BGSG

Volume 57

Research Paper

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DOI number:
http://dx.doi.org/10.12681/bgsg.25471

Keywords:
Carbonate rocks, groundwater, karst aquifer, salinity, springs

Citation:
Voudouris K. (2019), Status and Codification of Karst Aquifer System in Greece. Bulletin Geological Society of Greece, 57, 23-51.

Publication History:
Received: 03/12/2020
Accepted: 13/05/2021
Accepted article online: 07/06/2021

The Editor wishes to thank two anonymous reviewers for their work with the scientific reviewing of the manuscript and Ms Emmanouela Konstantakopoulou for editorial assistance.

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 αναπτύσσεται σε ιζηματογενή πετρώματα (ασβεστόλιθοι), έχει καλή ποιότητα νερού και χαρακτηρίζονται από καλή ποσοτική κατάσταση. Κακή 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 προκειμένου 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 (Andreo, 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 $35.3x10^3$ km^2, representing a percentage of 27.1% of the total area (approximately 132,000 km^2) (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 karstifiable, 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-Olonos, Tripolis-Gavrovo, Ionian, Paxos, and Plattenkalk-Talea Ori (Mountrakis, 1985; Papanikolaou, 2013).

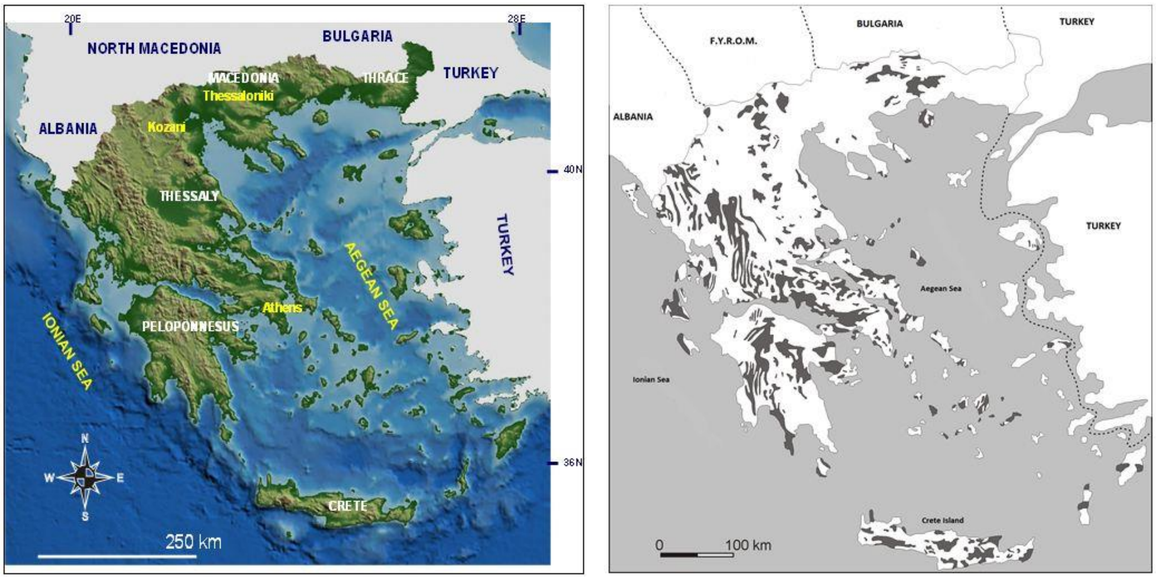

Fig. 1: Left: Map of Greece, Right: spatial distribution of carbonate rocks (black colour) (Mandilaras et al., 2006; Soulios, 1985 with modifications).

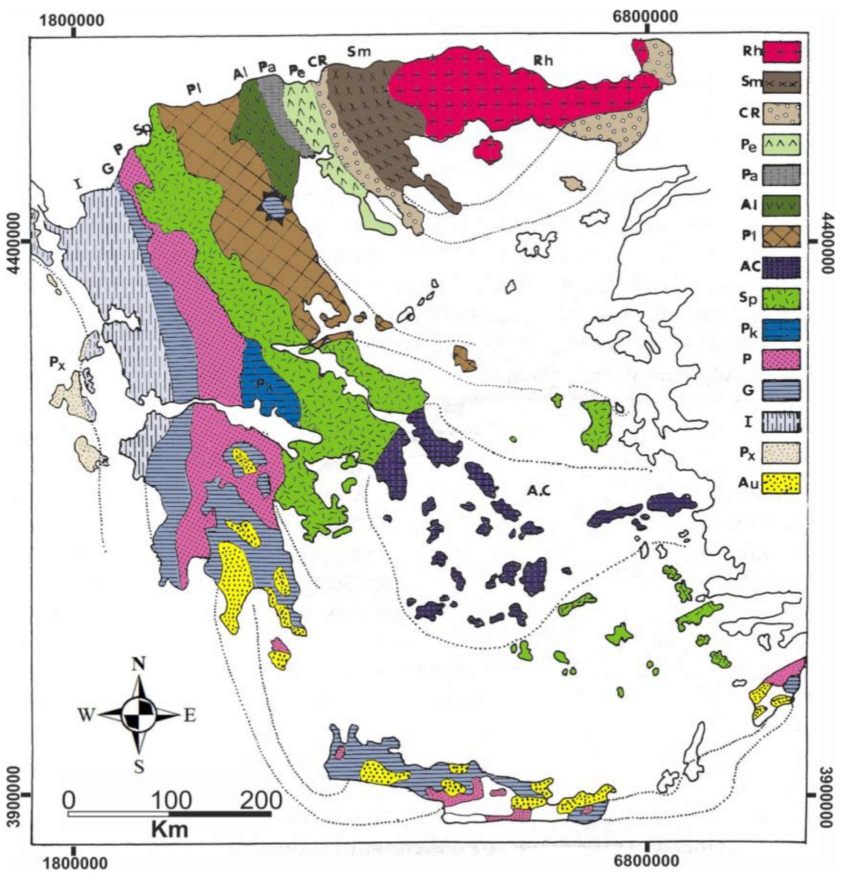

Fig. 2: Geotectonic zones of Greece (Mountrakis, 1985). Explanation: Rh=Rhodope Massif, Sm=Serbomacedonian, CR=Circum Rhodope, Pe=Peonias, Pa=Paikou, Al=Almopias, PI=Pelagonian, AC=Attico-Cycladic, Sp=Sub-Pelagonian, Pk=Parnassos-Giona, P=Pindos-Olonos, G=Tripolis-Gavrovo, I=Ionian, Px=Paxos, Au=Plattenkalk-Talea 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).

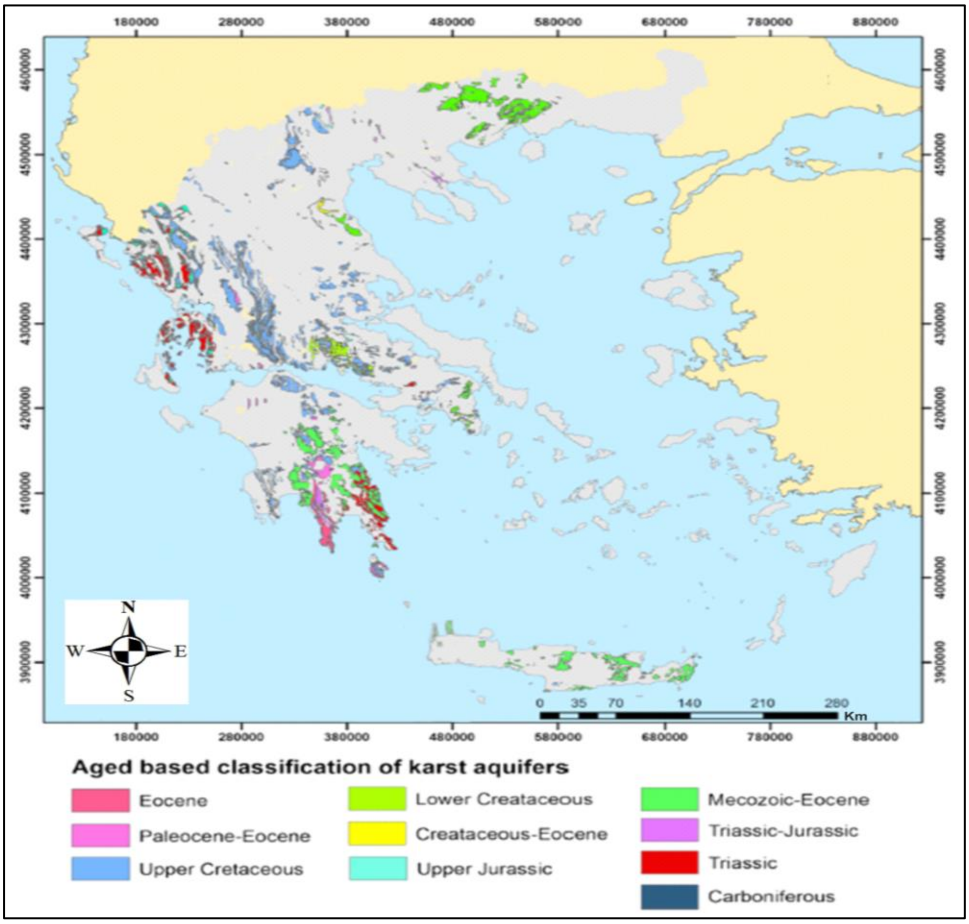

Fig. 3: Classification of karst aquifer systems in Greece based on their age (Kallioras & Marinos 2015).

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: $\mathbf{Q=P \cdot A \cdot I_c}$, 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 x 10^{-4} and 8.3 x 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 x 10^{-2} m^2/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 x 10^{-3} m^3/s to 9.7 x 10^{-2} m^3/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:

$$\mathbf{T = 0.94\ (Q/d) + 53.7} \qquad (r=0.68)$$

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_{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 x 10^{-3} and 7.2 x 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 x 10^{-3} to 6 x 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-HCO$_3$**) 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).

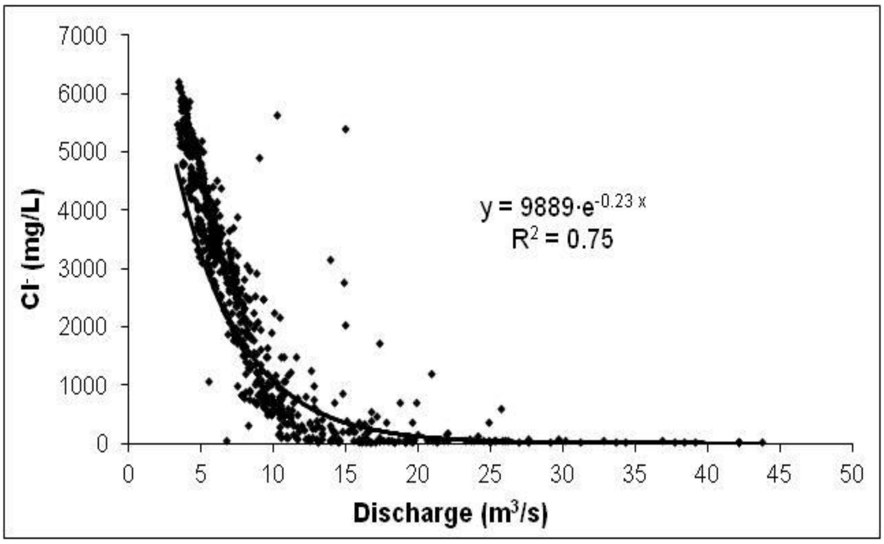

Fig. 4: Chloride concentration versus discharge in Almyros karst spring (Voudouris et al., 2010).

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 = $6.2x10^{-3}$, 2) Sakova spring in Symvolo Mountain: a = $4.1x10^{-2}$, 3) Militsa spring, Kastoria: a = $5.5x10^{-3}$, 4) Stymfalia spring, Kyllini Mountain: a = $2.4x10^{-2}$, 5) Paradisos spring, Xanthi: a = $3.6x10^{-3}$, 6) Maara spring, Aggitis karst system, Drama: a = $3x10^{-3}$ - $6x10^{-3}$, 7) Louros basin karstic springs: a = $1.5x10^{-3}$ – $1.2x10^{-2}$, 8) Agios Nikolaos Naousa: a = $2.4x10^{-3}$, 9) Almyros Agios Nikolaos, Crete Island: a = $1.7x10^{-3}$, 10) Almyros Heraklion, Crete Island: a = 10^{-3}.

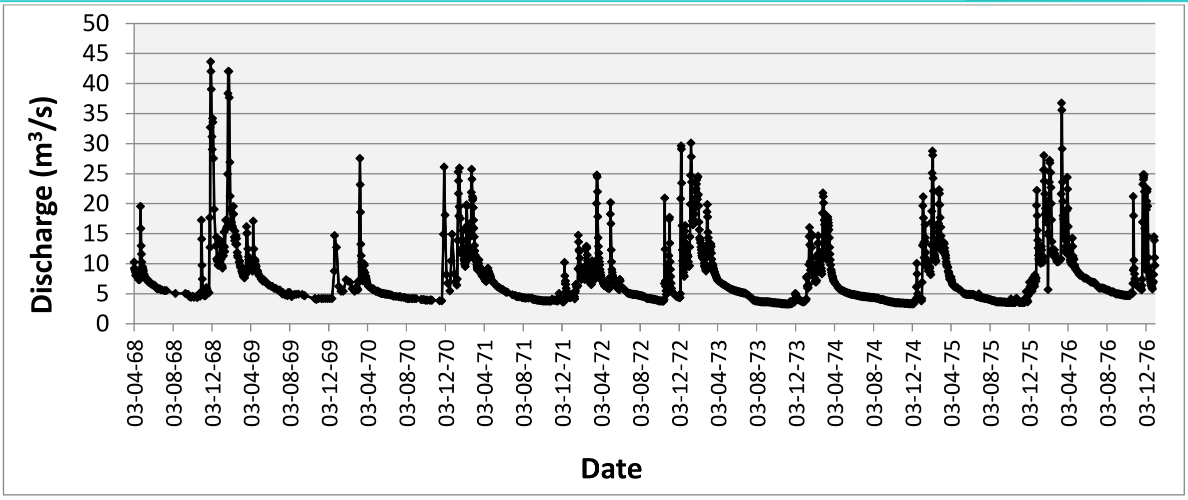

Fig. 5: Hydrograph of the Almyros Heraklion karst spring (Voudouris et al., 2010).

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 km^2 and the discontinuous carbonate rocks 23,400 km^2. 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.

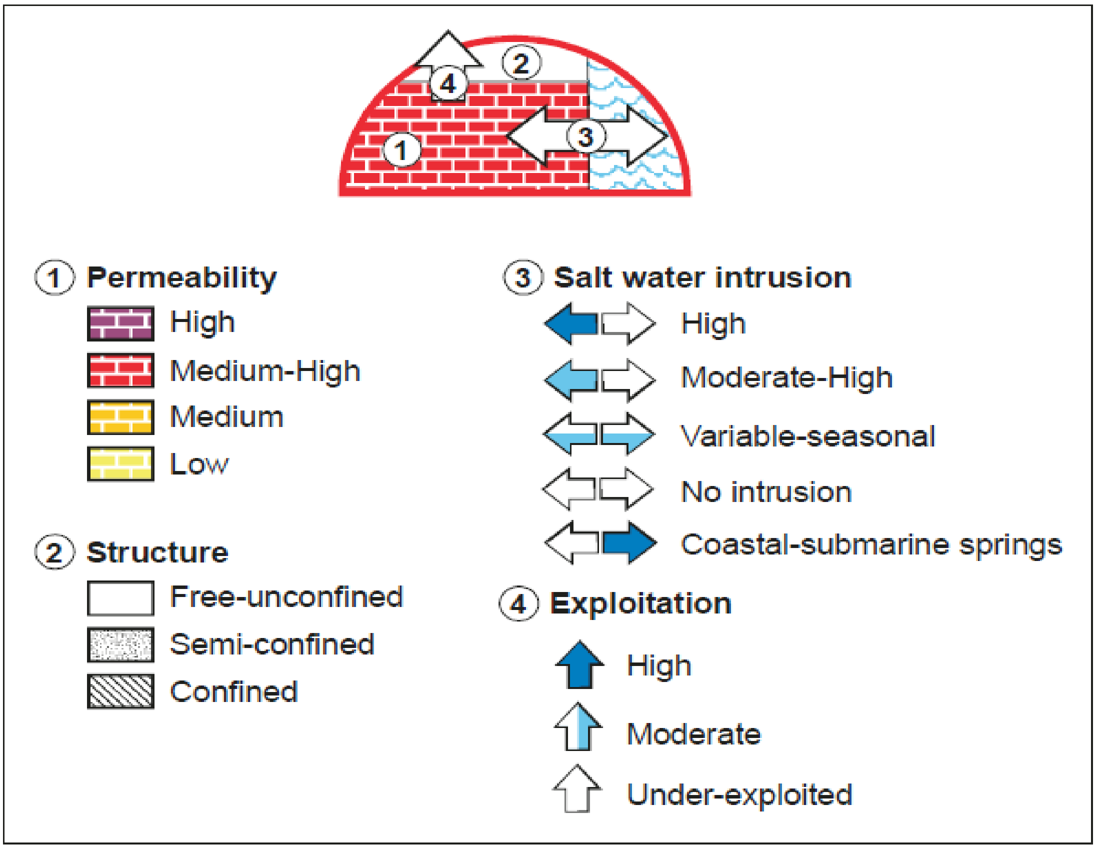

Fig. 6: Graph for classification of a coastal karst aquifer (Calaforra et al., 2004).

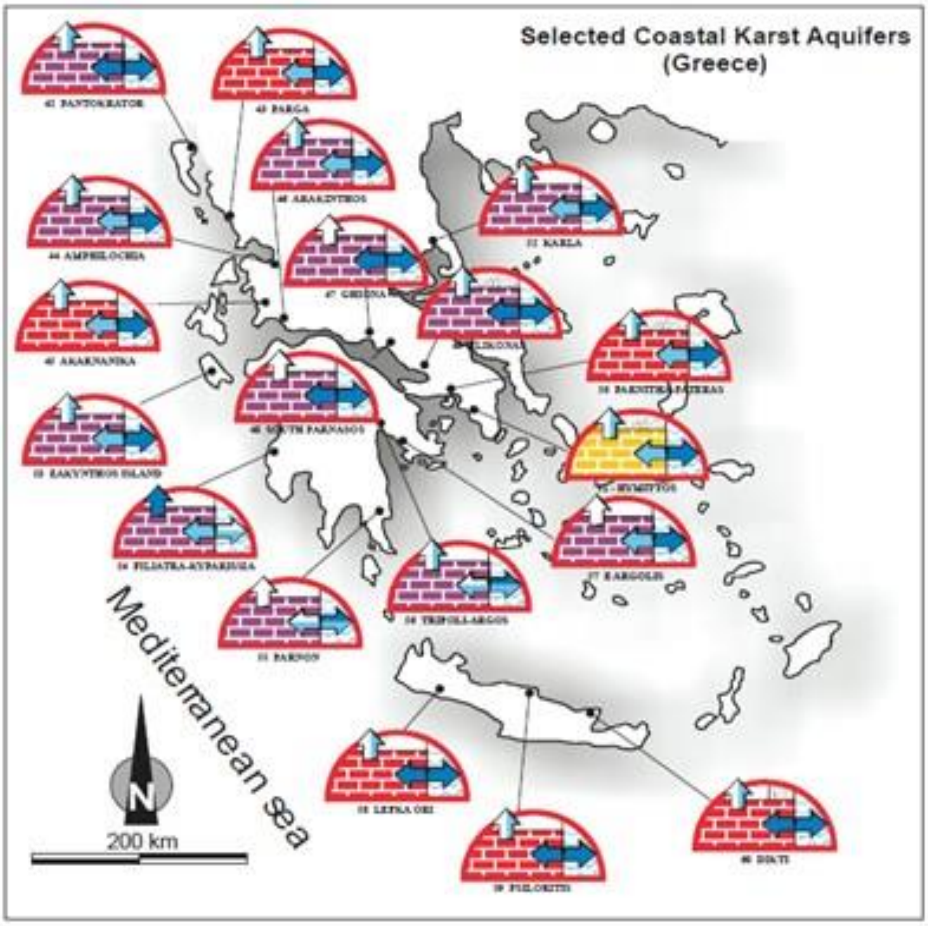

Fig. 7: Classification of selected coastal karst aquifers of Greece (Calaforra et al., 2004).

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, **L**

2) Position, **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 m^3/s, 2) moderate mean annual discharge 1-3 m^3/s, and 3) low mean annual discharge <1 m^3/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 quantitative status	E	Eu: under-exploitation, good 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	LmPcQgEuSs
4	East Macedonia	GR110B020	Aggistro	Good	Good	LmPiQgEuSs
5	East Macedonia	GR110B030	Menikio-Falakro	Good	Good	LmPiQgEuSb
6	East Macedonia	GR1100040	Aggitis	Good	Good	LmPiQgEuSb
7	East Macedonia	GR1100060	Pageo Mountain	Good	Good	LmPiQgEuSs
8	Central Macedonia	GR1000020	Paiko	Good	Good	LsPiQgEuSb
9	Central Macedonia	GR1000210	Gallikos	Good	Good	LsPiQgEuSs
10	Central Macedonia	GR1000270	Vafiochori	Good	Good	LsPiQgEuSs
11	Central Macedonia	GR100F280	Sterna	Good	Good	LsPiQgEuSs
12	Central Macedonia	GR1000220	Deve Koran	Good	Good	LsPiQgEuSs
13	West Macedonia	GR09AF012	Prespes	Good	Good	LsPiQgEuSb
14	West Macedonia	GR09AF015	Aposkepos	Good	Good	LsPiQgEuSs
15	West Macedonia	GR0900071	Vermio-Askio	Good	Good	LsPiQgEuSs
16	West Macedonia	GR0900075	Lefkopigi	Good	Good	LsPiQgEuSb
17	West Macedonia	GR0900081	West Vermio	Good	Good	LsPiQgEuSb
18	West Macedonia	GR0900142	Litochoro	Good	Good	LsPiQgEuSb
19	West Macedonia	GR0900220	Korissos	Good	Good	LsPiQgEuSb
20	Epirus	GR0500010	South Kerkyra	Good	Good	LsPcQgEuSm
21	Epirus	GR0500040	Paxi	Good	Good	LsPcQgEuSs
22	Epirus	GR0500050	Othoni	Good	Good	LsPcQgEuSs
23	Epirus	GR050A060	Mourgana	Good	Good	LsPiQgEuSs
24	Epirus	GR050A070	Filiates	Good	Good	LsPiQgEuSs
25	Epirus	GR0500080	Kalama	Good	Good	LsPiQgEuSb
26	Epirus	GR0500090	Souli-Paramythia	Good	Good	LsPiQgEuSm
27	Epirus	GR0500100	Tymfi-Aoos	Good	Good	LsPiQgEuSb
28	Epirus	GR0500110	Klimatia-Kalama	Good	Good	LsPiQgEuSm
29	Epirus	GR0500120	Kasidiari-Kalama	Good	Good	LsPiQgEuSm
30	Epirus	GR0500130	Koroni	Good	Good	LsPiQgEuSm
31	Epirus	GR0500150	Lourou	Good	Good	LsPiQgEuSb
32	Epirus	GR0500170	Parga	Good	Good	LsPiQgEuSb
33	Epirus	GR0500180	Mitsikeli-Vela	Good	Good	LsPiQgEuSb
34	Epirus	GR050A190	Pogoniani	Good	Good	LsPiQgEuSb
35	Epirus	GR0500210	Kourenton	Good	Good	LsPiQgEuSm

36	Epirus	GR0500250	Zalogou	Good	Good	LsPiQgEuSb
37	Thessaly	GR0800010	Koziaka	Good	Good	LmPiQgEuSm
38	Thessaly	GR0800020	Paleosamarina	Good	Good	LsPiQgEuSs
39	Thessaly	GR0800050	Krania-Elassona	Good	Good	LmPiQgEuSb
40	Thessaly	GR0800070	Damasi-Titanos	Good	Good	LmPiQgEuSb
41	Thessaly	GR0800080	Fylliou-Orfanon	Good	Poor	LmPiQgEoSm
42	Thessaly	GR0800100	Ekkaras-Velesioton	Good	Poor	LmPiQgEoSm
43	Thessaly	GR0800120	Olympos-Ossa	Good	Good	LmPiQgEuSb
44	Thessaly	GR0800180	Narthakio-Brision	Good	Poor	LmPiQgEoSm
45	Thessaly	GR0800150	Mavrovouni-Karla	Good	Good	LmPiQgEuSb
46	Thessaly	GR0800160	Orthrys	Good	Good	LmPiQgEuSb
47	Western Mainland	GR0400010	Monastiraki	Good	Good	LsPiQgEuSm
48	Western Mainland	GR0400020	Akarnanika Ori	Good	Good	LsPcQgEuSb
49	Western Mainland	GR0400050	Katouna-Lesinio	Good	Good	LsPiQgEuSm
50	Western Mainland	GR0400070	Arakynthos	Good	Good	LsPiQgEuSm
51	Western Mainland	GR0400130	Olonou-Pindou	Good	Good	LsPiQgEuSb
52	Western Mainland	GR0400140	Amfilochia	Good	Good	LsPiQgEuSm
53	Western Mainland	GR0400150	Valtou-Ebesou	Good	Good	LsPiQgEuSb
54	Western Mainland	GR0400180	Vonitsa-Voulkaria	Good	Good	LsPcQgEuSm
55	Western Mainland	GR0400110	Vardousia	Good	Good	LsPiQgEuSb
56	Western Mainland	GR0400160	Lefkada	Good	Good	LsPcQgEuSb
57	Eastern Mainland	GR0700010	Eastern Tymfristos	Good	Good	LsPiQgEuSb
58	Eastern Mainland	GR0700020	Zileftos-Mosxokarya	Good	Good	LsPiQgEuSm
59	Eastern Mainland	GR0700030	Lamia-Stylida	Good	Poor	LsPiQgEoSb
60	Eastern Mainland	GR0700040	Pelasgia	Good	Good	LsPcQgEuSb
61	Eastern Mainland	GR0700060	Ypati-Kallidromo	Good	Good	LsPiQgEuSb
62	Eastern Mainland	GR0700070	Knimidas	Good	Good	LsPcQgEuSb
63	Eastern Mainland	GR0700100	Kalapodi-Kastro	Good	Good	LsPiQgEuSb
64	Eastern Mainland	GR0700120	Giona	Good	Good	LsPcQgEuSb
65	Eastern Mainland	GR0700140	Gravia	Good	Good	LsPiQgEuSb
66	Eastern Mainland	GR0700150	Parnassos	Good	Good	LsPcQgEuSb
67	Eastern Mainland	GR0700160	Distomo	Good	Good	LiPcQgEuSs
68	Eastern Mainland	GR0700170	Elikona	Good	Good	LsPiQgEuSm
69	Eastern Mainland	GR0700190	Yliki-Paralimni	Good	Good	LsPcQgEuSb
70	Eastern Mainland	GR0700200	Ypatou	Good	Good	LsPcQgEuSm
71	Eastern Mainland	GR0700220	Skourton-Ag. Thoma	Good	Good	LsPiQgEuSm
72	Eastern Mainland	GR0700230	Antikyra-Kitheronas	Good	Good	LsPcQgEuSb
73	Eastern Mainland	GR0700240	Lichada	Good	Good	LsPcQgEuSs
74	Eastern Mainland	GR0700290	Dirfys	Good	Good	LsPcQgEuSm
75	Eastern Mainland	GR0700300	Politika-Psaxna	Poor	Good	LsPcQpEuSb
76	Eastern Mainland	GR0700310	Chalkida-Eretria	Good	Good	LsPcQgEuSb
77	Eastern Mainland	GR0700320	Vathia-Ksirovouni	Good	Good	LsPcQgEuSm
78	Eastern Mainland	GR0700330	Setas	Good	Good	LsPcQgEuSs
79	Eastern Mainland	GR0700340	Kymi-Aliveri	Good	Good	LsPcQgEuSb
80	Eastern Mainland	GR0700350	Dystos-S. Evia	Good	Good	LsPcQgEuSb
81	Eastern Mainland	GR0700360	Ochis	Good	Good	LsPcQgEuSs
82	Eastern Mainland	GR0700370	North Skyros	Good	Good	LsPcQgEuSs
83	Eastern Mainland	GR0700380	South Skyros	Good	Good	LsPcQgEuSs
84	Eastern Mainland	GR0700390	North Skiathos	Good	Good	LsPcQgEuSs
85	Eastern Mainland	GR0700410	Glossa, Skopelos	Good	Good	LsPcQgEuSs
86	Eastern Mainland	GR0700420	Eliou, Skopelos	Good	Good	LsPcQgEuSs
87	Eastern Mainland	GR0700430	Alonnisos	Good	Good	LsPcQgEuSs
89	Eastern Mainland	GR0700440	Peristera	Good	Good	LsPcQgEuSs
90	Eastern Mainland	GR0700450	Kyra Panagia	Good	Good	LsPcQgEuSs
91	Eastern Mainland	GR0700460	Gioura	Good	Good	LsPcQgEuSb
92	W. Peloponnesus	GR0100020	South Erymanthos	Good	Good	LsPiQgEuSb
93	W. Peloponnesus	GR0100030	Ladona	Good	Good	LsPiQgEuSb
94	W. Peloponnesus	GR0100040	Lagadia	Good	Good	LsPiQgEuSb
95	W. Peloponnesus	GR0100050	Methydrio	Good	Good	LsPiQgEuSm
96	W. Peloponnesus	GR0100060	Elissona	Good	Good	LsPiQgEuSm
97	W. Peloponnesus	GR0100220	Karitena-Stemnitsa	Good	Good	LsPiQgEuSm
98	W. Peloponnesus	GR0100230	Lousios	Good	Good	LsPiQgEuSm
99	W. Peloponnesus	GR0100240	Minthis	Good	Good	LsPiQgEuSm
100	W. Peloponnesus	GR0100260	Kaiafa	Good	Good	LsPiQpEuSb
101	W. Peloponnesus	GR0100080	Florou-Pidima	Good	Good	LsPiQgEuSm
102	W. Peloponnesus	GR0100090	W. Taygetos	Good	Good	LsPcQgEuSb

103	W. Peloponnesus	GR0100110	Koroni	Good	Good	LsPcQgEuSm
104	W. Peloponnesus	GR0100130	Kynigou	Good	Good	LsPcQgEuSm
105	W. Peloponnesus	GR0100150	Gargalianoi	Good	Good	LsPcQgEuSm
106	W. Peloponnesus	GR0100190	Kyparissia	Good	Good	LsPiQgEuSm
107	W. Peloponnesus	GR0100210	Diavolitsi	Good	Good	LsPiQgEuSm
108	N. Peloponnesus	GR0200130	Panachaiko	Good	Good	LsPiQgEuSb
109	N. Peloponnesus	GR0200150	Zarouchla	Good	Good	LsPiQgEuSm
110	N. Peloponnesus	GR0200180	Korfiotissa	Good	Good	LsPcQgEuSm
111	N. Peloponnesus	GR0200200	Arachneo	Good	Good	LsPcQgEuSm
112	N. Peloponnesus	GR0200220	Ziria	Good	Good	LsPiQgEuSb
113	N. Peloponnesus	GR0200250	North Erymanthos	Good	Good	LsPiQgEuSb
114	N. Peloponnesus	GR0200260	Western Erymanthos	Good	Good	LsPiQgEuSb
115	N. Peloponnesus	GR0200010	Kefalonnia	Good	Good	LsPcQgEuSb
116	N. Peloponnesus	GR0200030	Ithaki	Good	Good	LsPcQgEuSm
117	N. Peloponnesus	GR0200040	Vrachionas, Zante	Good	Good	LsPcQgEuSm
118	E. Peloponnesus	GR0300010	Kandilas	Good	Good	LsPiQgEuSb
119	E. Peloponnesus	GR0300020	Arkadia-W. Argolida	Good	Good	LsPcQgEuSb
120	E. Peloponnesus	GR0300050	Mavrovouni	Good	Good	LsPcQgEuSm
121	E. Peloponnesus	GR0300070	Ermioni	Poor	Good	LsPcQpEoSm
122	E. Peloponnesus	GR0300100	Parnonas	Good	Good	LsPcQgEuSb
123	E. Peloponnesus	GR0300110	Zarakas-Monemvasia	Good	Good	LsPcQgEuSb
124	E. Peloponnesus	GR0300120	SE Lakonia	Good	Good	LsPcQgEuSm
125	E. Peloponnesus	GR0300140	Kithyra	Good	Good	LsPcQgEuSm
126	E. Peloponnesus	GR0300160	Gerakiou	Good	Good	LsPiQgEuSb
127	E. Peloponnesus	GR0300180	Skalas	Good	Good	LsPiQgEuSm
128	E. Peloponnesus	GR0300210	Skoutariou	Good	Good	LsPcQgEuSm
129	E. Peloponnesus	GR0300220	E. Taygetos	Good	Good	LsPiQgEuSb
130	E. Peloponnesus	GR0300250	Zorou-Selasias	Good	Good	LsPiQgEuSm
131	E. Peloponnesus	GR0300260	Pellanas	Good	Good	LsPiQgEuSm
132	Attica	GR0600020	West Gerania	Good	Good	LsPcQgEuSb
133	Attica	GR0600040	East Gerania	Good	Poor	LsPcQpEuSm
134	Attica	GR0600060	Patera	Good	Good	LsPcQgEuSb
135	Attica	GR0600080	NE Parnitha	Good	Good	LsPiQgEuSb
136	Attica	GR0600120	Marathona	Good	Good	LmPcQgEuSm
137	Attica	GR0600140	Penteli	Good	Good	LmPcQgEuSb
138	Attica	GR0600160	Hymittos	Good	Good	LmPcQpEoSb
139	Attica	GR0600170	Lavreotiki	Good	Good	LmPcQgEuSm
140	Attica	GR0600240	Egina	Good	Poor	LmPcQpEuSm
141	Crete	GR1300011	Topolia	Good	Good	LsPiQgEuSm
142	Crete	GR1300012	Sfinari	Good	Good	LsPcQgEuSm
143	Crete	GR1300031	Lefka Ori (Agia)	Good	Good	LsPiQgEuSb
144	Crete	GR1300032	North Legka Ori	Good	Good	LsPiQgEuSm
145	Crete	GR1300033	NE Legka Ori	Good	Good	LsPiQgEuSm
146	Crete	GR1300035	Georgioupoli	Good	Good	LsPcQgEuSb
147	Crete	GR1300041	Armeni-Malaki	Good	Good	LsPiQgEuSs
148	Crete	GR1300044	Geranio	Good	Good	LsPcQgEuSs
149	Crete	GR1300061	Talea	Good	Good	LsPiQgEuSm
150	Crete	GR1300062	NW Psiloritis	Good	Good	LsPiQgEuSb
151	Crete	GR1300063	NE Psiloritis	Good	Good	LsPiQgEuSb
152	Crete	GR1300064	Keri-Tylisos	Poor	Poor	LsPcQpEoSb
153	Crete	GR1300172	Chrisoskalitsa	Good	Good	LsPiQgEuSm
154	Crete	GR1300301	Giouchtas	Good	Good	LsPiQgEuSm
155	Crete	GR1300311	Smari	Good	Good	LsPiQgEuSm
156	Crete	GR1300312	Gouves	Poor	Poor	LsPcQpEoSm
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	GR1300034	South Lefka Ori	Good	Good	LsPcQgEuSb
162	Crete	GR1300042	Kallikratis	Good	Good	LsPiQgEuSm
163	Crete	GR1300043	Kedros	Good	Good	LsPiQgEuSm
164	Crete	GR1300065	SE Psiloritis	Good	Good	LsPiQgEuSb
165	Crete	GR1300091	Pobia	Good	Good	LsPiQgEuSs
166	Crete	GR1300092	Pyrgos-Charakas	Good	Good	LsPcQgEuSs
167	Crete	GR1300093	Asterousia	Good	Good	LsPcQgEuSb
168	Crete	GR1300111	W. Dikti	Good	Good	LsPcQgEuSb

169	Crete	GR1300171	Paleochora	Good	Good	LsPcQgEuSm
170	Crete	GR1300173	Kantanos	Good	Good	LsPcQgEuSb
171	Crete	GR1300280	Gavdos	Good	Good	LsPcQgEuSs
172	Crete	GR1300302	Damani-Laranio	Good	Good	LsPiQgEuSs
173	Crete	GR1300330	Gypsi	Good	Good	LsPiQgEuSs
174	Crete	GR1300112	Malia-Selena	Good	Good	LsPcQgEuSb
175	Crete	GR1300113	NE Dikti	Good	Good	LsPiQgEuSb
176	Crete	GR1300114	Lakonia	Good	Good	LsPcQgEuSm
177	Crete	GR1300115	Fourni-Elounta	Good	Good	LsPiQgEuSs
178	Crete	GR1300116	Sissi-Milatos	Good	Good	LsPcQgEuSs
179	Crete	GR1300117	East-South Dikti	Good	Good	LsPiQgEuSb
180	Crete	GR1300132	Malavra	Good	Good	LsPcQgEuSm
181	Crete	GR1300152	NE Zakros	Good	Good	LsPcQgEuSb
182	Crete	GR1300153	E Zakros	Good	Good	LsPcQgEuSb
183	Crete	GR1300151	Zakros	Good	Good	LsPiQgEuSs
184	Crete	GR1300154	Zou	Good	Good	LsPiQgEuSm
185	Crete	GR1300131	Ornos	Good	Good	LsPiQgEuSm
186	Crete	GR1300134	Pefka-Maronia	Good	Good	LsPiQgEuSs
187	Crete	GR1300133	Thripti	Good	Good	LsPiQgEuSs
188	Aegean Islands	GR1400080	Larsos, Lesvos	Good	Good	LmPcQgEuSs
189	Aegean Islands	GR1400091	Mytilini, E. Lesvos	Good	Good	LmPcQgEuSs
190	Aegean Islands	GR1400092	Mytilini, N. Lesvos	Poor	Poor	LmPcQpEoSs
191	Aegean Islands	GR1400111	E. Plomari, Lesvos	Good	Good	LmPcQgEuSm
192	Aegean Islands	GR1400112	N. Plomari, Lesvos	Poor	Poor	LmPcQpEoSs
193	Aegean Islands	GR1400141	E. Kardamyla, Chios	Good	Good	LsPcQgEuSb
194	Aegean Islands	GR1400142	N. Kardamyla, Chios	Poor	Poor	LsPcQpEoSs
195	Aegean Islands	GR1400150	Korakari, Chios	Poor	Poor	LsPcQpEoSs
196	Aegean Islands	GR1400200	Evdilos, Ikaria	Good	Good	LsPcQgEuSs
197	Aegean Islands	GR1400220	Thymena	Good	Good	LsPcQgEuSs
198	Aegean Islands	GR1400241	N. Kerketea, Samos	Good	Good	LmPcQgEuSs
199	Aegean Islands	GR1400242	S. Kerketea, Samos	Poor	Poor	LmPcQpEoSs
200	Aegean Islands	GR1400280	Vourlioti, Samos	Good	Good	LmPcQgEuSs
201	Aegean Islands	GR1400311	Mesokabos, Samos	Good	Good	LmPcQgEuSs
202	Aegean Islands	GR1400312	Mesokabos, Samos	Poor	Poor	LmPcQpEoSs
203	Aegean Islands	GR1400320	Agathonisi	Good	Good	LmPcQgEuSs
204	Aegean Islands	GR1400330	Arki	Good	Good	LmPcQgEuSs
205	Aegean Islands	GR1400341	Panagia, Lipsi	Good	Good	LmPcQgEuSs
206	Aegean Islands	GR1400342	Panagia, Lipsi	Poor	Poor	LmPcQpEoSs
207	Aegean Islands	GR1400370	Pothia, Kalymnos	Poor	Poor	LsPcQpEoSs
208	Aegean Islands	GR1400380	Vathi, Kalymnos	Poor	Poor	LsPcQpEoSs
209	Aegean Islands	GR1400390	Kalymnos	Good	Good	LsPcQgEuSs
210	Aegean Islands	GR1400420	Kefalovrisi, Kos	Good	Good	LmPcQgEuSs
211	Aegean Islands	GR1400462	Linotopi, Astypalea	Poor	Poor	LsPcQpEoSs
212	Aegean Islands	GR1400470	Astypalea	Good	Good	LsPcQgEuSs
213	Aegean Islands	GR1400480	Tilos	Good	Good	LsPcQgEuSs
214	Aegean Islands	GR1400490	Simi	Good	Good	LsPcQgEuSs
215	Aegean Islands	GR1400500	Chalki	Good	Good	LsPcQgEuSs
216	Aegean Islands	GR1400520	Profitis Ilia, Rodos	Good	Good	LsPcQgEuSs
217	Aegean Islands	GR1400530	Epta Piges, Rodos	Good	Good	LsPcQgEuSs
218	Aegean Islands	GR1400560	Attavirou, Rodos	Good	Good	LsPcQgEuSs
219	Aegean Islands	GR1400590	Megisti, Kastelorizo	Good	Good	LsPcQgEuSs
220	Aegean Islands	GR1400620	Kasos	Good	Good	LsPcQgEuSs
221	Aegean Islands	GR1400671	Syros	Good	Good	LmPcQgEuSs
222	Aegean Islands	GR1400672	Syros	Poor	Poor	LmPcQpEoSs
223	Aegean Islands	GR1400751	Marathi, Paros	Good	Good	LmPcQgEuSs
224	Aegean Islands	GR1400752	Marathi, Paros	Poor	Poor	LmPcQpEoSs
225	Aegean Islands	GR1400780	East Naxos	Good	Good	LmPcQgEuSs
226	Aegean Islands	GR1400790	Donousa	Good	Good	LmPcQgEuSs
227	Aegean Islands	GR1400820	Sxinousa	Good	Good	LmPcQgEuSs
228	Aegean Islands	GR1400840	Heraklia	Good	Good	LmPcQgEuSs
229	Aegean Islands	GR1400850	Sikinos	Good	Good	LmPcQgEuSs

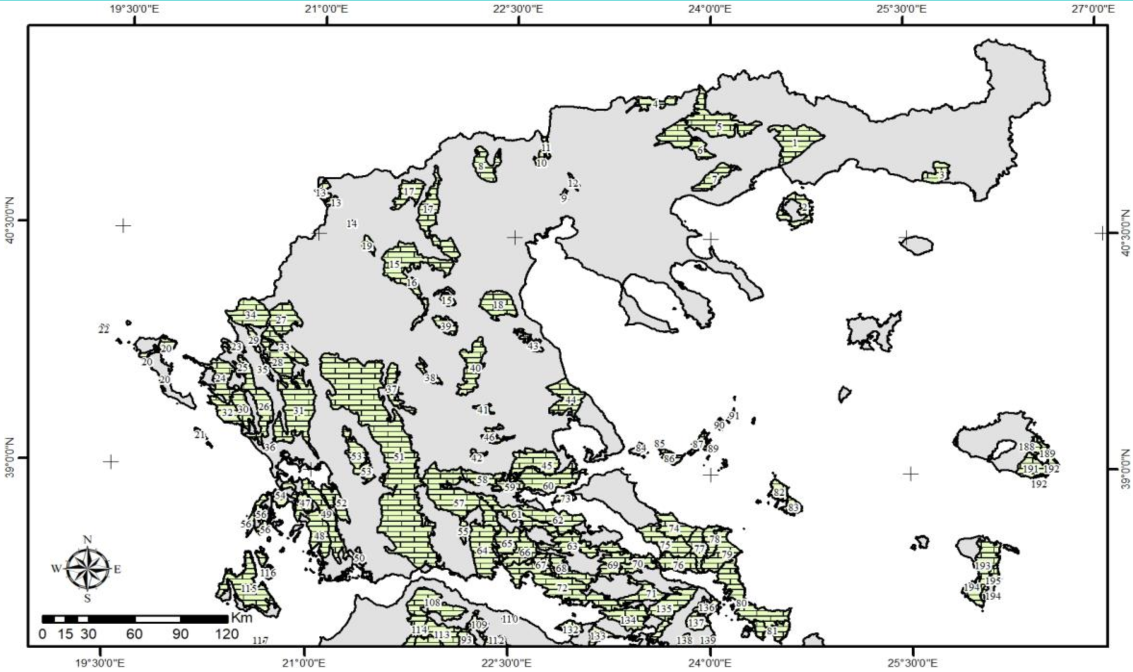

Fig. 8: Karstwater systems in North Greece.

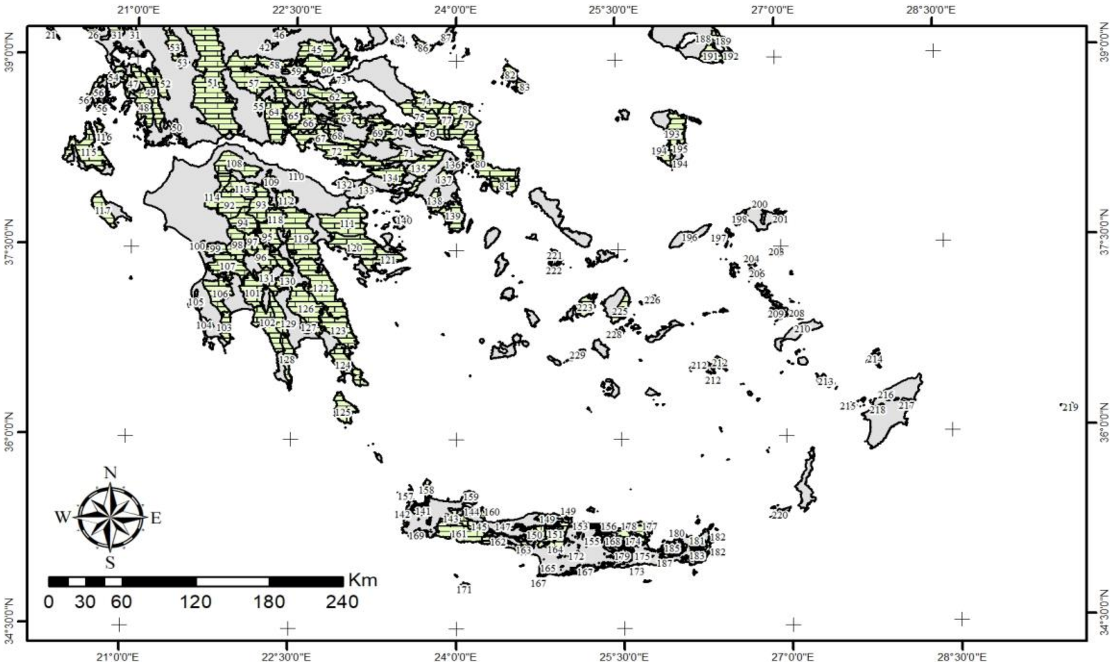

Fig. 9: Karstwater systems in South Greece.

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.

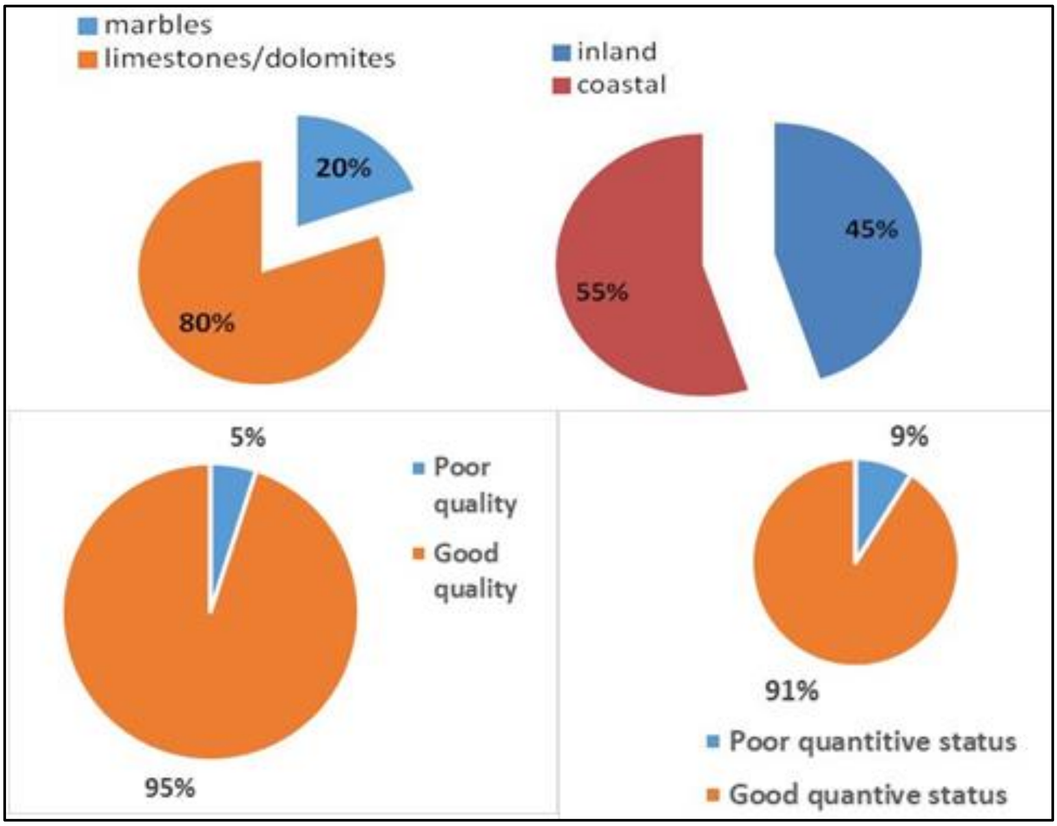

Fig. 10: Percentage (%) of different categories of karst aquifer systems in Greece.

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 m^3/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^{-6} m/s and the groundwater velocity in karstic aquifers ranges between 7.8 x 10^{-3} -7.2 x 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 x 10^{-3} and 8.3 x 10^{-2} m^2/s. The yield of boreholes drilled in karst aquifers has a wide range of values; 4 x 10^{-3} m^3/s to 9.7 x 10^{-2} m^3/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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