited area of brackish water in coastal aquifers, increased extensively when overpumping was applied due to the hydrodynamic disequilibrium between fresh and seawater. Exploitation of the Almyros aquifer (Crete) with deep bore-holes in areas of fresh water, has resulted in gradual salinisation (Monopolis, 1997).

Thus in karstic aquifers of anisotropic permeability groundwater movement is concentrated along selective pathways which ramify as water dissolves its way towards the base of karstification. Thus, the conduit splits into an upper vein and al lower one, which when below sea level allows seawater to enter the aquifer through the point of ramification. The "seawater-freshwater interface" in this case is an equilibrium plane defined by the point in its vein where the seawater pressure equals that of freshwater. The position of the equilibrium plane depends on the elevation of the hydraulic head. In recharge periods when the head is high, the equilibrium plane is low and lies below the point of ramification and the lower vein. However during dry periods when the piezometric surface is lower, the equilibrium plane is elevated and when it reaches the ramification level and the upper vein, seawater intrusion is triggered (Breznik, 1998). Under conditions of no exploitation, at high discharges the upper and lower veins operate as coastal and submarine freshwater springs respectively, but during the low discharges of the dry period, seawater enters the lower vein while the upper vein becomes a brackish spring. It is evident from the aforementioned that under exploita-tion seawater intrusion can be provoked even at high discharges if pumping allows the freshwater head to sink low enough.

In cases of coexistence of individual karstic con-duits and of an homogeneous and permeable sur-rounding environment, the mixing processes are largely affected by the shortcutting of the main per-meable mass by the conduits.

In the case of karstic aquifers of isotropic permeability salinization proceeds either due to a concentration gradient (diffusion) or is density driven. In the case of anisotropic permeability, salinization can either be density driven or attributed to hydrodynamic effects. It should be noted though that the presence of seawater in aquifers has been detected even 10 km inland under conditions of no exploitation (Breznik, 1998). In these cases saltwater entered the aquifer either at earlier geologic time under different conditions or it was assisted by large tidal waves (Burdon & Papakis, 1964). In cases of intense rainfall and abrupt rise of groundwater level, this relic seawater is flushed back towards the coast. The phenomenon might increase salinity levels in fresh-water springs or might cause discharge from previously non active springs (Breznik, 1998).

Brackish groundwater has a Na^{+}-Cl^{-} dominated water type but the portion of seawater varies into wide rates. Low values for example Gargalianoi (1%), (Panagopoulos & Lambrakis, 2001) and Argos areas (2%, Anavalos springs), (Leibundgut & Attinger, 1986) permit the groundwater exploitation. The capture of the Anavalos springs discharging at negative levels (-6 m b.s.l.) in the sea, has been accomplished by the construction of a dam that regulates the fresh water level relative to the seawater level. After the dam construction fresh water level is +0.5 m a.s.l. in the place of the springs (Leibundgut & Attinger, 1986). In the region of Epirus the coastal karstic brackish water has a chemical water type that includes Na^+ and Cl^-, but SO_4^{2-} also. This is due to the presence of evaporitic beds below the carbonate rocks that contribute to further reduction of groundwater quality (Nikolaou & Pasxos, 1999). This is also the case for other karstic aquifers in Western Greece such as those in the Akarnanika mountains. The exchange capacity in the studied aquifers is low, around 100 meq/l, and this allows rapid restoration of the water quality in a salinised aquifer due to overpumping, when natural hydrodynamic conditions are restored.

THE POROUS AQUIFERS OF GREECE

Porous aquifers are developed in Neogene formations and Quaternary deposits and are extensive in lowland and hilly areas. Neogene formations and Quaternary deposits cover the about 30% of the Greek territory. The Neogene formations generally comprise a sequence of alternate impermeable silt and marl beds and permeable beds of sandstones and conglomerates. The thickness of this formation sometimes surpasses 1000 m with a mean thickness of the (in most cases) confined aquifer beds to be 50-150 m. The mean specific capacity of boreholes is 2-3 m^3/hm. Average Transmisivity varies between 10^{-3} and $10^{-5} m^2/s$ while storativity is between 10^{-3} and 10^{-5}. The Quaternary deposits comprise a variation of gravels, sands, pebbles, silt and marl materials forming heterogeneous aquifer beds in both horizontal and vertical directions. The hydraulic characteristics of the aquifers developed in the Quaternary deposits are similar to those mentioned above. Significant differences are seen in the average total thickness of this formation which is a hundred of meters with a mean thickness of the aquifer beds of about 20% of the total. In the cases of the common responded unconfined aquifer beds, the storativity of the formation varies between 10 and 20%. The water quality of the above aquifers is characterized by an average total dissolved solids value (TDS) of 500-1000 mg/l, while in some cases the presence of evaporites (encountered mainly in the Neogene for-mations) contribute to increased TDS values that may exceed 10,000 mg/l.

Due to their location in the highly populated and cultivated lowland areas, together with their low groundwater depth, from land level the porous aquifers were first subjected to intense pumping in the 1950's. Overpumping led to seawater encroachment into the coastal porous aquifers and the subsequent deterioration of groundwater quality. Some major porous aquifers have shown a prolonged salinisation process since 1960. In the Greek islands, groundwater resources deteriorated very quickly due to seawater intrusion (Lambrakis, 1997).

Although the lowering of the water table is the main cause of salinisation in coastal aquifers, these are cases where salinisation is also due to the presence of thermal water and/or to the presence of connate fossil waters in recent sediments as in other orogenic areas of the world (Minissaqle & Duchi, 1988). Such water is common in Tertiary orogenic basins such as the Alexandroupolis, (area "A" in figure 1), Komotini-Xanthi (area "B" in figure 1), Nestos (area "C" in figure 1), Drama (area "D" in figure 1), Strymonas (area "E" in figure 1). The deep thermal waters are localised in aquifers in Neogene sediments such as conglomerates in the regions of Komotini-Xanthi (Kolios 1985), Strymonas, Drama (Karydakis and Kavouridis 1983, 1989). The faults bordering the basins played a very significant role in allowing the thermal fluids to rise from their storage zones (reservoirs) to the aquifers (Dimopoulos & Aggelidis, 1986, Andronopoulos 1967, Kolios 1985 & 1986, Dimopoulos, 1989).

The chemical water types of the salinised aquifers are Na^+ - Cl^- dominated. However, other water types are very common such as: the Ca^{2+}- Cl^- dominated water type which indicates the seawater intrusion process, namely ion exchange phenomena; the Na^+- HCO_3^- type indicating the freshening process, also exchange phenomena; and Na^+-Mg^{2+}-Cl^- -SO_4^{2-}, a mixed water type. The exchange capacity for the studied aquifers varies between 400 and 1100 meq/l. Hence, due to exchange phenomena that take place in such aquifers where the presence of clay minerals and organic carbon is the rule, not only does the groundwater quality change due to seawater intrusion, but the "quality" of the exchanger (the aquifer matrix) also changes. Although aquifer deterioration is a relatively quick process, restoration under natural recharge conditions takes hundreds or millions of years contrary to the karstic aquifers where restoration takes tens of years (Lambrakis & Kallergis, 2001).

CASE STUDIES

To provide more details on the salinisation of coastal aquifers, we present five examples taken from northern, central and southern Greece. In these examples, the different aquifers were selected to represent the two larger groups of coastal aquifers, the karstic and porous aquifers. For the porous aquifers, the first is developed in loose, deltaic deposits, while the second is in sandstone and consolidated conglomerates of Neogene formations.

The deltaic deposits of Lissos river- The coastal area of Rodope region

As reported by Petalas (1997), Petalas and Diamantis (1999), and Petalas et al. (2002), the groundwater of the system of two main successive coastal aquifers in southern Rodope (one confined and one unconfined aquifer), has been salinised by seawater encroachment due to human activities. These activities include overpumping, the alignment and confinement of the Lissos riverbed, and the construction of an artificial network of surface water drainage and the subsequent reduction of groundwater level. The very heterogeneous aquifers are developed in loose materials which for the confined aquifer comprise gravels, conglomerates, sands and silt of a large variety of grain diameter. The unconfined aquifer is developed on clay, silty sands, and coarse materials. The confined aquifer has a mean thickness of 60 m, a mean transmissivity of around 2.1 x10^{-6} m^2/s and a mean storativity of 0.001. The specific capacity of the boreholes is estimated to be around 2-2.5 $m^3/h/m$. The unconfined aquifer has a thickness that varies between several to 30 m and a specific capacity of around 0.5 $m^3/h/m$ due to the presence of the silty and clayey materials. The recharge of this aquifer system takes place directly by infiltration of rain-water, or infiltration of runoff through the riverbed in winter.

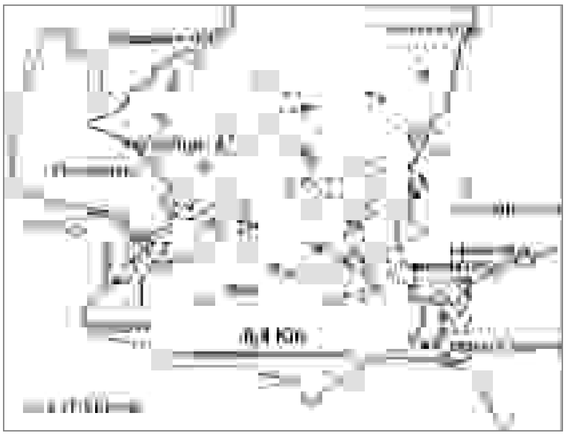

Figure 2. Distribution of Cl (mg/l) in the coastal aquifers of the Rhodope region.

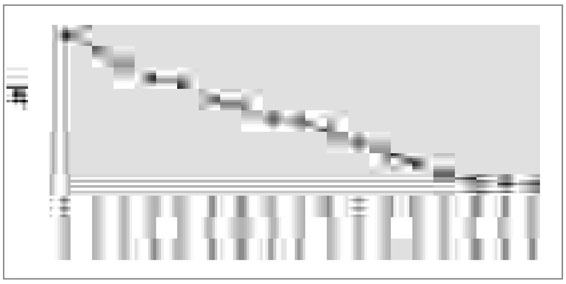

Figure 3. Maximum annual piezometric level in a coastal borehole.

In figure 2 above, the high Cl^- concentration values indicate seawater intrusion, while figure 3 shows the maximum annual absolute groundwater level in a borehole 8 km from the coast during the period 1984-2000 indicating the overpumping of the aquifers. Hydrochemical characteristics of groundwater are given in table 1.

This system was subjected to a tectonic fault of E-W, NW-SE orientation which took place during the Miocene. The echelon faults reactivated and affected the Neogene sediments generating block displacement of several to tens of meters. In the area surrounding the Kalamos springs, boreholes encountered karstic conduits at an absolute depth of 150m a.s.l. The presence of the conduits at such a depth is explained by fault blocks strongly controlled by upward and downward movements due to the extentional stress of the Quaternary period that reactivated old faults and displaced blocks in negative absolute elevations. Therefore, a substantial part of the karst network moved from positive absolute elevation, or sea level, to negative absolute elevations. Seawater mixing took place in the convergence of fresh water conduits originated from the inland and the seawater conduits. This convergence is of a small influence and is found at such a depth that given the densities of fresh and saline water, the difference of the potential between fresh and seawater remained at negative levels (Kuscer, 1950). This model has a rather general application to the Greek coastal karst. The groundwater quality is good inland. In the coastal area around the springs the water is brackish (table 2) and of Na^+-Cl^- chemical type. Seawater contribution to the quality of the spring water is about 14%.

	pH	E.C	Ca	Mg	Na	K	HCO_3^-	Cl	SO_4^{2-}	NO_3^-	PO_4^{3-}	Fe^{2+}	Zn^{2+}
Aver	7.47	1871	164	41	151	3	263	450	47	21	0.04	0.55	0.23
Min	6.70	290	13	2	11	0.5	102	7.3	6	0	0.00	0.00	0.00
Max	8.10	11000	992	351	1023	21	550	3992	293	230	1.50	16.0	5.00
St.D	0.25	1835	209	53	137	2.6	67	638	48	31.5	0.15	2.79	0.86

Table 1. The main statistical parameters of groundwater chemical composition (130 samples) in deposits of the coastal area of Ro-dope region (Petalas, 1997).

The Kalamos spring (North Attica) - coastal karstic aquifer

After Morfis (1995), the hydrogeology of northern Attica is composed of two hydrogeological systems. The first one comprises fractured and karstified carbonate rocks overlying a folded schistic substratum. The second comprises Neogene and Quaternary sediments with alternate beds of conglomerates, sandstones, marls and clays that host aquifers of a local interest. The first hydrogeological system comprises the subsystem of the Mesozoic limestone, coastal karstic aquifer of Ag. Apostoloi brackish springs. These springs have a mean yield of 2 m^3/s (figure 4).

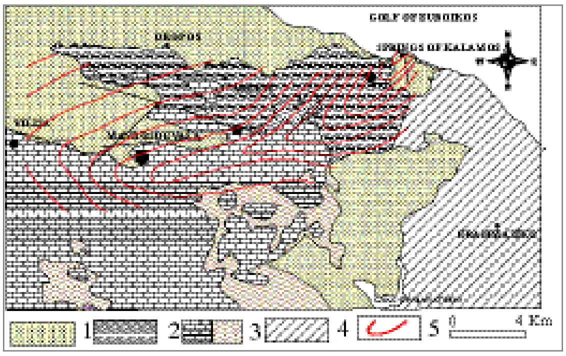

Figure 4. Hydrolithological map of Northern Attica. (Morfis, 1995). 1 Quaternary deposits, 2 Noeogene formations, 3 Mesozoic limestones, 4 Metamorhic system of Parnitha, 5 Groundwater potential distribution (November 1992).

The Almyros spring, Iraklio-Crete

The Almyros spring is located 1 km from the northern coast of Crete, near Iraklio, and is recharged through the carbonate massif of

T °C	pH	E.C	Ca	Mg	Na	K	HCO_3^-	Cl	SO_4^{2-}	NO_3^-	NO_2^-	TFe	TMn
19	7.3	7500	190	122	1214	92	330.6	2241	296	3.7	0.0	<0.07	<0.03

Table 2. Chemical composition (in mg/l) of Ag. Apostoloi coastal karstic springs.

Psiloritis mountain. The carbonate mass can be divided in two karstic systems with different characteristics. The upper karstic system is developed in the limestones of the "Tripoli unit" where groundwater circulation is shallow and rapid while the lower karstic system is developed in the "Plattenkalk" marbles and water circulation is very deep. Hydraulic connection between the two systems does occur but is limited. The spring of Almyros discharges the lower karstic system. The formed spring pool has a diameter of 60 m and receives water mainly through a karstic channel at a depth of 20 m (figure 5). The spring yields fresh water during the winter with discharges that exceed 40 m^3/s but is brackish during other seasons and particularly in summer with discharges in the order of 3-4 m^3/s and 4000-5000 mg/L of Cl^-. The increased water needs for domestic and agricultural purposes imposed the need for extensive investiga-tions that were launched in the 60s and were carried out on an on/off mode until recently.

All possibilities were considered for the development of the spring including isolation by means of grout curtain, interception of fresh water landward of the brackish zone and raising of the spring level. After integration of hydrogeological, geophysical and geochemical investigations and with the valuable aid of diving operations it was concluded by process of elimination that the most feasible and viable method of development is the raising of the spring level taking also into the account the financial aspect of the operation.

It was realized early, with some skepticism though, that a raise of the spring's level would alleviate the problem of salinization (Burdon & Papakis, 1964). A dam was built and the spring level was raised in summer of 1977 from 2 m asl to 10 m asl but with practically no impact on the salinity of 4500 mg/l of Cl^- and on the discharge of 4 m^3/s which were somewhat reduced (Breznik, 1978). During the winter-spring period of 1987, the spring level was raised again at an elevation of 10 m asl and the spring water yielded was fresh at discharges of 10-11 m^3/s but became brackish at lower discharges (Breznik, 1998).

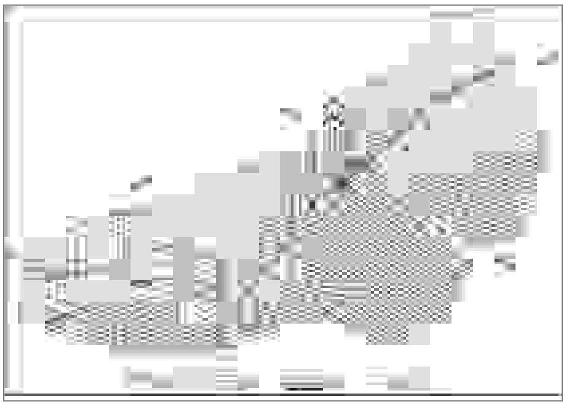

Figure 5. Schematic geologic block diagram of the area with the assumed position of the spring veins (Breznik, 1978, in Breznik, 1998).

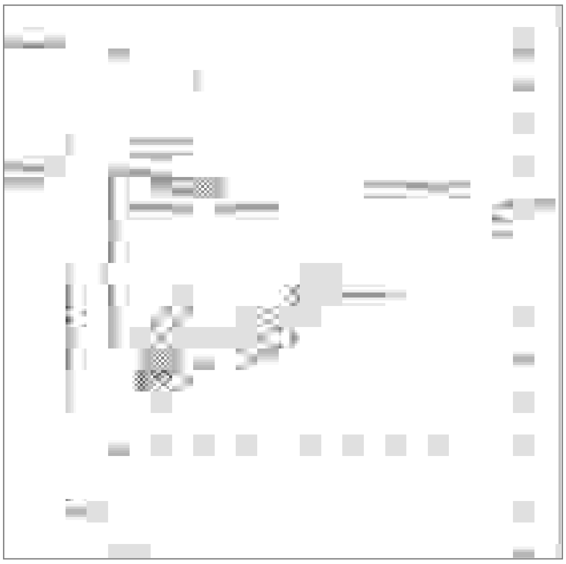

Figure 6. Cross section of the Almyros spring with the works needed for third stage of raising the spring level (Breznik, 1990, in Breznik, 1998).

It was proposed that the spring elevation should be raised 20-30 m above sea level compared to a present spring level of 3 m asl so that spring water becomes fresh (Bezes, Breznik). This would be achieved with the construction of a dam 20-30 m of height with all accompanying structures such as grout curtains, spillways etc (figure 6). The construction of the dam should proceed in stages as the exact spring level raise needed was determined with the abovementioned precision and will be further refined.

It should be mentioned that exploitation of the upper karstic system started in 1987 with withdrawals from boreholes at the Tylissos field and later the Keri and Goniano Faragi well fields were incorporated. Most of the boreholes tap the upper "Tripoli" limestones and only few reach the lower karstic system.

Intensification of pumping led to rapid water level decline and salinization of groundwater in the Tylissos field that were stabilized in the following years. The three fields are under controlled exploitation today with lower pumping rates while new well fields have been drilled and are currently exploited (total of 78 wells). Exploitation of these fields is not believed to affect the circulation of groundwater recharging the Almyros spring (Monopolis).

Figure 7. Simplified geological map of the Gouves area, Crete (Lambrakis and Kallergis, 2001). (1) Quaternary and Neogene deposits, (2) Pindos flysch of Middle – Upper Eocene, (3) Pindos Limestones of Maastrichtian-Lower Eocene, (4) Tripolis Flysch of Upper Eocene-Oligocene, (5) Tripolis Limestones and Dolomites of Upper Triassic - Upper Eocene, (6) Overthrust, (7) Fault, (8) Contour interval 100m, (9) Geological cross section, (10) Villages, (11) Chloride ion contours (October 1993, concentration in mg/l).

The Gouves aquifer

The Gouves aquifer in Crete is developed in Neogene formations that comprise a sequence of alternated beds of marls, clays, sandy-marly limestones and conglomerates that cover unconformably the carbonate rocks of the Tripolis zone (figure 5) (Lambrakis & Kallergis 2001). Quaternary formations without hydrological significance cover the Neogene sediments. The partially confined aquifer of sandy limestone and conglomerates has a mean hydraulic conductivity of 5.10^{-3} m/s, a mean storativity of 0.018 and is recharged directly by infiltration of precipitation. Depletion of these aquifers has occurred in recent years due to overpumping and a long, dry period, which caused a new piezometric regime with negative water levels. Thus, seawater encroached and groundwater quality degraded continuously (figure 7, table 3).

	pH	E.C	Ca	Mg	Na	K	HCO_3^-	Cl	SO_4^{2-}	NO_3^-
Aver	7.98	2674	84	57	407	15	263	669	122	1.0
Min	7.53	900	53	27	83	3	248	155	38	0.0
Max	8.46	4080	110	74	670	24	276	1045	190	2.0
St.D	0.39	1385	24	21	245	9	63	382	63	0.8

Table 3. The main statistical parameters of the chemical compositions of the groundwater (16 samples) of the aquifer of Gouves (Kallergis et al, 1996).

The Malia karstic aquifer, Crete

A small (30 km^2) coastal karstic aquifer occurs in Northern and Central Crete. Due to the strong natural recharge during winter, the aquifer is characterised by the presence of a low yielding coastal brackish spring and a puissant freshwater bed. The coastal karstic aquifer of Malia is developed in limestones of the Tripolis isopic zone. Under these rocks, a series of alternating chloritic schistes, phyllites and quartzites belonging to the Phyllite-Quartzite isopic zone acts as the impermeable substrate of the region. The Tripolis series consists of faulted and karstified Upper Triassic - Upper Eocene thick-bedded limestones, dolomites and calcareous dolomites. These groundwater-bearing carbonate sequences are thrusted on the abovementioned bedrock. The stratigraphy terminates with Neogene deposits that consist of bioclastic Messinian limestones and Quaternary clastic sediments hosting two aquifers of limited extent which are hydraulic communication with the underlying karstic aquifer. The whole system behaves as an heterogeneous and discontinuous aquifer system, traversing not only the Mesozoic formation but also the Neogene formation (see figure 8). The transmisivity coefficient determined from pumping tests in the aquifer varies between 0.5x10^{-1} and 1.2x10^{-3} m^2/s, while the storage coefficient reaches 2.5%.

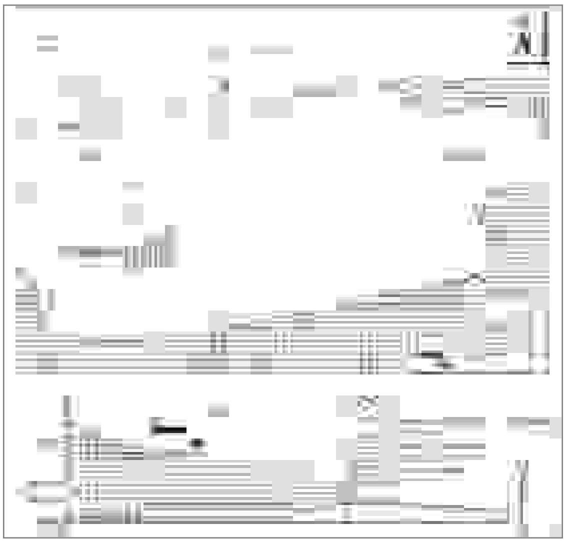

Figure 8. Simplified geological map of the Malia area, Crete (Lambrakis & Kallergis 2001). (1) Neogene and Olocene deposits, (2) Karstified limestones of the Cretaceous period, (3) Chloride ion contours (September 1994, concentration in mg/l).

Although the water balance was counterbalanced, it has been observed in recent years that rain falls in few discrete events with high intensity and short duration, resulting in higher runoff and lower recharge of the aquifer. The exploitation of the aquifer system is realized by many (over 500) shallow wells mainly in the coastal lowland due to its favorable morphology, and by fifty deeper boreholes in the high land caused by sea encroachment and groundwater quality deterioration (see figure 9 and table 4).

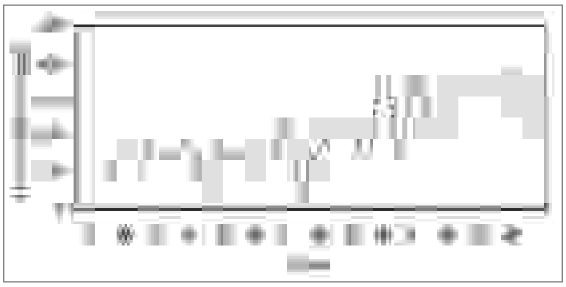

Figure 9. Chloride concentration trend in waters from lowland boreholes.

CONCLUSIONS

Due to its geology, many important aquifers are developed in the coastal areas of Greece. The majority of these aquifers are salinised by seawater encroachment due to overexploitation and physical mechanisms also, concerning the coastal karstic aquifers. Seawater encroachment is more significant in karstic aquifers than in porous ones and in cases of remediation, porous aquifers restore at very slow rates. Regarding groundwater resources, minor aquifers in the Greek island are pratically unsuitable for pumping potable water. To prevent further seawater intrusion the application of one or more appropriate groundwater management strategies and suitable restoration measures is considered urgent.

	pH	E.C	Ca	Mg	Na	K	HCO_3^-	Cl	SO_4^{2-}	NO_3^-	PO_4^{3-}	Fe^{2+}
Mean	7.18	1035	100	31.2	170	5.4	170	369	74	9.65	0.11	0.017
Min	6.45	290	39	0.24	12	0.7	136	22	0.0	3.54	0.0	0.00
Max	7.78	5000	351	232	1200	29	253	2180	390	39.0	2.6	0.19
St.D	0.22	1100	72	45	27	8.12	32	521	94	6.97	0.5	0.042

Table 4. The main statistical parameters of groundwater chemical composition (twenty samples) in the karstic aquifer of Malia (Lambrakis, 1998).

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