STATUS AND CODIFICATION OF KARST AQUIFER SYSTEMS IN GREECE

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Abstract

Karst groundwater is an important natural resource for the water supply. The karst aquifer systems of Greece are developed within carbonate sedimentary (limestone, dolomite) and metamorphic rocks (marbles) and contribute significantly to water supply for domestic and irrigation use. They are discharged through springs: submarine, coastal brackish and inland freshwater springs. This review presents the general characteristics of karst aquifers focusing on hydraulic properties. Evaluation of the results shows that the hydraulic parameters of the karstic aquifer systems range within a large scale of values depending on karstification, tectonics and stratigraphy. High values of transmissivity and specific capacity are recorded in the upper stratigraphically levels of the karstic aquifer systems. In addition, a total of 229 different karst systems were classified according to five criteria: 1) Lithology, 2) Position, 3) Quality status, 4) Exploitation and quantitative status and 5) Discharge of springs. The majority (80%) of karst systems is developed in sedimentary rocks (limestones) and is of good water quality and quantitative status. Poor water quality status is recorded in coastal karst aquifers (mainly on islands) due to seawater intrusion phenomena. Finally, this work summarizes the characteristics of the karst aquifers in Greece in order to ensure the sustainable management of groundwater resources.

Keywords: carbonate rocks; groundwater; karst aquifers; salinity; springs
Περίληψη

Τα καρστικά νερά είναι ένας σημαντικός φυσικός πόρος για την προμήθεια νερού. Τα καρστικά υδροφόρα συστήματα της Ελλάδας αναπτύσσονται εντός ανθρακικών ιζημάτων (ασβεστόλιθοι, δολομίτες) και μεταμορφωμένων πετρωμάτων (μάρμαρα) και συμβάλλουν σημαντικά στην προμήθεια νερού για οικιακή και αρδευτική χρήση. Εκφορτίζονται μέσω υποθαλάσσιων, παράκτιων υφάλμυρων και εσωτερικών πηγών γλυκού νερού. Στην παρούσα εργασία παρουσιάζονται τα γενικά χαρακτηριστικά των καρστικών υδροφορέων, εστιάζοντας στις υδραυλικές ιδιότητες. Από την αξιολόγηση των αποτελεσμάτων προκύπτει ότι οι υδραυλικές παράμετροι των καρστικών υδροφορέων κυμαίνονται μεταξύ μεγάλου εύρους τιμών, ανάλογα με την καρστικοποίηση, την τεκτονική και τη στρωματογραφία. Υψηλές τιμές της μεταβιβαστικότητας και της ειδικής ικανότητας καταγράφονται στα ανώτερα στρωματογραφικά επίπεδα των καρστικών υδροφορέων. Επιπλέον, τα 229 διαφορετικά καρστικά υδροφόρα της Ελλάδας συστήματα ταξινομήθηκαν και κωδικοποιήθηκαν σύμφωνα με πέντε κριτήρια: 1) Λιθολογία, 2) Θέση, 3) Ποιοτική κατάσταση, 4) Εκμετάλλευση και ποσοτική κατάσταση, και 5) Παροχή των πηγών. Η πλειονότητα (80%) των καρστικών συστημάτων αναπτύσσονται σε ιζηματογενή πετρώματα (ασβεστόλιθοι), έχει καλή ποιότητα νερού και χαρακτηρίζονται από καλή ποσοτική κατάσταση. Κατά ποιοτική κατάσταση καταγράφεται στους παράκτιους καρστικούς υδροφορείς (κυρίως στα νησιά), λόγω διείσδυσης θαλασσινού νερού. Τέλος, η εργασία αυτή συνοψίζει τα χαρακτηριστικά των καρστικών υδροφορέων στην Ελλάδα προκείμενου να διασφαλιστεί η βιώσιμη διαχείριση των υπόγειων υδατικών πόρων.

Λέξεις-κλειδιά: ανθρακικά πετρώματα; υπόγεια νερά; καρστικοί υδροφορείς; αλατότητα; πηγές

1. INTRODUCTION

Karst aquifers, developed within carbonate rocks, supply drinking water to approximately 10% of the world’s population (Goldscheider et al., 2020). Carbonate rocks are extensively outcropped in all Mediterranean countries and the karst groundwater has been an essential resource since the establishment of civilization in these countries (Bacalowicz, 2015). Furthermore, karst water supports unique ecosystems, which are rich in biodiversity (Andreo, 2012). Karst water storage and flow occur in three distinct media: rock matrix, fractures, and conduits, governed by radically different flow regimes (Auler & Stevanovic, 2021). In general, karst aquifers...
have a heterogeneous structure and are characterized by the concentration of groundwater flow through a network of conduits (Andreou, 2012). Karstic areas are characterized by the shortage of surface water and lack of perennial streams, except during extreme rainfall events. The epikarst ("skin" of karst, below the soil zone and high permeability karstified zone) is an important component of the recharge and generally of the hydrogeology of karst (Bacalowicz, 2004).

The hydrogeological behaviour of carbonate rocks is controlled by tectonic deformation, which favors infiltration and karstification. Besides, karst aquifers are very vulnerable to external pollution due to their high permeability (Polemio, 2016), as well as to climate change (Stevanovic et al., 2021). The karst features in Mediterranean countries were determined by the following three factors (Bacalowicz, 2015): 1) the Messinian salinity crisis causing karstification in great depths below the present sea level, 2) the cold periods during the Quaternary that caused weathering of the epikarst, and 3) post-Miocene tectonics that created horst and graben structures causing sedimentation and filling of large basins.

Karst in Greece presents specific characteristics compared to other Mediterranean karst, because a large part of Greece territory emerged recently e.g. after Middle Miocene-Pliocene, affected by neotectonic activity. Therefore, a significant part of carbonate formations was not suffered by Jurassic or Cretaceous karstification phases, as in many other regions. The outcrops of carbonate rocks in Greece cover an area of 35.3x10^3 km², representing a percentage of 27.1% of the total area (approximately 132,000 km²) (Chen et al., 2017). Carbonate sedimentary rocks (limestones, dolomites) in Greece mainly date from the Triassic to the Lower Miocene, whereas marbles are of Paleozoic-Eocene age (Mountrakis, 1985). Both are well karstified, forming excellent aquifer systems with commonly high yield boreholes and large storage capacity (Soulios, 1985). The Messinian crisis of salinity had as result the development of karst phenomena below the present sea level and produced the most original features of karst in Greece (Bacalowicz, 2015). Carbonate rocks are well karстifiable, due to intensive tectonic deformation, altitude, morphology, climatic conditions, etc. providing significant hydraulic heads at different levels. This has led to the development of very complex karst massifs. Karstification is reflected in karst springs, sinkholes and caves, and quickly decreases with depth (Voudouris, 2003). Thousands of caves have been recorded in Greece; some of them are impressive. The majority of karst aquifers in Greece has a holokarst type shape (Soulios, 1985). The karst aquifers discharge through springs or set of springs that are submarine, coastal brackish, inland freshwater, and thermal springs due to the volcanic activity and
Tectonic structure of Greece. The freshwater springs contribute to the drinking water supplies of many cities in Greece (Kavala, Drama, Korinthos, Xanthi, etc.). Also, in some basins springwater covers the irrigation demands.

The systematic modern hydrogeological study of karst in Greece started after the end of the second world war and civil war in the 1950s. In the 1960s, the first PhD Thesis was published by Mastoris (1968). During the next decades the number of published papers has been rapidly increased. Koumantakis (1993) reports 205 titles of papers and studies during the period 1950-1991. The Hellenic Survey of Geology and Mineral Exploration (HSGME, former IGME) conducted numerous studies for the investigation of karst aquifers including boreholes drilling, pumping tests and discharge measurements of karst springs. In recent years, many papers and doctoral dissertations concerning the Greek karst have been continuously published by Greek and foreign researchers. It is must be pointed out that references about hydrogeological phenomena can also be found in ancient Greek philosophers (Aristotle, Thales, Plato, etc.) or in Greek mythology (Angelakis et al., 2016). Furthermore, the Minoans developed advanced hydro-technologies, including groundwater wells and exploitation of springs in Crete since the early 2nd millennium BC.

The aim of this study is to determine the general characteristics and classify the different types of karst aquifers in Greece according to lithology, position, water quality status, exploitation conditions, and springs discharge. For this purpose, 229 karst systems of Greece codified by the Ministry of the Environment and Energy were collected, digitized, and classified.

2. STUDY AREA DESCRIPTION

Greece is located within an active plate margin where the African plate is subducted below the European plate. The spatial distribution of carbonate rocks in Greece is shown in Figure 1. Carbonate rocks and karst aquifers are more abundant in the central and western part of Greece, as well as the island of Crete. Geologically, Greece is divided into a number of geotectonic units (Fig. 2): Rhodope massif, Serbomacedonian, Circum Rhodope, Peonias, Paikou, Almopias, Pelagonian, Attico-Cycladic, Sub-Pelagonian, Parnassos-Giona, Pindos-Olono, Tripolis-Gavrovo, Ionian, Paxos, and Plattenkalk-Talea Ori (Mountrakis, 1985; Papanikolaou, 2013).
Fig. 1: Left: Map of Greece, Right: spatial distribution of carbonate rocks (black colour) (Mandilaras et al., 2006; Soulios, 1985 with modifications).

Fig. 2: Geotectonic zones of Greece (Mountrakis, 1985). Explanation: Rh=Rhodope Massif, Sm=Serbomacedonian, CR=Circum Rhodope, Pe=Peonias, Pa=Paikou, Al=Almopias, PI=Pelagonian, AC=Attico-Cycladic, Sp=Sub-Pelagonian, Pk=Parnassos-Giona, P=Pindos-Olonos, G=Tripolis-Gavrovo, I=Ionian, Px=Paxos, Au=Plattenkalk-Talea Ori.
The climate of Greece is mild with warm summers. Rainfall decreases eastwards. The mean annual rainfall is strongly correlated with the altitude increasing by 60 mm per 100 m of ground elevation. Western Greece gets the majority of rainfall, more than 1500 mm/year, while Eastern Greece has lower rainfall depth (400-500 mm/year) (Mimikou, 2005). Rainfall occurs mainly during the wet period, from early October to April. In the wet season rainfall peaks in November and December. The driest months are July and August. The karst aquifer systems of Greece are developed within carbonate rocks: sedimentary (limestones, dolomites) and metamorphic rocks (marbles). These rocks range in age from Carboniferous to Eocene (Kallioras & Marinos, 2015). Limestones mainly date from the Triassic to Lower Miocene (Fig. 3). The marbles have a Palaeozoic-Eocene age. In some areas e.g., in Crete, aquifer systems are developed in the Neogene deposits consisting of marly limestones and bioclastic limestones. These limestones are characterized by increased secondary porosity and have major hydrogeological significance (Voudouris, 2003).

![Classification of karst aquifer systems in Greece based on their age (Kallioras & Marinos 2015).](image)

**Fig. 3:** Classification of karst aquifer systems in Greece based on their age (Kallioras & Marinos 2015).
The karstification of Greek karst can be distinguished into three stages (Katsanou & Lambrakis, 2017): 1) Upper Cretaceous to Upper Miocene/Early Pliocene period with warm and humid conditions (karstification of palaeokarst), 2) Mid-glacial to the mid Pliocene/Holocene period where younger karst developed under warmer conditions with higher humidity than the recent ones, and 3) the late karstification stage that occurred under recent climatic conditions forming the younger karst. The existing karst of Greece was mostly formed during the second stage and is characterised as mature and features like dolines, poljes, caves are abundant (Lambrakis, 2017). Existing literature and previous researches suggest that karst structures extent at depth of hundred meters below the present sea level (Bacalowicz, 2015).

3. DATA COLLECTION AND ANALYSIS

Pumping test data were provided by HSGME (former IGME), Ministry of Agriculture, the author and by other organizations (Mandilaras, 1997). Constant rate and step drawdown pumping tests were used to determine transmissivity (T), hydraulic conductivity (k) and storage coefficient (S), applying Theis, Jacob and recovery methods (Batu, 1998; Todd, 1980).

Data provided by the Ministry of Environment and Energy were also used for the quality and exploitation status of the karst aquifers systems. For the classification data from 229 distinct karst aquifers codified by the Ministry of the Environment and Energy were used (http://www.ypeka.gr, accessed 10 November 2019; now https://ypen.gov.gr/). Firstly, the karst aquifers were digitized and their borders are shown in maps of Figures 8 and 9. Secondly, existing data for each karst system were collected and finally all the systems are classified according to the proposed criteria (see section 5).

4. RESULTS

4.1. Recharge

Karst aquifers are mainly recharged by the direct infiltration of rainfall and snowfall. The percentage of rainfall which infiltrates through the carbonate rocks (coefficient of infiltration) ranges between 40-55% of the annual precipitation (Soulios, 1985). The annual water volume (Q) can be estimated using the formula: \[ Q = P \cdot A \cdot I_c \], where: \( P \) = annual precipitation (mm), \( A \) = karstic surface area (km\(^2\)), \( I_c \) = coefficient of infiltration (%).
In addition, karst systems are recharged by surface runoff from non-karstic geological formations. A representative example is the case of Aggitis karst system developed in the marbles of the Rhodope massif (NE Greece). It has an allogenic recharge by surface waters through sinkhole from a polje 9 km away, in Nevrokopi plain (Novel et al., 2007).

4.2. Hydraulic parameters

Karst systems are highly dynamic and heterogeneous with complex hydrological and hydrogeochemical processes and flow regimes ranging from laminar to turbulent flow (Milanovic, 2018). The hydraulic parameters calculated by pumping test analyses are shown in Table 1. The karst aquifers show inhomogeneity, anisotropy and variable permeability (Worthington, 2021). The hydraulic parameters range within a large scale of values, depending on karstification, stratigraphy faulting and folding (Mandilaras et al., 2006; Voudouris, 2015). Generally, the permeability of Greek karst systems is medium to high. Based on pumping test analyses it is concluded that, high values of transmissivity are recorded in the upper stratigraphic levels of the karstic aquifers, due to the intense karstification (Soulios, 1985; Mandilaras et al., 2006; Kallioras & Marinos, 2015).

The depth of the aquifers varies according to the depth of the “base level”, usually impermeable substrate either the sea level in coastal zones or the bottom of river valleys or plains. The karst springs represent the lowest elevation defined as base level (Milanovic, 2018). The karstification decreases with depth, e.g., karstic process was not developed at the level of the tunnel of the karstic mountain of Giona under a maximum cover of 1700 m (Voudouris et al., 2016). The deepest borehole in carbonate rocks, cutting karst features, has been drilled on the island of Crete (limestones of Plattenkalk-Talea unit) at a depth of about 625 m below earth surface (Voudouris, 2003; Bouloukakis & Voudouris, 1997). Data form Dinaric karst shows that the permeability at 300 m below the ground surface is only about one-tenth of that at 100 m and one-thirtieth of that of 10 m (Ford & Williams, 1989; Milanovic, 2018).

The hydraulic conductivity ranges between $10^{-2}$ m/s and $10^{-6}$ m/s and transmissivity values range between $1.4 \times 10^{-4}$ and $8.3 \times 10^{-2}$ m$^2$/s. High values of transmissivity and specific capacity are recorded in the upper karstic aquifer systems of the geotectonic
zones, due to the intense karstification. The highest transmissivity values \( (9 \times 10^{-2} \text{ m}^2/\text{s}) \) correspond to boreholes drilled along the faulted zone. The yield of boreholes drilled in karst aquifers has a wide range of values, e.g., \( 4 \times 10^{-3} \text{ m}^3/\text{s} \) to \( 9.7 \times 10^{-2} \text{ m}^3/\text{s} \) (Mandilaras et al., 2006). The average transmissivity \( (T) \) correlates strongly with the specific capacity \( (Q/d) \), which is defined as the ratio of discharge \( (Q) \) to drawdown \( (d) \) at the pumping borehole for a given time (Mandilaras, 1997). The obtained equation from the simple regression between \( T \) and \( Q/d \) is:

\[
T = 0.94 \times (Q/d) + 53.7 \quad (r=0.68)
\]

Table 1. Hydraulic parameters (mean values) of karst aquifers in geotectonic zones of Greece (Mandilaras et al., 2006; Mandilaras, 1997).

| Geotectonic zone        | Pumping tests number | \( Q_{\text{max}} \) (m\(^3\)/s) | \( Q/d \) (m\(^2\)/s) | \( T \) (m\(^2\)/s) | \( k \) (m/s) | \( S \) (%) |
|-------------------------|----------------------|-------------------------------|------------------|----------------|----------|----------|
| Pelagonian              | 13                   | 0.074                         | 0.056            | 0.090          | 0.002    | 1.96     |
| Attic-Cycladic          | 7                    | 0.033                         | 0.072            | 0.036          | 0.003    | 6.41     |
| Sub-Pelagonian          | 85                   | 0.087                         | 0.065            | 0.075          | 0.002    | 5.62     |
| Parnassos-Giona         | 15                   | 0.011                         | 0.013            | 0.012          | 0.000    | 9.57     |
| Pindos-Olonos           | 52                   | 0.048                         | 0.040            | 0.046          | 0.001    | 4.85     |
| Tripolis- Gavrovo       | 35                   | 0.051                         | 0.029            | 0.056          | 0.002    | 4.58     |
| Ionian                  | 5                    | 0.044                         | 0.029            | 0.015          | 0.002    | 7.58     |
| Plattenkalk unit        | 13                   | 0.013                         | 0.020            | 0.009          | 0.001    | 4.23     |
| Paxos                   | 23                   | 0.015                         | 0.024            | 0.026          | 0.001    | 2.18     |

The effective porosity ranges between 0.5\% and 3\%, decreasing with the depth (Soulios, 1985; Voudouris, 2015). According to the international bibliography, the effective porosity is always less than 3\% (Milanovic, 2018). Based on tracing tests applied in Greece, groundwater velocity in karstic aquifers ranges between \( 7.8 \times 10^3 \) and \( 7.2 \times 10^2 \) m/s with a maximum value of \( 0.24-0.27 \) m/s in Aggitis system developed in the karstified marbles (Soulios, 1985). A tracing test using eosin was conducted in karstified carbonate rocks of Crete Island during 2002. The results indicated that the water velocity between sinkhole Chonos (Lasithi Plateau) and springs/boreholes (at distance of 2.8 - 11.2 km) ranges from \( 9 \times 10^{-3} \) to \( 6 \times 10^{-2} \) m/s (Kikili-Polychronaki et al., 2003). White (2007) using data from 2877 tracer tests between sinkholes and springs from around the world suggest that the distribution of velocities is log-normal; the values of the highest frequency range from \( 10^{-2} \) m/s to \( 10^{-1} \) m/s with maximum values of 0.8 m/s. The hydraulic gradient in karst aquifers has greater values than in porous aquifers, ranging within 0.5\% - 2\% (Voudouris, 2015). Flow within karst aquifers is Darcian or turbulent, depending upon the fracture and conduit permeability (Todd, 1985; White, 2007).
4.3. Groundwater Quality

The main hydrochemical type of karst groundwater in Greece is calcium-bicarbonate (Ca-HCO₃) for the karst systems unaffected by seawater intrusion and sodium-chloride type (Na-Cl) for the coastal karst aquifers affected by seawater intrusion. High concentrations of Cl⁻ in karst aquifers were recorded at a distance of 15 km from the coastline along faulting zone (Voudouris, 2015). The concentrations of ions do not show variability in inland freshwater springs, unaffected by seawater intrusion, whereas the coastal springs are characterized by significant variability between wet and dry periods. For example, the Cl⁻ concentration in Almyros karst spring (Crete island) is very low (<50 mg/L) in wet period at high discharges and very high during the dry period at low discharges (6,000 mg/L). Chloride concentration versus discharge in Almyros spring is shown in Figure 4 (Voudouris et al., 2016). The presence of open conduits at different depths below sea level favors seawater intrusion processes. It must be noted that the karst aquifers are highly vulnerable to external pollution from surface anthropogenic activities due to the quick infiltration of the water (Kazakis et al., 2015; Kavouri et al., 2016). Several different methods for karst aquifer vulnerability assessment and mapping exist (Kavouri et al., 2011; Polemio, 2016). Until now, eight (8) main karst groundwater vulnerability mapping methods have been used: EPIK, REKS, RISKE, RISKE 2, PI, Slovene approach, KARSTIC, and COP & COP+K method (Fidelibus, 2017; Nanou & Zagana, 2018).

![Fig. 4: Chloride concentration versus discharge in Almyros karst spring (Voudouris et al., 2010).](image-url)
4.4. Karstic springs

The mean annual discharge of karst springs ranges between 0.14 and 0.28 m$^3$/s. It must be pointed out that in many parts, the limestones are in contact with the sea and the karst aquifers often discharge groundwater through large submarine springs with brackish water (Athanasiadou et al., 2020). In many areas of Greece (e.g. Crete) the brackish water springs are called “almyros”, which means salty. The seawater intrusion is increased by pumping in coastal areas and has been favored by some preferential paths along faulting zones. Arfib et al. (2007) suggests that the Almyros karst spring in Crete Island discharges brackish water because of seawater intrusion phenomena occurring at depth of 600 m below sea level.

The discharge of springs strongly depends on atmospheric precipitation (rainfall, snowfall). During storms, some of them become muddy. The hydrograph of a spring (discharge versus time) is used to characterize the karst system, which feeds the spring. A representative hydrograph is shown in Figure 5. The recession curve is used to calculate the coefficient of recession ($a$) and the volume of the dynamic storage, i.e. the volume of groundwater which is renewable yearly. The parameter ($a$) is a function of the aquifer transmissivity ($T$), storage coefficient ($S$) and the catchment geometry. Values between $10^{-2}$ and $10^{-1}$ days$^{-1}$ indicate water flow dominant in conduits, whereas values between $10^{-4}$ and $10^{-3}$ days$^{-1}$ indicate water flow dominant in fractures. Characteristic values of coefficient $a$ (days$^{-1}$), according to Maillet analysis, are (Soulios, 1985; 1992): 1) Kanaki spring in marbles of Pageon Mountain: $a = 6.2 \times 10^{-3}$, 2) Sakova spring in Symvolo Mountain: $a = 4.1 \times 10^{-2}$, 3) Militsa spring, Kastoria: $a = 5.5 \times 10^{-3}$, 4) Stymphalia spring, Kyllini Mountain: $a = 2.4 \times 10^{-2}$, 5) Paradosos spring, Xanthi: $a = 3.6 \times 10^{-3}$, 6) Maara spring, Aggitis karst system, Drama: $a = 3 \times 10^{-3} - 6 \times 10^{-3}$, 7) Louros basin karstic springs: $a = 1.5 \times 10^{-3} - 1.2 \times 10^{-2}$, 8) Agios Nikolaos Naousa: $a = 2.4 \times 10^{-3}$, 9) Almyros Agios Nikolaos, Crete Island: $a = 1.7 \times 10^{-3}$, 10) Almyros Heraklion, Crete Island: $a = 10^{-3}$. 
5. CLASSIFICATION OF KARSTIC SYSTEMS

Mangin (1975) introduced a semi-quantitative classification of karst systems based on hydrodynamic behavior. He suggested two parameters: 1) regulation power, defined as the ratio between dynamic volume and spring discharge, and 2) infiltration delay. Dynamic volume is the volume of water in storage in the saturated zone above the level of outflow spring (Kovacs, 2021). Infiltration delay is the time lag between recharge and discharge of spring. Later, another one attempt to characterize the karst aquifers was presented in Todd (1980). Todd tried to analyze the springs discharge time series. In addition, the discharges of selected springs were plotted using appropriate diagrams and classified according to their magnitude. Hobbs & Smart (1986) suggested a qualitative classification of carbonate aquifers based on three parameters: 1) recharge, 2) storage, and 3) transmission. Kovacs (2021) proposed a quantitative classification of carbonate hydrogeological systems based on hydrodynamic behavior (spring hydrograph analysis, baseflow recession, analytical solutions, etc.).

In the frame of the World Karst Aquifer Map (WOKAM) project a procedure was applied for karst mapping (Chen et al., 2017). This procedure includes generalization, differentiation of continuous and discontinuous carbonate rocks and the identification of non-exposed karst aquifers. The continuous carbonate rocks cover an area of 30,000 km² and the discontinuous carbonate rocks 23,400 km². From this work it is concluded that the actual carbonate outcrops are 27.1% of the total area of Greece.
Calaforra et al. (2004) and Tulipano et al. (2004) proposed a graphical approach in order to classify the karstic coastal aquifers in Mediterranean Sea (Figure 6). They used a semicircle graph which is divided in four sectors corresponding to four variables: 1) permeability, 2) structure, 3) salt water intrusion, and 4) exploitation. Based on the aforementioned approach, the main karstic coastal aquifers of Greece are characterized by medium to high permeability discharging through submarine springs with moderate exploitation and variable-seasonal to moderate-high salt water intrusion (Fig. 7). The overexploitation of coastal aquifers always produces a lowering of the freshwater levels, contributing to seawater intrusion processes.

Fig. 6: Graph for classification of a coastal karst aquifer (Calaforra et al., 2004).
The previous classification presents a small number (19) of coastal karst aquifers in Greece where there is available data. In this review, a classification and codification of the karst aquifers is proposed. Therefore, this is a first attempt to classify all the karst systems of Greece.

Firstly, all the karst aquifers reported and codified in the Implementation of the Water Framework Directive of the Special Secretariat for Water (Ministry of Environment & Energy) are presented. The delimitation of aquifers was based on outcrop extension, grouping of coherent units (e.g., limestones of Vigla, Pantokratoras and limestones of Senonian age in Ionian tectonic unit), and the discharge through springs. In the case of mixed aquifer systems, (e.g., karstic aquifer and aquifer of fissured rocks), the characterization was based on the dominant type of the aquifer.

The classification is based on the following five /criteria:
1) Lithology, \textbf{L}
2) Position, \textbf{P}
3) Quality status, Q
4) Exploitation and quantitative status, E
5) Spring discharge, S.

According to the lithology criterion, the karst aquifers of Greece are classified as sedimentary (limestones, dolomites) and marbles. Although both types of aquifers have similar behavior, it was necessary to distinguish them in two categories due to different age, structure, etc.

The position considers the geographical site of the aquifer related to the coastline; inland or coastal. This criterion was chosen because the coastal aquifers are generally under considerable pressures (urbanization, tourism development, etc.) in contrast to the interior aquifers.

Karstwater quality mainly relates to the salinization status and the karst aquifers can be grouped into two classes: affected and not affected by seawater intrusion. It is pointed out that Greece has a coastline of 13,680 km along the Mediterranean Sea and many islands. This creates conditions of hydraulic communication between coastal karst aquifers and seawater, named open karst. As mentioned above the karst aquifers covers water demands for irrigation and domestic use. The criterion of exploitation represents the quantity of abstractions in relation with the recharge. For this purpose, the quantitative status can be classified as over- and under-exploitation. Data provided by the Ministry of Environment and Energy were also used for the quality and exploitation status of the aquifer systems, according to the Water Framework Directive 2000/60 of European Commission.

The classification of springs includes three types of springs: 1) high mean annual discharge greater than 3 m³/s, 2) moderate mean annual discharge 1-3 m³/s, and 3) low mean annual discharge <1 m³/s. In the absence of accurate measurements of springflow, the characterization was based on the assumed recharge area of the karst system feeding the spring and annual rainfall.

The subcategories are shown in Table 2 and the main karstic systems of Greece are shown in Table 3 and Figures 8, 9.
Table 2. Factors for classification of karst aquifers in Greece.

| Factor                        | Symbol | Subcategories                                      |
|-------------------------------|--------|----------------------------------------------------|
| 1 Lithology                   | L      | Ls: sedimentary rocks (limestones, dolomites)      |
|                               |        | Lm: marbles                                        |
| 2 Position                    | P      | Pi: inland                                         |
|                               |        | Pc: coastal                                        |
| 3 Quality status              | Q      | Qg: good quality                                   |
|                               |        | Qp: poor quality, unsuitable for drinking purpose  |
| 4 Exploitation and            | E      | Eu: under-exploitation, good quantitative status    |
| quantitative status           |        | Eo: over-exploitation, poor quantitative status     |
| 5 Discharge of spring         | S      | Sb: discharge of spring >3 m$^3$/s                  |
|                               |        | Sm: discharge 1-3 m$^3$/s                          |
|                               |        | Ss: discharge of spring < 1 m$^3$/s                |

Table 3. The main karstic systems of Greece, as codified by the Ministry of Environment & Energy.

| S.N | Region     | Code       | Name                | Qualitative status | Quantitative status | Type                   |
|-----|------------|------------|---------------------|--------------------|---------------------|------------------------|
| 1   | Thrace     | GR1200070  | Lekani Mountain     | Good               | Good                | LmPiQgEuSb             |
| 2   | Thrace     | GR1200080  | Thasos              | Good               | Good                | LmPiQgEuSs             |
| 3   | Thrace     | GR1200030  | Makris              | Good               | Good                | LmPiQgEuSs             |
| 4   | East Macedon | GR110B020 | Aggistro            | Good               | Good                | LmPiQgEuSb             |
| 5   | East Macedon | GR110B030 | Menikio-Falakro     | Good               | Good                | LmPiQgEuSb             |
| 6   | East Macedon | GR1100040 | Aggitis             | Good               | Good                | LmPiQgEuSb             |
| 7   | East Macedon | GR1100060 | Pageo Mountain      | Good               | Good                | LmPiQgEuSs             |
| 8   | Central Macedon | GR1000020 | Paiko               | Good               | Good                | LmPiQgEuSb             |
| 9   | Central Macedon | GR1000210 | Gallikos            | Good               | Good                | LmPiQgEuSs             |
| 10  | Central Macedon | GR1000270 | Vafiochori          | Good               | Good                | LmPiQgEuSs             |
| 11  | Central Macedon | GR100F280 | Sterna              | Good               | Good                | LmPiQgEuSs             |
| 12  | Central Macedon | GR1000220 | Deve Koran          | Good               | Good                | LmPiQgEuSb             |
| 13  | West Macedon | GR09AF012  | Prespes             | Good               | Good                | LmPiQgEuSb             |
| 14  | West Macedon | GR09AF015  | Aposkepos           | Good               | Good                | LmPiQgEuSs             |
| 15  | West Macedon | GR0900071  | Vermio-Askio        | Good               | Good                | LmPiQgEuSs             |
| 16  | West Macedon | GR0900075  | Lefkopigi           | Good               | Good                | LmPiQgEuSb             |
| 17  | West Macedon | GR0900081  | West Vermio         | Good               | Good                | LmPiQgEuSb             |
| 18  | West Macedon | GR0900142  | Litochoro           | Good               | Good                | LmPiQgEuSb             |
| 19  | West Macedon | GR09000220 | Korissos            | Good               | Good                | LmPiQgEuSb             |
| 20  | Epirus     | GR0500010  | South Kerkrya       | Good               | Good                | LmPiQgEuSm             |
| 21  | Epirus     | GR0500040  | Paxi                | Good               | Good                | LmPiQgEuSs             |
| 22  | Epirus     | GR0500050  | Othoni              | Good               | Good                | LmPiQgEuSs             |
| 23  | Epirus     | GR050A060  | Mourgana            | Good               | Good                | LmPiQgEuSs             |
| 24  | Epirus     | GR050A070  | Filipates           | Good               | Good                | LmPiQgEuSs             |
| 25  | Epirus     | GR0500080  | Kalamáta            | Good               | Good                | LmPiQgEuSb             |
| 26  | Epirus     | GR0500090  | Souli-Paranáthia    | Good               | Good                | LmPiQgEuSm             |
| 27  | Epirus     | GR0500100  | Tymfrí-Aoos         | Good               | Good                | LmPiQgEuSb             |
| 28  | Epirus     | GR0500110  | Klimatía-Kaláma     | Good               | Good                | LmPiQgEuSm             |
| 29  | Epirus     | GR0500120  | Kássándri-Kaláma    | Good               | Good                | LmPiQgEuSm             |
| 30  | Epirus     | GR0500130  | Koróni              | Good               | Good                | LmPiQgEuSm             |
| 31  | Epirus     | GR0500150  | Lourou              | Good               | Good                | LmPiQgEuSb             |
| 32  | Epirus     | GR0500170  | Parga               | Good               | Good                | LmPiQgEuSb             |
| 33  | Epirus     | GR0500180  | Mitsikéli-Vela      | Good               | Good                | LmPiQgEuSb             |
| 34  | Epirus     | GR050A190  | Pogoníani           | Good               | Good                | LmPiQgEuSb             |
| 35  | Epirus     | GR0500210  | Kourénton           | Good               | Good                | LmPiQgEuSm             |
| Page | GR050250 | Zalogou | Good | Good | LsPcQgEuSm |
|------|----------|---------|------|------|-------------|
| 36   | GR080010 | Koziaka | Good | Good | LmPiQgEuSm |
| 37   | GR080020 | Paleosamaria | Good | Good | LsPcQgEuSs |
| 38   | GR080050 | Krania-Elassona | Good | Good | LmPiQgEuSm |
| 39   | GR080070 | Damasi-Titanos | Good | Good | LmPiQgEuSm |
| 40   | GR080080 | Fylliou-Orfanon | Good | Poor | LmPiQgEuSm |
| 41   | GR080100 | Ekkaras- Velesiotion | Good | Poor | LmPiQgEuSm |
| 42   | GR080120 | Olympus-Ossa | Good | Good | LmPiQgEuSm |
| 43   | GR080180 | Narthakio-Brison | Good | Poor | LmPiQgEuSm |
| 44   | GR080150 | Mavrovouni-Karla | Good | Good | LmPiQgEuSm |
| 45   | GR080160 | Orthrys | Good | Good | LmPiQgEuSm |
| 46   | GR040010 | Monastiraki | Good | Good | LsPcQgEuSm |
| 47   | GR040020 | Akarnania Kia | Good | Good | LsPcQgEuSb |
| 48   | GR040050 | Katooua-Lesinion | Good | Good | LsPcQgEuSm |
| 49   | GR040070 | Arakynthos | Good | Good | LsPcQgEuSm |
| 50   | GR040130 | Olonou-Pindou | Good | Good | LsPcQgEuSm |
| 51   | GR040140 | Amfilochia | Good | Good | LsPcQgEuSm |
| 52   | GR040150 | Valtiou-Ebesou | Good | Good | LsPcQgEuSm |
| 53   | GR040180 | Voniita-Voulkaria | Good | Good | LsPcQgEuSm |
| 54   | GR040010 | Vardousia | Good | Good | LsPcQgEuSm |
| 55   | GR040010 | Vardousia | Good | Good | LsPcQgEuSm |
| 56   | GR0400160 | Lefkada | Good | Good | LsPcQgEuSm |
| 57   | GR070010 | Eastern Tyrifristos | Good | Good | LsPcQgEuSm |
| 58   | GR070020 | Zilefos-Mosokarya | Good | Good | LsPcQgEuSm |
| 59   | GR070030 | Lamia-Stylida | Good | Poor | LsPcQgEuSm |
| 60   | GR070040 | Pelasia | Good | Good | LsPcQgEuSm |
| 61   | GR070060 | Ypati-Kallidromo | Good | Good | LsPcQgEuSm |
| 62   | GR070070 | Knimidas | Good | Good | LsPcQgEuSm |
| 63   | GR0700100 | Kalapodi-Kastro | Good | Good | LsPcQgEuSm |
| 64   | GR0700120 | Giona | Good | Good | LsPcQgEuSm |
| 65   | GR0700140 | Gravia | Good | Good | LsPcQgEuSm |
| 66   | GR0700180 | Parnassos | Good | Good | LsPcQgEuSm |
| 67   | GR0700170 | Distomo | Good | Good | LsPcQgEuSm |
| 68   | GR0700180 | Elikona | Good | Good | LsPcQgEuSm |
| 69   | GR0700190 | Yliko-Parallimi | Good | Good | LsPcQgEuSm |
| 70   | GR0700200 | Ypatou | Good | Good | LsPcQgEuSm |
| 71   | GR0700220 | Skourton-Ag. Thoma | Good | Good | LsPcQgEuSm |
| 72   | GR0700230 | Antikyira-Kitheronas | Good | Good | LsPcQgEuSm |
| 73   | GR0700240 | Lichada | Good | Good | LsPcQgEuSm |
| 74   | GR0700290 | Darlys | Good | Good | LsPcQgEuSm |
| 75   | GR0700300 | Politika-Paxna | Poor | Good | LsPcQgEuSm |
| 76   | GR0700310 | Chalkida-Eretria | Good | Good | LsPcQgEuSm |
| 77   | GR0700320 | Vathia-Ksirovouni | Good | Good | LsPcQgEuSm |
| 78   | GR0700330 | Setsas | Good | Good | LsPcQgEuSm |
| 79   | GR0700340 | Kymi-Aliveri | Good | Good | LsPcQgEuSm |
| 80   | GR0700350 | Dystos-S. Evia | Good | Good | LsPcQgEuSm |
| 81   | GR0700360 | Ochis | Good | Good | LsPcQgEuSm |
| 82   | GR0700370 | North Smyros | Good | Good | LsPcQgEuSm |
| 83   | GR0700380 | South Smyros | Good | Good | LsPcQgEuSm |
| 84   | GR0700390 | North Siatostos | Good | Good | LsPcQgEuSm |
| 85   | GR0700410 | Glossa, Skopelos | Good | Good | LsPcQgEuSm |
| 86   | GR0700420 | Eliou, Skopelos | Good | Good | LsPcQgEuSm |
| 87   | GR0700430 | Alonnisos | Good | Good | LsPcQgEuSm |
| 88   | GR0700440 | Peristera | Good | Good | LsPcQgEuSm |
| 89   | GR0700450 | Kyra Panagia | Good | Good | LsPcQgEuSm |
| 90   | GR0700460 | Gioura | Good | Good | LsPcQgEuSm |
| 91   | GR010020 | South Erymanthos | Good | Good | LsPcQgEuSm |
| 92   | GR010030 | Ladona | Good | Good | LsPcQgEuSm |
| 93   | GR010040 | Lagadia | Good | Good | LsPcQgEuSm |
| 94   | GR010050 | Methyriro | Good | Good | LsPcQgEuSm |
| 95   | GR010060 | Elissosona | Good | Good | LsPcQgEuSm |
| 96   | GR010070 | Karitena-Stennitsa | Good | Good | LsPcQgEuSm |
| 97   | GR010080 | Louissos | Good | Good | LsPcQgEuSm |
| 98   | GR010090 | Minthis | Good | Good | LsPcQgEuSm |
| 99   | GR010090 | Minthis | Good | Good | LsPcQgEuSm |
| 100  | GR010090 | Minthis | Good | Good | LsPcQgEuSm |
| 101  | GR010080 | Flourou-Pidima | Good | Good | LsPcQgEuSm |
| 102  | GR010090 | T. Taqgetos | Good | Good | LsPcQgEuSm |
| 103 | W. Peloponnesus | GR0100110 Kedros | Good | Good | LsPcQgEuSm |
| 104 | W. Peloponnesus | GR0100130 Kallikratis | Good | Good | LsPcQgEuSm |
| 105 | W. Peloponnesus | GR0100150 Gargalianoi | Good | Good | LsPcQgEuSm |
| 106 | W. Peloponnesus | GR0100190 Kyparissia | Good | Good | LsPcQgEuSm |
| 107 | W. Peloponnesus | GR0100210 Diavolitsi | Good | Good | LsPcQgEuSm |
| 108 | N. Peloponnesus | GR200130 Panachaiko | Good | Good | LsPcQgEuSm |
| 109 | N. Peloponnesus | GR200150 Zarouchla | Good | Good | LsPcQgEuSm |
| 110 | N. Peloponnesus | GR200180 Korfotissa | Good | Good | LsPcQgEuSm |
| 111 | N. Peloponnesus | GR200200 Arachneo | Good | Good | LsPcQgEuSm |
| 112 | N. Peloponnesus | GR200220 Ziria | Good | Good | LsPcQgEuSm |
| 113 | N. Peloponnesus | GR200250 North Erymanthos | Good | Good | LsPcQgEuSm |
| 114 | N. Peloponnesus | GR200260 Western Erymanthos | Good | Good | LsPcQgEuSm |
| 115 | N. Peloponnesus | GR200010 Kefalonia | Good | Good | LsPcQgEuSm |
| 116 | N. Peloponnesus | GR200030 Ithaki | Good | Good | LsPcQgEuSm |
| 117 | N. Peloponnesus | GR200040 Vrachionas, Zante | Good | Good | LsPcQgEuSm |
| 118 | E. Peloponnesus | GR0300010 Kandilas | Good | Good | LsPcQgEuSm |
| 119 | E. Peloponnesus | GR0300020 Arkadia-W. Argolia | Good | Good | LsPcQgEuSm |
| 120 | E. Peloponnesus | GR0300050 Mavrovouni | Good | Good | LsPcQgEuSm |
| 121 | E. Peloponnesus | GR0300070 Ermioni | Poor | Good | LsPcQgEuSm |
| 122 | E. Peloponnesus | GR0300100 Parnonas | Good | Good | LsPcQgEuSm |
| 123 | E. Peloponnesus | GR0300110 Zarakas-Monemvasia | Good | Good | LsPcQgEuSm |
| 124 | E. Peloponnesus | GR0300120 SE Lakonia | Good | Good | LsPcQgEuSm |
| 125 | E. Peloponnesus | GR0300140 Kithyra | Good | Good | LsPcQgEuSm |
| 126 | E. Peloponnesus | GR0300160 Gerakiou | Good | Good | LsPcQgEuSm |
| 127 | E. Peloponnesus | GR0300180 Skalas | Good | Good | LsPcQgEuSm |
| 128 | E. Peloponnesus | GR0300210 Skoutariou | Good | Good | LsPcQgEuSm |
| 129 | E. Peloponnesus | GR0300220 E. Taygetos | Good | Good | LsPcQgEuSm |
| 130 | E. Peloponnesus | GR0300250 Zorou-Selasias | Good | Good | LsPcQgEuSm |
| 131 | E. Peloponnesus | GR0300260 Pelianas | Good | Good | LsPcQgEuSm |
| 132 | Attica | GR0600020 West Gerania | Good | Good | LsPcQgEuSm |
| 133 | Attica | GR0600040 East Gerania | Good | Poor | LsPcQgEuSm |
| 134 | Attica | GR0600060 Patera | Good | Good | LsPcQgEuSm |
| 135 | Attica | GR0600080 NE Parnitha | Good | Good | LsPcQgEuSm |
| 136 | Attica | GR0600120 Marathona | Good | Good | LmPcQgEuSm |
| 137 | Attica | GR0600140 Penteli | Good | Good | LmPcQgEuSm |
| 138 | Attica | GR0600160 Hymittos | Good | Good | LmPcQgEuSm |
| 139 | Attica | GR0600170 Lavreotiki | Good | Good | LmPcQgEuSm |
| 140 | Attica | GR0600240 Egina | Good | Poor | LmPcQgEuSm |
| 141 | Crete | GR1300011 Topolia | Good | Good | LsPcQgEuSm |
| 142 | Crete | GR1300012 Stinari | Good | Good | LsPcQgEuSm |
| 143 | Crete | GR1300031 Lefka Ori (Azia) | Good | Good | LsPcQgEuSm |
| 144 | Crete | GR1300032 North Legka Ori | Good | Good | LsPcQgEuSm |
| 145 | Crete | GR1300033 NE Legka Ori | Good | Good | LsPcQgEuSm |
| 146 | Crete | GR1300035 Georgioupoli | Good | Good | LsPcQgEuSm |
| 147 | Crete | GR1300041 Armeni-Malaki | Good | Good | LsPcQgEuSs |
| 148 | Crete | GR1300044 Geranio | Good | Good | LsPcQgEuSs |
| 149 | Crete | GR1300061 Talea | Good | Good | LsPcQgEuSm |
| 150 | Crete | GR1300062 NW Psiloritis | Good | Good | LsPcQgEuSb |
| 151 | Crete | GR1300063 NE Psiloritis | Good | Good | LsPcQgEuSb |
| 152 | Crete | GR1300064 Keri-Tylisos | Poor | Poor | LsPcQgEuSb |
| 153 | Crete | GR1300172 Chrisoskalitsa | Good | Good | LsPcQgEuSm |
| 154 | Crete | GR1300301 Giouchtas | Good | Good | LsPcQgEuSm |
| 155 | Crete | GR1300311 Smari | Good | Good | LsPcQgEuSm |
| 156 | Crete | GR1300312 Gouveas | Poor | Poor | LsPcQgEuSm |
| 157 | Crete | GR1300321 Gramvousa | Good | Good | LsPcQgEuSm |
| 158 | Crete | GR1300322 Spathas | Good | Good | LsPcQgEuSm |
| 159 | Crete | GR1300323 Soudas | Good | Good | LsPcQgEuSm |
| 160 | Crete | GR1300324 Apokorona | Good | Good | LsPcQgEuSs |
| 161 | Crete | GR1300334 South Lefka Ori | Good | Good | LsPcQgEuSb |
| 162 | Crete | GR1300422 Kallikratis | Good | Good | LsPcQgEuSm |
| 163 | Crete | GR1300433 Kedros | Good | Good | LsPcQgEuSm |
| 164 | Crete | GR1300456 SE Psiloritis | Good | Good | LsPcQgEuSm |
| 165 | Crete | GR1300991 Pobia | Good | Good | LsPcQgEuSs |
| 166 | Crete | GR1300992 Pyrgos-Charakas | Good | Good | LsPcQgEuSs |
| 167 | Crete | GR1300993 Asterousia | Good | Good | LsPcQgEuSb |
| 168 | Crete | GR1301111 W. Diki | Good | Good | LsPcQgEuSb |
| Code   | Location   | Results | Details                      |
|--------|------------|---------|------------------------------|
| 169    | Crete      | Good    | Paleochora                   |
| 170    | Crete      | Good    | Kantanos                     |
| 171    | Crete      | Good    | Gavdos                       |
| 172    | Crete      | Good    | Damiani-Laranio              |
| 173    | Crete      | Good    | Gypsi                        |
| 174    | Crete      | Good    | Malia-Selena                 |
| 175    | Crete      | Good    | NE Dikti                     |
| 176    | Crete      | Good    | Lakonia                      |
| 177    | Crete      | Good    | Fourni-Elounta               |
| 178    | Crete      | Good    | Sissi-Milatos                |
| 179    | Crete      | Good    | East-South Dikti             |
| 180    | Crete      | Good    | Malavra                      |
| 181    | Crete      | Good    | NE Zakros                    |
| 182    | Crete      | Good    | E Zakros                     |
| 183    | Crete      | Good    | Zakros                       |
| 184    | Crete      | Good    | Zou                          |
| 185    | Crete      | Good    | Ornos                        |
| 186    | Crete      | Good    | Perka-Maronia                |
| 187    | Crete      | Good    | Thrapi                       |
| 188    | Aegean Islands | Good | Larsos, Lesvos             |
| 189    | Aegean Islands | Good | Mytilini, E. Lesvos         |
| 190    | Aegean Islands | Good | Mytilini, N. Lesvos         |
| 191    | Aegean Islands | Good | E. Plomari, Lesvos          |
| 192    | Aegean Islands | Good | N. Plomari, Lesvos          |
| 193    | Aegean Islands | Good | E. Kardamylia, Chios        |
| 194    | Aegean Islands | Good | N. Kardamylia, Chios        |
| 195    | Aegean Islands | Good | Korakari, Chios             |
| 196    | Aegean Islands | Good | Evdilos, Ikaria             |
| 197    | Aegean Islands | Good | Thymena                      |
| 198    | Aegean Islands | Good | N. Kerketea, Samos          |
| 199    | Aegean Islands | Good | S. Kerketea, Samos          |
| 200    | Aegean Islands | Good | Yourlioti, Samos            |
| 201    | Aegean Islands | Good | Mesokabos, Samos            |
| 202    | Aegean Islands | Good | Mesokabos, Samos            |
| 203    | Aegean Islands | Good | Mesokabos, Samos            |
| 204    | Aegean Islands | Good | Agathonisi                  |
| 205    | Aegean Islands | Good | Arki                         |
| 206    | Aegean Islands | Good | Panagia, Lipsi              |
| 207    | Aegean Islands | Good | Pothia, Kalymnos            |
| 208    | Aegean Islands | Good | Vathi, Kalymnos             |
| 209    | Aegean Islands | Good | Kalymnos                     |
| 210    | Aegean Islands | Good | Kefalovristi, Kos           |
| 211    | Aegean Islands | Good | Linotopi, Astypalea         |
| 212    | Aegean Islands | Good | Astypalea                   |
| 213    | Aegean Islands | Good | Tilos                        |
| 214    | Aegean Islands | Good | Simi                         |
| 215    | Aegean Islands | Good | Chalki                       |
| 216    | Aegean Islands | Good | Profitis Illa, Rodos        |
| 217    | Aegean Islands | Good | Epta Piges, Rodos           |
| 218    | Aegean Islands | Good | Attavirou, Rodos            |
| 219    | Aegean Islands | Good | Megisti, Kastelorizo        |
| 220    | Aegean Islands | Good | Kasos                        |
| 221    | Aegean Islands | Good | Syros                        |
| 222    | Aegean Islands | Good | Syros                        |
| 223    | Aegean Islands | Good | Marathi, Paros              |
| 224    | Aegean Islands | Good | Marathi, Paros              |
| 225    | Aegean Islands | Good | East Naxos                   |
| 226    | Aegean Islands | Good | Donousa                      |
| 227    | Aegean Islands | Good | Sxinousa                     |
| 228    | Aegean Islands | Good | Heraklia                     |
| 229    | Aegean Islands | Good | Sikinos                      |
Based on the aforementioned classification of karstic aquifer systems in Greece it is concluded that the majority of them, representing a percentage of 80%, are developed within sedimentary rocks (limestones and dolomites), mainly in Western Greece, Epirus, Peloponnesus and Crete Island. 103 out of a total of 229 karst systems are inland (percentage 45%) and the rest coastal (percentage 55%).
Only a percentage of 5% is of poor quality recorded in coastal aquifers (mainly on islands) due to seawater intrusion processes, whereas the majority of the karst aquifers are in good groundwater quality status, which shows important role in supplying water for domestic use. In Figure 9, the distribution of different categories of karst aquifer systems in Greece is shown.

![Figure 9: Distribution of different categories of karst aquifer systems in Greece.](image)

Fig. 10: Percentage (%) of different categories of karst aquifer systems in Greece.

In addition, three representative karstic aquifers were classified according to the aforementioned criteria:

1) **Aggitis system** (s.n. 6, GR1100040) in East Macedonia, is developed in marbles of Rhodope massif (Falakro Mountain) and as mentioned above is an allogenic karst system, far away from the coastline. It is characterized by good quality status, discharging through spring with flow rate greater than 3 m$^3$/s and is under-exploitation conditions; thus, it is classified as type: LmPiQgEuSb,

2) **Mitsikeli autogenic system** (s.n. 33, GR0500180) in Epirus, far away from the coastline, is developed in limestones of Ionian unit with good quality status, discharging through springs (Vela, Touba, Krya) with flow rate greater than 3 m$^3$/s and being under-exploitation conditions is classified as type: LsPiQpEuSb, and
3) Ziria karst system in North Peloponnesus (s.n. 112, GR0200220) far away from the coastline is developed in karstified limestones. It is characterized by good quality status, discharging through springs with flow rate greater than 3 m³/s. It is under-exploitation conditions and is classified as type: LsPiQpEuSb.

6. DISCUSSION - CONCLUSIONS

The karst aquifer systems of Greece are developed in carbonate sedimentary (limestones, dolomites) and metamorphic rocks (marbles). Generally, the limestones of all the geotectonic units and marbles in Greece are well karstified with medium to high permeability. Karst aquifers produce large springs, supplying many cities with high quality karstwater. In coastal areas of mainland Greece and Greek islands, the carbonate rocks host karst aquifers that are in direct hydraulic continuity with seawater (open karst), favoring seawater intrusion. It is pointed out that the Messinian crisis of salinity had led to the development of karst phenomena below the present sea level.

Hydraulic parameters range within a large scale of values: the hydraulic conductivity (k) ranges between $10^{-2}$ m/s and $10^{-8}$ m/s and the groundwater velocity in karstic aquifers ranges between $7.8 \times 10^{-3}$ - $7.2 \times 10^{-2}$ m/s with a maximum value of 0.24-0.27 m/s. Local flow direction is towards karst conduits. Transmissivity values range between $8.3 \times 10^{-3}$ and $8.3 \times 10^{-2}$ m²/s. The yield of boreholes drilled in karst aquifers has a wide range of values; $4 \times 10^{-3}$ m³/s to $9.7 \times 10^{-2}$ m³/s. It must be pointed out that the results from the previous methods should be used carefully and never generally to the entirety of the karst system.

The classification of 229 karst systems codified in the Implementation of the Water Framework Directive of the Special Secretariat for Water (Ministry of Environment and Energy) is based on the five factors: 1) Lithology (sedimentary rocks or marbles), 2) Position related to the coastline, 3) Quality status, 4) Exploitation and quantitative status, and 5) Spring discharge. According to the classification, 103 (out of a total of 229) karst systems are inland (percentage 45%) and the rest coastal (percentage 55%). The majority of them (80%) is developed in sedimentary carbonate rocks (limestones, dolomites) and is of good quality and quantitative status. The fresh waters unaffected by seawater intrusion are of the calcium-bicarbonate type. Poor quality status (5%) is recorded in coastal aquifers (mainly in islands) due to seawater intrusion phenomena. The brackish waters are of the sodium-chloride (Na-Cl) type. Some karstwater is
characterized as thermometallic waters which relate to fault structures (e.g. Kaiafa, West Peloponnesus, s.n. 100, code GR0100260). The thermal springs of Greece are correlated to volcanic activity, and the tectonic structure of Greece due to its geographical position between Eurasia and Africa (Lambrakis & Kallergis, 2005; Athanasiadou et al., 2020).

It is obvious that the current classification could be completed with more detailed data in the future. The classification of karst aquifers would be benefited by improvement in data monitoring concerning structure (presence of epikarst, confined or unconfined, etc.), recharge conditions (autogenic or allogenic karst systems) and spring flow rates (spring-discharge hydrograph analysis), the application of isotopic analysis, tracer tests, remote sensing and computer modelling (Kresic & Panday, 2021) to estimate the hydraulic properties (permeability, groundwater velocity, etc.), and assessment of the vulnerability to external pollution. Hydrograph analysis can be used for parameter estimation, understanding flow behavior and quantitative classification (Xu et al., 2018). In addition, dolomite karst systems could locally be a special group of carbonate aquifers where karstification hasn't produced an interconnected network of karst conduits (Kovacs, 2021).

Karstwater is an important natural resource and contributes significantly to water supply for drinking and irrigation use (Stevanovic, 2019). It is noted that the Sustainable Development Goal 6 (SDG6) of the United Nations aims to ensure the availability and sustainability of water and sanitation for all as a long-term prospect (Marin et al., 2021). This is particularly important in the context of climate change that will have a significant impact on regional hydrogeological systems (Walter et al., 2018).

Increasing water demands in Greece require the exploitation of non-conventional water resources, such as the brackish coastal springs and effective management of karst aquifers. The results of the above mentioned classification can support the protection and sustainable development of karstwater resources. Based on the aforementioned classification a road map for each case should be designed aiming to a sustainable management in terms of protection, preservation and exploitation of Greek karst aquifers (Kazakis et al., 2018). The "anthropic pressure" (abundance of population and economic activities on the karst systems, pollution from agriculture and wastewaters, changes of land uses) and the trend towards an overexploitation (for instance the decreasing of spring discharge, because of both climate and pumping) should be considered and taken into account for a rational management of karst
systems. The delineation of protection zones for karstic springs and the implementation of protection measures are useful tools and keys to managing and protecting karst groundwater (Valle et al., 2021). In addition, early warning systems can be designed to identify and detect contamination episodes by using karstwater quality monitoring networks (Marin et al., 2021).

Finally, an integrated management scheme aiming at sustainability of karst aquifer systems is therefore of paramount importance to Greece. For this purpose, detailed hydrogeological investigations of each karst system should be launched by the Ministry of Environment & Energy and local authorities in order to develop reliable databases.

7. ACKNOWLEDGMENTS

Parts of this review were presented in the International Conference “All about Karst & Water”, held on 9 – 11 October 2006 in Vienna, in XXX IAHR Congress “Water Engineering and Research in a Learning Society”, held on 24-29 August 2003 in Thessaloniki Greece, in National Conference with international participation “Geosciences 2018”, held on December 2018 in Sofia Bulgaria, and in “International Earth Science Colloquium on the Aegean Region (IESCA)” held on October 2019 in Izmir Turkey. The author would like to thank Dr. Nerantzis Kazakis for his help in designing the maps.

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