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SUSTAINABLE DEVELOPMENT OF KARST AQUIFERS IN THE MEDITERRANEAN BASIN AND ADJACENT AREAS FOR WATER SUPPLY: AN OVERVIEW

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INTRODUCTION

The soluble karstic rocks occupy approximately 20% of the planet's ice-free land, of which around 10-15% is extensively karstified; however, the contribution of karstic aquifers to the world's potable water supply is higher, in magnitude of 20-25%. The Mediterranean basin and the adjacent areas are characterised by abundant but still not fully utilised karst groundwater reserves. Although some authors (Margat, 1998) estimate that carbonate outcrops cover at least 15% of the Mediterranean surface and that carbonate aquifers provide for at least 25% of the domestic water supply - not counting industrial, agricultural, and tourist consumption - our assessment is that these two figures should be increased by at least 5-10%, respectively. This has been confirmed by the on-going WOKAM project (World Karst Aquifer Map), conducted by a team of experts of the International Association of Hydrogeologists (IAH) and the German Geological Survey, and supported by many local experts as well (Goldscheider, Chen, *et al.* 2014).

KARST AQUIFER REGIONALISATION

This part of Europe is considered the classical karst region; not only was the term "karst" coined in this area (the German derivation of the local name "Carso"), but a new scientific discipline – karstology – was also established there at the end of the 19th century by a group of researchers led by Jovan Cvijić (1893).

The Mediterranean karst was created in the Tethys sedimentary basin and it includes three sub-groups: *Littoral*, *Hilly-Mountains* and *High Alpine karst*. The islands (Mallorca, Malta, Sicily, Sardinia, Corsica, Crete, etc.), shorelines and adjacent coastal areas of Northern African and Near East countries, Turkey, Greece, Albania, former Yugoslavia, Italy, France and Spain belong to the *Littoral* group. In the Iberian Peninsula, the major *Hilly-Mountains* structures with carbonate and evaporitic rocks are found in Andalucía and Murcia provinces in the South (e.g. Sierra Morena, Sierra Nevada), as well as in the Pyrenees and its foothills. In Southern France they are: Massif Central, Provencale Mts. and the Alps, which consist predominantly of carbonate rocks. The Apennines are a major Italian reservoir of karstic waters, while SE Europe has large karstic aquifers in the southern Alpine branches and mountain ranges that surround the basin: Dinarides, Pindes, Hellenides, Carpathians, Taurides massifs (Fig. 1). *High Alpine karst* extends over the central Alps. In the Eastern Mediterranean and in Northern Africa there are two types of structures: *platform, slightly deformed karst,* often covered by younger sediments (e.g. Bekaa Plain in Lebanon or Cyrenaica in Libya) and *orogenic karst* of the

mountain ranges. Structures such as Lebanon Mountains (Jebel Liban) and Atlas Mountains in Algeria and Morocco (A. Tellien, A. Saharien, Haut, Moyen and Anti Atlas) belong to the latter group.
Bakalowicz (2015) distinguishes three major events which caused the development of specific karst drainage structures that produced the various characteristics of Mediterranean carbonate aquifers:
– the Messinian Salinity Crisis (MSC) at the end of the Miocene (5.9 to 5.3 Ma), which caused rivers to incise deep valleys in order to reach the remaining sea, 1500–2500 m below the present sea level;
– cold periods during the Quaternary that caused weathering of the epikarst, even its destruction, which led to the development of a thick sediment cover above the elevation of 1000 m; and
– post-Miocene tectonics that generated hydrothermalism and deep CO_2 flux, causing continental sediments to fill in the large basins in compressional environments.

- During MSC thick gypsum and salts were deposited in numerous small isolated hypersaline basins while along today's French coast very deep, now submerged, canyons were created as a result of intensive karstification and much deeper position of the erosional base level. One of such submarine canyons, more than 300m deep, is evidenced in Cassidaigne near Marseille (Gilli, 2001). Such deep karstification resulted in the fact that today over 90% of all the known submarine springs in the world are located in the Mediterranean basin (Fleury *et al.*, 2007).

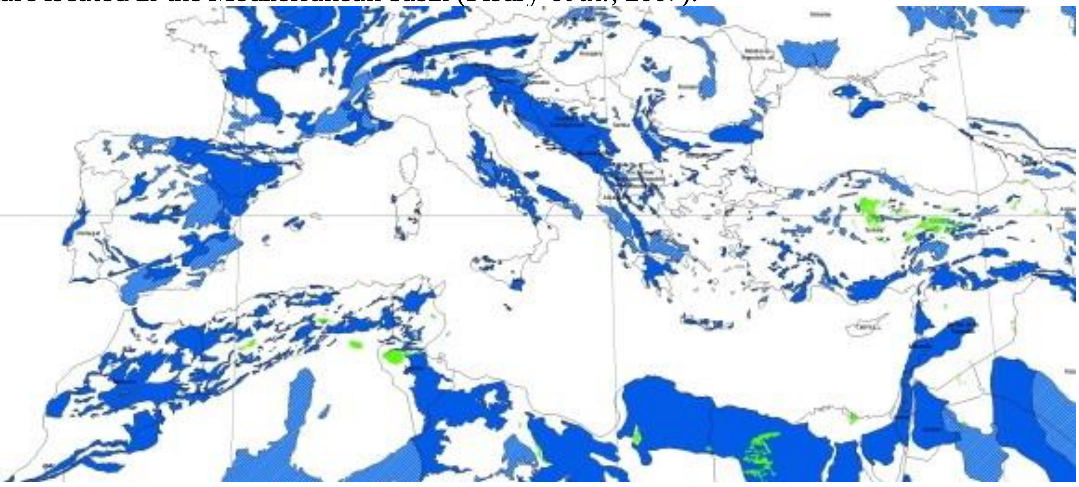

Fig.1 A part of the preliminary WOKAM map: Karst distribution in the Mediterranean basin and adjacent areas

- Mediterranean karst is very rich in various surficial and underground features. The mountain karstic relief is dissected by numerous karstic poljes and wide valleys and characterized by rough relief, steep slopes and highly folded rocks. For instance, the Dinarides contain all types of karst landforms and features (Cvijić, 1893; Herak, 1972; Stevanović 2009). As an example, the number of sinkholes (dolines) in certain Dinaric areas can reach 150/km^2; the world's largest karst polje, Livanjsko Polje, covers the area of 380 km^2; Herak (1972) confirmed that more than 12,000 caves have been explored in former Yugoslavia alone, more than 5,000 being in Croatia. At the Kameno more („Stone Sea") and the Orjen Mountain above the Bay of Kotor (Montenegro), more than 300 vertical shafts were registered within an area of only 8 km^2, with depth of 200-350 m (Milanović, 2005).
- In areas where karst is overlaid by younger sediments, the karstification may continue to occur hypogenically, depending on the faulting and fissuration and equally on the presence of thermal and CO_2 fluxes. In areas where karst is overlaid by younger sediments, In some parts of Tunisia or Algeria (*Intercontinentale Calcaire*), several very deep karstic structures of Upper Cretaceous or Paleogene ages, tapped by deep wells, represent the single source of water supply. Due to temperature which sometimes exceeds 50-60^{0}C, this water must be cooled before being delivered to consumers.

The climate conditions in the Mediterranean basin are quite diverse: from glacial karst at the top of the Alps to the semi-arid and arid karst in North Africa. The karstified rocks recharge predominantly from precipitation, and average infiltration rate can be very high (e.g. in certain karstic areas: 38% in Algeria, 53% in Tunisia and Israel, 69-78% in Italy; from Stevanović, 2015a). In addition to this, many perennial or temporary streams sink their waters into ponors located in karstic terrains. This is why more than 50 kilometres of riverbed of the largest European sinking stream, Trebišnjica, have been regulated in the 1970s. Prior to that, Popovo polje was almost completely dry for more than 150 days per year.

DRAINAGE AND UTILISATION OF KARST AQUIFERS

Many of the world's largest springs are draining Mediterranean karstic aquifers. The "king" among them is Fontaine du Vaucluse, in Southern France. The spring is not the world's largest if we consider its capacity – its average discharge is 20 m^3/s – but it became the *locus typicus* for all the world's ascending springs outflowing from lake-like structures (they are now called *vauclusian*). Marseille and other coastal towns heavily depend on karstic springs, but the mixing of fresh and saline water represents a major problem. This is why many specific intake structures have been constructed (e.g Port Miou, Potié *et al.* 2005).

In Italy, there are a few hundred large springs (Fiorillo, 2009). Perhaps the most famous and largest spring on the Northern Italian coast is Timavo, which supplies water to Trieste (average discharge Q=30 m^3/s). This is a group of springs discharging at or below the sea level, and one of the first tracing experiments in the world proved their connection with the sinking Reka River, on the Slovenian side of the border. During certain periods, the ancient Rome was supplied with 13 m^3/s of mostly karstic waters from several aqueducts, of which Aqua Marcia, constructed in the 2nd century BC and 90 km long, was one of the first (the Aniene catchment). Today, the city of Rome obtains more than half of its water from the karstic spring Peschiera (Q_{av}=18 m^3/s). Large cities in Southern Italy such as Naples and Bari are also supplied from large karstic springs such as Caposele, Serino, etc. (Fiorillo *et al.* 2015).

Along the Adriatic and Ionian coastal areas there are plenty of springs and their position had dictated the establishment of ancient settlements and – later on – big Roman cities (Split –Spalato, Dubrovnik – Ragusa, etc.). As such, Rižana karstic spring (Q_{av}= 4 m^3/s) is the main water source for all Slovenian coastal cities, while Riječina spring along with Zvir gallery is supplying potable water to Rijeka city and port (Q_{av}= 8 m^3/s). Jadro spring (Q= 0.5-70 m^3/s) supplies drinking water to Split, while Ombla spring (Q= 2.3 - >150 m^3/s), with >90% of its catchment in the neighbouring Bosnia and Herzegovina, represents the main water source of the city of Dubrovnik. The two latter springs are good examples of the importance of local barriers that prevent mixing of fresh karstic and sea waters (Fig.2). These local barriers, present in many locations along the coast, consist of impervious flysch sediments, and their existence increases the chances of avoiding the mixing of waters. In case of Jadro spring the barrier is high, almost 50m above the sea level, while in the case of Ombla the contact between Eocene flysch and Cretaceous karstic aquifer occurs at the altitude of only 2.3 m. Some other springs along the Bay of Kotor in Montenegro are discharging at or below the sea level as submarine springs, but their upper channels can activate an overflow during the periods of flooding. Such is the case of Sopot spring, one of the world's largest springs as regards maximal discharge (Qmax > 150 m^3/s), or Ljuta spring (Radulović, 2000). Before the new system was constructed (Bolje Sestre spring, Stevanović, 2015b), supplying water from the Skadar basin, the city of Kotor had used water from the Škurda spring, which issues directly at 0,0 +/- few cm. asl. As a result, and depending on the pressure in the aquifer, the local population had consumed water that was always more or less brackish. The situation is not much different in the case of Almyros, the largest spring on island Crete in Greece, which supplies Heraklion with potable water. The spring issues at the elevation of 5 m asl, but the deeper part of the aquifer is under the strong influence of salt. The spring discharge varies from 3.3 to 30 m^3/s and the problem with salinity starts with the discharge lower than about 15 m^3/s (during the minimal yields, concentration of the Cl ion reaches 6 g/l). The concrete dam constructed at the discharge point in order to increase the fresh water level only partly mitigates the problematic brackish flux (Mijatović, 2005).

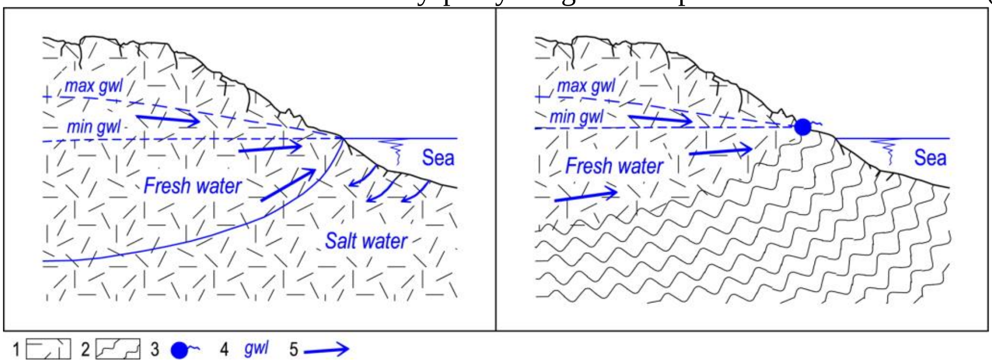

Fig. 2 Left: Direct interface between fresh and salty water; Right: Flysch barrier is preventing the mixing and dictates the position of the spring which drains fresh waters from the karstic aquifer. Legend: 1. Karstic aquifer, 2. impervious flysch sediments, 3. spring, 4. groundwater level, 5. groundwater flow direction

Similarly, many coastal water intakes in Libya and Tunisia have faced saline intrusions due to forced over-pumping. In contrast, the Bistrica group of springs in Albania (including the well-known "Blue Eye" spring) has an impervious barrier at over 100 m asl. With its minimal discharge of 12 m^3/s (Eftimi, 2010), it is becoming a candidate for water export to the Puglia province in Italy through a 70 km-long overseas pipeline.

Concerning the spring discharge, of the 124 large springs in this wide region which are included in WOKAM database, 28 or 1/5 have a minimal discharge greater than 2 m^3/s which represents key evidence of water availability. The largest is the famous Dumanli spring in Turkey (38 m^3/s), nowadays impounded by the Oymapinar reservoir. As regards regional distribution, the largest number of springs regularly discharging over 2 m^3/s are in Bosnia and Herzegovina (8) and Turkey (8), followed by Montenegro (5).

In terms of proportion of karst waters in water supply systems, Montenegro, with over 75%, and Austria, with over 50%, are the leaders in the region. In some other countries (Italy, Croatia, Slovenia, Bosnia and Herzegovina, Turkey) the percentage is lower but still considerable. The population of six capitals in the wider Central and Eastern Mediterranean region consumes water exclusively or dominantly from karst (Vienna, Rome, Sarajevo, Tirana, Podgorica, Skopje). The population of neighbouring countries such as Bulgaria, Serbia and Romania also uses a considerable percentage of karstic sources for national potable water supply (ca.15-20%). However, the availability situation is not favourable everywhere, and over-extraction is present in Lebanon, Morocco and Syria. In the latter country, one of the largest springs – Ras el Ain – has completely dried out as a result of forced pumping for irrigation on the Turkish side of the border. This is just one of the many examples indicating the importance of sustainable transboundary water management. Moreover, engineers and water managers are facing many problems in their attempt to ensure water provision: due to the unstable regime of karstic springs, the main challenge for most of the waterworks is to overcome water shortage during recession periods, which coincide with summer and early autumn months when consumption is also at its highest. Several successfully completed projects based on utilisation of groundwater from considerable storage in the deeper parts of aquifers provide a new prospect for development of aquifer systems in many locations, as has been done in Lez (Montpellier, France) and Bolje Sestre (the Montenegrin coast).

From the standpoint of water quality, these are mainly waters of high natural quality that do not require expensive treatment if they are not artificially polluted. In the event that pollutants do exist, extremely vulnerable karstic aquifers with low attenuation capacity require special protection measures which, in some cases, may result in imposing four or more protection zones with different preventive measures.

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