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Management and research strategies of karst aquifers in Greece: Literature overview and exemplification based on hydrodynamic modelling and vulnerability assessment of a strategic karst aquifer

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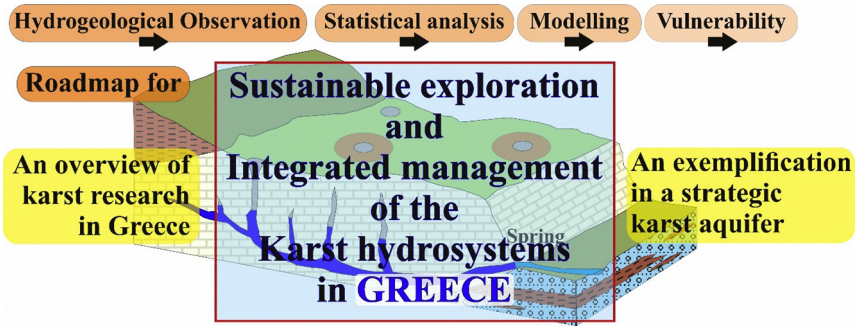
HIGHLIGHTS

- An overview of Karst aquifer researches in Greece was obtained.
- Hydrodynamic analysis was coupled with vulnerability assessment.
- The novel PaPRIKa plugin was used for the vulnerability assessment.
- The importance of allogenic Rivers was highlighted.
- A road map for sustainable exploration and integrated management was developed.

GRAPHICAL ABSTRACT



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ABSTRACT

Karst aquifers are valuable water resources in terms of quantity and quality, hence, their protection and rational management is of utmost importance to sustain water supply. An overview of research articles regarding Karst aquifers in Greece was obtained revealing that progressively the initial simple statistical analysis was replaced from advanced tools but rarely coupled. Additionally, a combined approach including the concept of groundwater vulnerability and pollution risk in conjunction with statistical and hydrodynamic analysis was performed in the complex karst aquifer of Damasi-Titanos in Thessaly Central Greece.

The karst aquifer discharges via three springs and it is in dynamic interaction with one of the two rivers that cross the system. The water demands of the area are mainly met with groundwater from the karst aquifer rendering its protection fundamental priority for the sustainability of the area. The hydrodynamic analysis of the karst system was performed by pairing statistical techniques and KarstMod. The analysis revealed a high correlation between the springs that highlights the karstification maturity of the aquifer. Additionally, spring discharge is mainly controlled by the percolation of River Titarisios rather than precipitation. Following the hydrodynamic analysis, the PaPRIKa method was applied and validated using sensitivity analysis in order to assess the intrinsic vulnerability. The vulnerability and hazard maps were combined to produce the pollution risk map of the karst aquifer. The majority of the karst aquifer is characterized by high to very high vulnerability as well as pollution risk.

The case study and the obtained overview revealed that a holistic approach can provide mutually supported results increasing their reliability. In this base, a four-step road map including hydrogeological observation,

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statistical analysis, modelling and vulnerability assessment is suggested in order to obtain the sustainable exploration and integrated management of karst aquifers in Greece.

1. Introduction

Karst aquifers constitute the drinking water source for almost a quarter of the world's population (Ford and Williams, 2007). Ford and Williams (1989) estimated that carbonate rocks cover 12% of the Earth's continental area, while karst regions occupy about 7–10% of the planet. Despite their low surface coverage, karst aquifers are usually positioned underneath a thick sediment cover and hence can be considered one of the most important aquifer types (Bakalowicz, 2005). Karst aquifers are the result of the karstification process which involves the solution of carbonate minerals (calcite and/or dolomite) due to the acidity of water that contains dissolved CO_2. The process is driven by climatic conditions because dissolved CO_2 concentrations are controlled by temperature and atmospheric CO_2 partial pressure (Bakalowicz, 1992). Knowledge of the hydrogeological and hydrodynamic characteristic of a karst aquifer is essential to adapt exploitation management practices and protection measurements. When these characteristics are neglected the productivity of karst aquifer may be over/underestimated and the system can be depleted by over/underexploitation. Additionally, when protectiveness is taken for granted groundwater quality deterioration occurs. The internal structure of a karst aquifer can be studied by analyzing spring hydrograph shape (ex. White, 2002). However, discharge of karst springs is strongly dependent on rainfall events and/or diffuse river recharge (ex. Manga, 1999). According to future climate projections, a large decrease in precipitation is predicted in the Mediterranean region and this may cause a reduction in the quality and quantity of karst water resources (Christensen et al., 2007).

Karst aquifers of Greece include the aquifers developed in carbonate rocks: sedimentary (limestones and dolomites) and metamorphic rocks (marbles). Carbonate rocks occupy about 35% of the surface area of Greece and are mainly located in the western, central and southern parts of the country (Daskalaki and Voudouris, 2008). Carbonate rocks in Greece mainly date from the Triassic to the Cretaceous periods, whereas marbles have a Paleozoic-Mesozoic age.

According to Katsanou and Lambrakis (2017), karstification of Hellenic karst can be distinguished into three stages: a) Upper Cretaceous to upper Miocene/early Pleiocene period during which the warm and humid conditions of a savanna climate type drove the karstification process of palaeokarst, b) Mid-glacial to the mid Pliocene/Holocene period where younger karst developed under warmer conditions with higher humidity than the recent ones, and c) late karstification stage that occurred under recent climatic conditions and formed younger karst. The majority of karst hydrosystems in Greece were formed during the second karstification stage, while the majority of the country's karst aquifers have a holokarst type shape. Karst aquifers are more abundant in the western part of Greece. This region receives high amounts of precipitation that can reach up to 1800 mm/year. In contrast, significantly lower precipitation of up to 600 mm/year occurs in the eastern part of the country (Mimikou, 2005). Nevertheless, water demands are geographically opposed to precipitation distribution because the main agricultural activities are located in the lowlands of eastern Greece.

The prefecture of Larissa is a representative example of where excessively irrigated agriculture in conjunction with relatively low groundwater recharge rates has led to groundwater depletion and quality deterioration. The karst system of Damasi-Titanos is located in this region and is the main drinking water source for the cities of Larissa and Tyrnavos which house a total population of 175,000. Additionally, numerous wells exploit this karst aquifer and supply water for local agricultural and livestock activities. Indisputably, the karst system constitutes a strategic resource of water in the region and preserving its quantity and quality is of the utmost importance for the sustainability of the wider area. The complexity of the site's hydrogeological and hydrodynamic regime also stipulates wider scientific interest for this karst aquifer. Three springs discharge the aquifer, two rivers cross the system, and agricultural activities cover a significant part of its surface.

Considering the strategic importance of the Damasi-Titanos karst aquifer in terms of quantity and quality, the aims of this study were to a) determine the hydrodynamic interactions between the system's allogenic rivers and springs, and b) assess resource vulnerability and groundwater pollution risk.

First an overview based on the published scientific results (included in Scopus platform) was performed to present the applied tools and approaches in karst hydrosystem research in Greece. Second, a two steps methodological approach was developed to meet the aims of Damasi-Titanos karst aquifer study: 1) Hydrodynamic analysis of the karst system was performed by pairing statistical techniques and KarstMod, 2) Following the hydrodynamic analysis, the PaPRIKa method was applied with the novel QGIS-environment plugin and validated using sensitivity analysis in order to assess the intrinsic vulnerability. The vulnerability and hazard maps were combined to produce the pollution risk map of the karst aquifer.

Finally, in addition to our case study limitations the overview was the base to develop a road map suggesting mandatory steps from field survey to modelling and protection to achieve the sustainable exploration and integrated management of Greek karst aquifers.

2. Overview of karst system research in Greece

The research interest of karst aquifers in Greece was significantly increased during the period of 1970 due to the increasingly water demands for agricultural, livestock, domestic and industrial use. During that period, the exploitation of karst aquifers was mainly limited to the discharge of springs. Additionally, there was no significant pollution stressors to karst aquifers due to their location at hilly and mountainous parts of Greece. Nevertheless, the socioeconomic development of Greece in conjunction with the population rise resulted in the expansion of agricultural land and industrial activities also in the karst aquifers boundaries. Similarly, to Damasi-Titanos karst system, the first studies were performed with National founding while the research groups consisted of mixed hydrogeological groups with researchers from Greece, France, Germany and other countries (SOGREAH, 1974). The boundaries of the karst systems were initially defined according to the geological maps, while spring discharge was measured during that studies. Additionally, groundwater quality was monitored in the majority of the karst systems mainly in spring's discharge. The Greek Institute of Geological and Mineral Exploration (IGME) conducted numerous studies (unpublished reports) for the characterization of karst aquifer systems including works such as: geological mapping, construction of boreholes, pumping tests, chemical analysis, meteorological analysis and discharge measurements of karst springs. In many cases the collected data from the agencies where the basis for further analysis and karst aquifers characterization. The first research included four karst systems – Korissos-Militsa, Voula and Xerovouni – aiming to determine the effective infiltration based on empirical methods such as Turc's, Countagne's and Thornthwaite's and Mather's (Soulios, 1984). Drogue and Soulios (1988) studied the salt water flow into the natural cavities of karst aquifers along the coast of Kefalonia Island. The first attempt for the characterization of karst systems based on hydrographs analysis was obtained at the early 1990s (Soulios, 1991). After the decade of 2000, groundwater depletion and quality deterioration of