

Karst at depth below the sea level around the Mediterranean due to the Messinian crisis of salinity. Hydrogeological consequences and issues

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ABSTRACT. For many Mediterranean countries, karst aquifers offer an essential water resource. Their characteristics are mentioned as well as the specificity of Mediterranean karsts, determined by a particular climate and over all a recent complex geological history. The Messinian Crisis of Salinity (MCS), a major event which occurred 5.3 My ago, allowed the development of valleys and karst very lowly below present sea-level. Ignored by hydrogeologists and karstologists until the 90's, the MCS is now considered as a major period for developing karst conduits at great depth below the present sea level. The karst system of Chekka, Lebanon, and its large submarine springs are taken as an example to show the functioning of such coastal aquifers. The main consequences are here presented and analyzed in order to point out the absolute necessity for improving the knowledge on karst aquifers and regional hydrogeology. Karst submarine springs, typical of Mediterranean coasts, are considered as a non-conventional interesting resource, what will be discussed. The main issue is an efficient and sustainable management and protection of these groundwater resources in regions where the population density is highest and the economic activities are concentrated. Some new avenues of research and development are proposed.

KEYWORDS: coastal aquifer; karst groundwater; submarine spring; monitoring

RÉSUMÉ. Dans de nombreux pays méditerranéens, les aquifères karstiques sont une ressource en eau essentielle. Leurs caractéristiques sont décrites ainsi que la spécificité des karsts méditerranéens, déterminée par un climat particulier et surtout une histoire géologique récente complexe. La Crise Messinienne de Salinité (CMS), un événement majeur qui s'est produit il y a 5,3 Ma, a permis le développement des vallées et de karst très au-dessous du niveau marin actuel. Ignorée par les hydrogéologues et les karstologues jusque dans les années 90, la CMS est maintenant considérée comme une période essentielle pour le développement de conduits karstiques à grande profondeur sous le niveau marin actuel. Le système karstique de Chekka au Liban, et ses grandes sources sous-marines sont pris comme exemple pour montrer le fonctionnement de ces aquifères côtiers. Les principales conséquences sont présentées et analysés ici afin de montrer la nécessité absolue d'améliorer les connaissances sur les aquifères karstiques et l'hydrogéologie régionale. Les sources sous-marines karstiques, typiques des côtes méditerranéennes, sont considérées comme une ressource intéressante non-conventionnelle, ce qui sera discuté. Le principal problème est une gestion et une protection efficaces et durables de ces ressources en eaux souterraines dans des régions où la densité de population est la plus élevée et les activités économiques sont concentrées. Quelques nouvelles pistes de recherche et de développement sont proposées.

MOTS CLÉS: aquifère littoral; eau souterraine karstique; source sous-marine; monitoring

1. Introduction

Most of the karst submarine and brackish coastal springs of the world discharge along the Mediterranean coasts. Some of them are supposed to have the highest fresh water discharge into the sea among all known submarine springs (Kareh, 1967). The increasing water demand and the thought of lack of fresh water because of climate change make that relevant investigations about this non-conventional water resource are proceeded.

Another reason for this renewed interest is the geological evidence of the fundamental part plaid by the Messinian Crisis of Salinity (MCS) in the development of fluvial and karst landscapes well below the present sea-level (Clauzon, 1982; Rouchy et al., 2006). This important recent advances made on the geology of the Mediterranean basin allow the issue of submarine groundwater discharge from karst aquifers to be tackled in new terms.

Since approximately twelve years several academic as well as applied studies on Mediterranean coastal karst aquifers (Arfib, 2001; Bakalowicz et al., 2007; Cavalera, 2007; El-Hajj, 2008; Fleury, 2005; Fleury et al., 2007a, 2007b, 2008) were dedicated to submarine and coastal springs which look interesting to exploit in regions where water demand is increasing with economic development. Many aspects of their functioning still remain very unclear, especially the depth of karst development, the role of sediment infilling, the development of special karst in the fresh – sea water mixing zone (Plummer, 1975). However the broad outline of the structure and functioning of Mediterranean coastal karst aquifers with submarine outlets are presently known, so that it is possible to make some suggestions about the exploitation of their groundwater resource.

2. The Messinian Crisis of Salinity (MCS)

Around 5.96 Ma because of the northward movement of the African plate, the strait between the Atlantic Ocean and the Mediterranean Sea closed, stopping the ocean water inflow into

the Mediterranean (Clauzon, 1982; Rouchy, 1999; Krijgsman, 2002; Rouchy et al., 2006; Bache et al., 2009). The evaporation in the Mediterranean basin, much higher than the fresh water inflow from rivers and groundwater, is normally counterbalanced by an inflow from the Atlantic Ocean. In the absence of this inflow an important water balance deficit occurred, producing a drastic lowering of sea level and important salt deposition in the remaining basins. The sea level dropped down by 1500 to 2500 m in some tens of millenniums, partly corrected by uplift (Krijgsman, 2002; Gargani, 2004; Jolivet et al., 2006; Rouchy et al., 2006; Krijgsman et al., 2010).

A threshold appeared between Italy and Tunisia, dividing the Mediterranean at least in two independent basins, the western and eastern basins (Krijgsman et al., 2010). In the western basin, restricted oceanic water inflow fed salt deposits, creating very thick evaporate deposits (300 km³). In the eastern basin, no oceanic inflow occurred; consequently, the sea level was probably lower and the evaporate deposits are thin (1 km³).

Around 5.33 Ma the opening of the strait of Gibraltar by erosion caused a sudden inflow. This is defined as the beginning of Pliocene (Zanclean, 5.3 Ma). The flood filled up the Mediterranean basin in a few decades, lowering the global ocean by 15 m (Blanc, 2002). The main lower valleys were completely flooded. The MCS had very important geomorphic consequences which are not yet fully known. Although the crisis of salinity was identified during the 70's, the process and its consequences were roughly understood and described later (Clauzon, 1982; Rouchy et al., 2006).

The main rivers deeply cut the bottom of their valley to reach the low sea level. Several hundred meters deep canyons are known below Pliocene and Quaternary sediments in some of the main valleys. For instance the Rhone River valley was dug up to Lyon, deep of about 600-700 m near Avignon. The Nile River deepened its valley up to Cairo and Aswan. The flooding of the Mediterranean basin at the beginning of Zanclean caused a thick infilling of marine blue clays along the coasts and in the valleys

which blocked up all groundwater flows, particularly from karst aquifers. Where the main rivers flowed, alluvial fan sediments (Gilbert deltas) topped the blue clays. Present investigations by means of geophysics reveal aerial morphologies now flooded and partly plugged by Pliocene sediments (Le Strat et al. 2004; Gorini et al., 2005; de la Vaissière et al., 2007; Arfib & Douchet, 2011).

3. Karst around the Mediterranean Sea

In carbonate rock aquifers, karst processes develop a conduit system, which is an integrated set of voids, draining groundwater for discharging it at a spring (or a group of springs). The spring is located at the lowest elevation allowed by the carbonate formation, defined as the base level. It is either the bottom of a valley, or the sea coast, or the bottom of the geological formation.

Any change in base level changes the spring location. A lowering of the base level causes the lowering of the spring and of the conduit system, i.e. the return of karst development at least in the lower part on the carbonate formation. At the opposite, a rising of the base level results in the flooding of at least the lower part of the conduit system and the overflow of the aquifer at higher elevation, potentially rejuvenating abandoned karst structures. Such events occurred during tectonic phases, creating superimposed conduit systems, well known for instance in the Alps, and flooded karst aquifers in foreland basins.

The MCS was a major crisis in terms of base-level changes. The duration was geologically short (0.6 My), but fully compatible with the time required for developing new conduit systems, i.e. a few ten thousand years. Thus the drop in sea level could contribute to the development of karst conduits deeply below the present sea level to join either the bottom of the main valleys or the base of carbonate formations. The maximum potential is around -1500 m below present sea-level.

In 1979, two pioneers in karst hydrogeology J.V. Avias and B. Gèze assumed that deep conduits discharging at springs such as Lez spring and Fontaine de Vaucluse, in southern France, were the consequence of the MCS, unfortunately without any explanation (Gèze, 1979). In fact the consequences of the MCS on Mediterranean karst were confirmed in 2001 by a BRGM team working on coastal karst aquifers (Doerfliger et al., 2001; Aunay & Le Strat, 2002; Le Strat et al., 2004), and afterwards by Arfib (2001), Fleury (2005), Mocochain (2007), Cavalera (2007), El-Hajj (2008), during their PhD studies. European projects were dedicated to the study of Mediterranean coastal karst aquifers and karst submarine springs (Tulipano et al., 2004; Bakalowicz et al., 2007). They all agree in showing that karst structures do exist

at depths of several hundred meters below present sea-level, in Crete Island, France and Lebanon.

The fact that most karst submarine springs in the world, and especially the deepest, occur along the Mediterranean coasts (Fleury et al., 2007b) indicates that they should be all related to conditions specific to the Mediterranean basin (Fig. 1). The MCS, which probably followed two or more similar crises during the upper Miocene (Rouchy & Saint-Martin, 1992; Krijgsman et al., 2010), created a very high karst potential, very efficient for rapidly developing conduit systems in the numerous carbonate massifs outcropping around the basin. The karst potential, or potential for developing karst (Mangin, 1994; Bakalowicz, 2005) is the set of conditions controlling the development of conduit systems in soluble rocks, including the flow energy and the solution capacity. The flow energy is controlled by rainfall and the hydraulic head, which reached its highest values during the MCS. The rainfall and the solution capacity were also high, under tropical humid climate conditions favoring plant cover development and soil CO₂ production (Rouchy et al., 2006). For these reasons, other types of karst development, such as hypogean (Klimchouk & Ford, 2000) or ghost karstification (Quinif, 2010) were never considered. Moreover it is unlikely that these special types of karst could be generalized and developed in all Mediterranean carbonate rock massifs to explain the existence of karst conduits below the present sea level.

The opening of the Strait of Gibraltar marked the end of the MCS. The sudden rise of the sea level at the beginning of Zanclean flooded the entire basin, including the river valleys. The thick marine blue clays carried by the main rivers were not deposited everywhere along the coasts. Consequently some aquifers and their conduit systems were completely blocked isolated from the sea, by the thick Zanclean clay formation. These aquifers do not discharge any groundwater off-shore and are protected from natural sea-water intrusion.

Some other karst aquifers were covered by lowly permeable formations, such as Pliocene basalts (Al-Charideh, 2007), allowing groundwater leakage through the rock cover. The aquifer which is then confined on shore leaks through its cover as fresh water diffuse discharge at small springs scattered over a large submarine area. They also are protected from natural sea-water intrusion by the high hydraulic head in the aquifer. Karst aquifers connected to a large river valley, flooded by the sea at the end of the MCS are now completely isolated by the thick impermeable formation deposited during Pliocene and Quaternary (Mocochain et al., 2006, 2009).

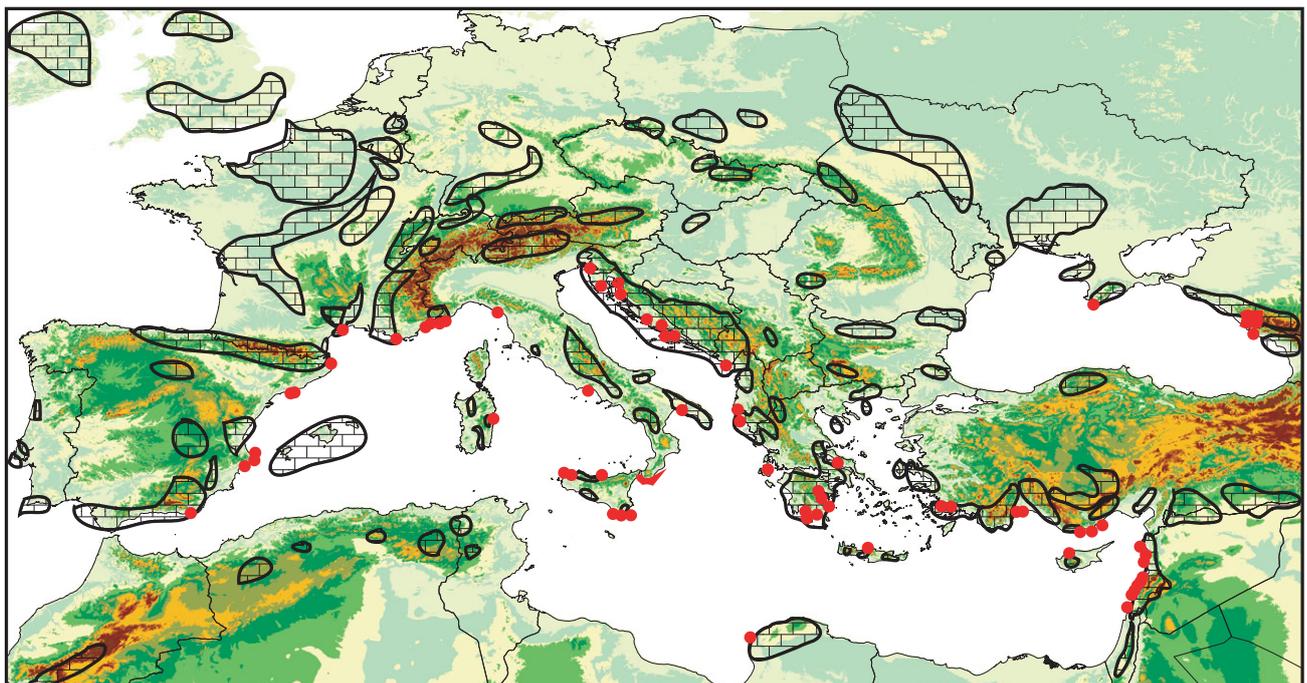


Figure 1. Map of Mediterranean karst areas with their coastal or submarine springs.

In fact many carbonate aquifers are not plugged with impermeable sediments, because of either the erosion or non-deposition of plugging or covering sediments. The sediments were easily removed later by floods during rainy seasons, what is typical of karst functioning. These aquifers are subject to a normal karst functioning in their shallow submarine part. They are characterized by concentrated discharge related to karst features, such as former outlets or most frequently sinkholes or collapsed conduits. This type of coastal carbonate aquifer is particularly common along the Mediterranean coasts, characterized by spectacular groundwater discharge during flood seasons. The conduits discharge fresh or brackish water at Karst Submarine Springs (KSMS). These aquifers are naturally subject to sea-water intrusion, even at great depth: >600 m at Almyros Heraklion, Crete; >200 m at Port Miou, Marseille, France, as demonstrated by recent studies (Arfib et al., 2007; Arfib & Douchet, 2011).

4. The Chekka karst system as an example

Several KSMS were studied in France (la Vise, Thau lagoon; Mortola, French Italian border), Spain (Toix and Moraig), Turkey (Gökova), Syria (Banyias) and Lebanon (Chekka). The aquifers discharging at La Vise, Gökova and Banyias are partially plugged, confining the aquifer in its coastal part and spreading its discharge at a vast number of small springs. Moraig and Chekka aquifers are not plugged at all, showing karst conduits directly open to the sea, what allows the understanding of natural sea-water intrusion.

We present here the main results from investigations on the Chekka system, which is the best documented thanks to the PhD of El-Hajj (2008).

The Chekka bay located in northern Lebanon is known for the huge amount of fresh water discharging at several KSMS especially during the flood season, during winter and spring. The first hydrogeological investigations were done in the frame of a UN project concerning the assessment of groundwater resource of Lebanon during the 60 and 70's (Kareh, 1967). Since that time our knowledge of karst hydrogeology as well as of geology of Lebanon considerably improved what allows new investigations on this set of KSMS known as one of the most important submarine discharge in the world.

A dozen of permanent and seasonal submarine springs were identified in the bay. They all are located along the bottom of the flooded valley of the Asfour River (Fig. 2). They open at the top of the Cenomanian and Turonian limestone formation. In the Chekka area, the limestone dipping westwards is covered by Senonian white marl, deeply cut by the Asfour River which flows

on limestone in the bottom of the canyon. The valley extends off-shore in a rather flat area, compared to the on-shore landscape. The springs open at karst landforms, probably originally swallow holes or sinkholes, developed. Currently, they are permanently flooded and function as permanent (S1 to S6, from 5 to 30 m below sea level) or seasonal (S7 to S12, from 35 to 104 m b.s.l.) submarine springs, depending on the water head relations between groundwater and the sea. S2 spring is the main permanent one at 23 m b.s.l., with a supposed outflow of 2 m³/s during low flow for a total assumed to be 6 m³/s, and of some tens m³/s during floods (Kareh, 1967). The S12 seasonal spring was supposed by Kareh (1967) to discharge several tens m³/s during high floods. Kareh (1967) made a rough estimate of the total discharge by measuring at some places the vertical flow velocity above the sea bottom, at two seasons (high and low flow) integrating the data for the several springs and during a year. He supplemented his rough approach by an estimation of the extension of the recharge area and of the mean annual rainfall on it. He concluded that the total annual discharge was between 0.75 and 1 billion m³, i.e. 24 to 32 m³/s. The extension of the recharge area was roughly evaluated to be "around 700 km²", i.e. an area covering a large part of the North Lebanon region, comprising the basins of the main rivers. In fact, Kareh (1967) largely overestimated the recharge area, by including in it the basin of the Abou Ali River at North which has a permanent flow. That estimation was unrealistic.

El-Hajj (2008) showed that the total annual discharge is much lower. His hydrogeological study allowed the determination of the extension of the recharge area (about 154 km²). The boundary conditions were determined from detailed field surveys, identifying impermeable boundaries with no lateral exchange, sinkholes swallowing partly or totally rivers, and on-shore discharge at permanent and seasonal small springs. The input flow at sinkholes and the discharge of on-shore springs were measured. The agricultural, domestic and industrial withdrawals were estimated from administrative data and from personal inquiries (Aulong et al., 2009). The rainfall and the evapotranspiration were measured or calculated from climatic data (El-Hajj, 2008). The water balance indicates a probable total annual off-shore discharge around 68 millions m³, i.e. 2.15 m³/s. The main uncertainty is related to the rainfall. This total annual discharge is much lower than that assumed by Kareh (24 to 32 m³/s), which was considered by Lebanese scientists and stakeholders as the current coastal fresh water resource (Ayoub et al., 2002).

In order to check this assumption, the main submarine spring was provided with a monitoring device for pressure, temperature

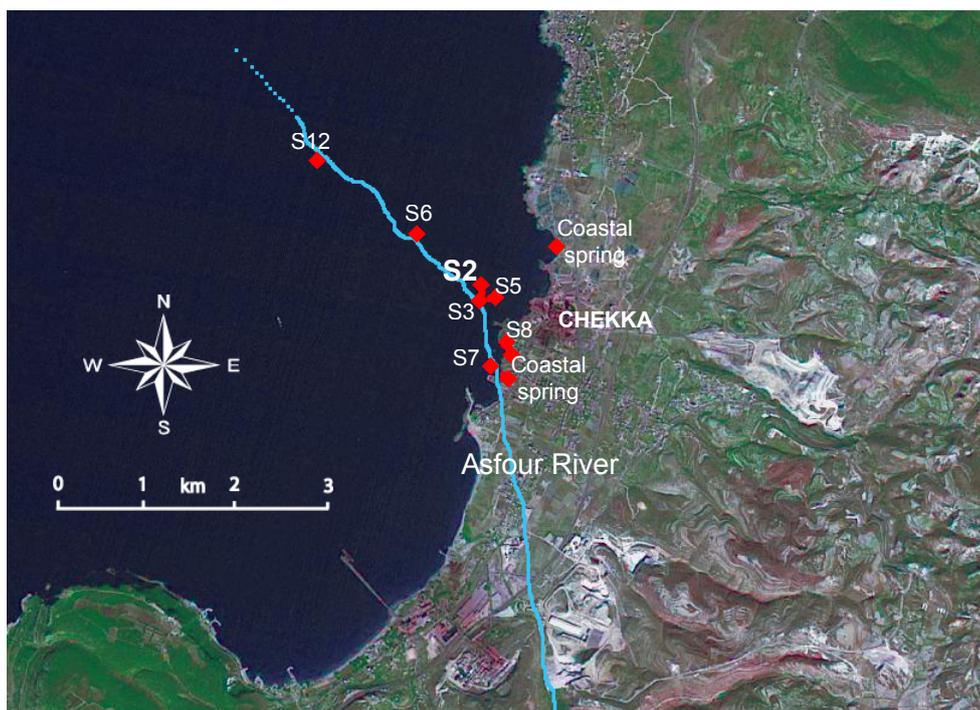
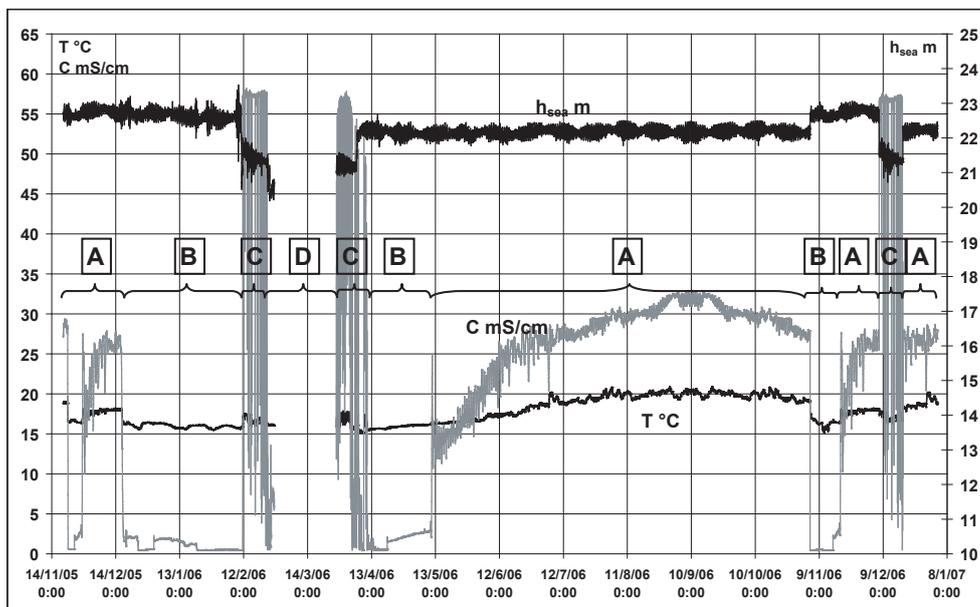


Figure 2: The Chekka bay and the location of the main submarine springs along the flooded valley of Asfour River.

Figure 3: Monitoring of sea level, water conductivity and temperature at submarine spring S2 at Chekka, Lebanon, during the 2006 hydrological year, from 2005, Nov. 20 to 2007, Jan. 3. The different phases A, B, C and D are explained in the text.



and electrical conductivity. After several destructions by floods and storms, a capturing system controlling most of the outflow at S2 was operated with a flowmeter added during the low flow season. The device allowed investigating the aquifer and submarine springs functioning. The data from the flowmeter are only reliable during low flow stage (flow < 200 L/s), the device being not working at high flow velocity. The main results are here briefly presented.

During winter and spring high flow, the outflow changes its characteristics very rapidly, from freshwater (conductivity around 500 μ S/cm) to brackish water (up to 24 mS/cm). The change occurs in few hours (Fig. 3), either decreasing with increasing discharge (beginning of flood), or increasing with decreasing discharge (beginning of the recession). Four phases are identified in the record, noted as A, B, C and D in Figure 3.

During phases A, the water conductivity is high, more than 12 up to 33 mS/cm, subject to daily changes of 5 to 7 mS/cm. At the beginning of the monitoring (November 2005, i.e. the end of the low flow season) the total outflow at S2 was 60 L/s with no daily change. The same total, constant flow was measured during the 2007 low flow, from July to October. During that time the conductivity increased from 30 to 38 mS/cm, i.e. from 58 to 68% sea water contribution.

During phase B, the conductivity is low (1 mS/cm or lower) without any daily change and the temperature is lower than during phase A by 1 or 2°C. During phase C very large changes occur from very low conductivity to high conductivity up to 58 mS/cm, the conductivity of sea water. The device was picked up for checking its good working order at the lab (phase D). The long delay for replacing it in S2 spring was due to the important storms and floods at that season which prevent diving operations.

Phases B are identified as the floods during rainy periods when freshwater flows out. Phases C are related to pumping tests done in a well of a cement factory located on the coast at about 800 m from spring S2. It caused a massive sea-water intrusion at S2 and probably at the other springs. The intrusion stopped each time pumping stopped, at least once a week. Unfortunately no information could be collected about it, the cement factory considering that it is an industrial secret.

5. Discussion

The functioning of the main Chekka KSMS S2 informs about the behavior of the aquifer and its relationships with the sea. During most of the year, the spring flow is low, less than 200 L/s, discharging brackish water in proportion to 20 to 68% of sea-water. This is the situation during phases A, typical of the low flow stage of the aquifer.

During phases B, occurring the rainy periods of winter and spring, all permanent as well seasonal springs discharge fresh

water, what characterizes the high flow stage. The high water head in the karst conduits prevents the intrusion of sea water. When recession occurs, the discharge, in the conduit, decreases as well as the water head. When the fresh-water head in the conduit is lower than the sea-water head, an intrusion of sea-water may occur in the conduits if they open at a greater depth than the main spring S2. Actually the S12 seasonal spring is a deep depression as a window open to the conduit explored by divers at 105 m b.s.l., i.e. much deeper than the S2. At S2, the sea-water head above fresh groundwater is 22 m, while it is 105 m at S12 when it stops flowing. Then sea-water intrudes easily and fast through the conduit at S12, pushing upwards fresh groundwater, mixing with it and flowing out at S2 and other permanent springs as brackish water. The inversion of flow at S12 does occur suddenly because of the conduit flow conditions.

The sea level changes periodically with the daily and monthly sea tide cycles, what modifies the water head relationship between groundwater and sea water, even under small changes less than 0.50 m. The rapid and large range of conductivity changes can be explained only by the exchange between the sea and the aquifer through conduits widely open to the sea.

The karstic structure developed at depth greater than 500 m, because the whole area is subject to an important uplift, 300 m at least since the beginning of Quaternary (Sanlaville, 1977; Gomez et al., 2006; Elias et al., 2007). That depth is consistent with a low sea-level at about 1500 m b.s.l. during the MCS, and not with low sea-levels during glacial events which lowered the sea level of only 120-140 m b.s.l. This is also consistent with other data from Port Miou, France (>200 m, Cavallera, 2007), Banyias, Syria (>200 m, Bakalowicz et al., 2007), and Almyros Heraklion, Crete (>600 m, Arfib & de Marsily, 2004).

During pumping test in an on-shore well (phases C), a sea-water intrusion artificially occurs at S2 spring. That shows that the well is certainly well connected to the conduit system. Therefore during the pumping, the water head in the conduits is lower than 22 m at S2 spring.

The rapid and large changes of groundwater quality related to sea tide or pumping in an on-shore well show that the coastal karst aquifer of Chekka is very sensitive to slight changes in water head in the conduit system. Consequently the coastal aquifer needs to be managed very carefully in order to avoid a general sea-water intrusion.

All the studied coastal karst systems present an interesting groundwater resource, with annual discharge around 600 hm³ in Gökova, Turkey, 200 hm³ in Banyias, Syria, 70 hm³ in Chekka, Lebanon, 125 hm³ at Port Miou, France (Blavoux et al., 2004). However the hydrogeological studies of the aquifers in Syria and Lebanon showed that from the extension of the recharge areas and the water budget, the estimated total outflow is at least 5 to 10 times lower than the previous estimates. These results are in good

agreement with the first direct flow measurements. Moreover, when the aquifer is not confined, then not protected from natural sea-water intrusion, the water at permanent springs is brackish during a large part of the year, sometimes with a high proportion of sea water (up to 60% at Chekka at the end of the low flow season).

6. Conclusion

The Chekka karst system with its important submarine discharge has a typical karstic functioning, characterized by permanent and seasonal (overflow) springs and important and fast changes in flow rate and water quality. However the changes in water quality are mainly due to sea-water intrusion through deep conduits during time of low water head in the conduit system, more than to the contribution of long residence time groundwater as it is the case in karst aquifers. Its functioning looks comparable to some other Mediterranean coastal karst aquifers (Fleury et al. 2007b, 2008; Arfib et al., 2007). It may be considered as representative of all Mediterranean coastal carbonate aquifers in which karst processes actively developed surface landforms and conduit systems deeply below the present sea-level during the Messinian Crisis of Salinity, due to very low base-levels imposed by the drying of the basin.

Existing equipment (CTD probes, flow meters, data loggers) are now very efficient and reliable, well fitted for monitoring KSMS. It allows the monitoring of pressure (water level), temperature, conductivity, flow rate, at depth up to 30 m, in seawater, with an autonomy long of several months, even with short sampling time (5 mn). It will give all information necessary for a sustainable management of coastal groundwater resource.

The fact that those karst aquifers discharge most of their groundwater at high flow rate directly into the sea makes them consider as a profitable target capable of meeting the drastic increase of water demand of coastal areas. Among the main issues in coastal karst groundwater management, the question about the possibility of capturing fresh groundwater at KSMS is topical. Several companies tempt stakeholders and decision makers with the exploitation of this "lost" resource and the capturing of the submarine springs. All the recent studies obviously show that it is not realistic either because the exploitable flow is too low, or too brackish with high daily and/or seasonal variability of their quality. Moreover the different tests show that a capturing system of a submarine spring cannot be perfectly watertight to sea-water intrusion, and may modify the water head relationship between the sea and the conduits, contributing to increasing sea water intrusion.

Despite these problems these coastal karst aquifers provide an important resource connected to storage, which could be exploited. An efficient and sustainable management and protection of these groundwater resources is necessary in coastal regions where the maximum of population and the economic activities are concentrated. Some new avenues of research and development are proposed.

Currently, capturing groundwater at on-shore wells must be preferred to capturing KSMS. Monitoring KSMS is a key for managing coastal karst aquifers:

- i) to characterize the functioning of the aquifer, basically the water head relationships between the aquifer and the sea, through the conduit system;
- ii) to monitor natural and man-made sea-water intrusion, and to fit the exploitation rate of groundwater from on-shore wells in order to limit or avoid sea-water intrusion;
- iii) to determine whether the spring could be captured and exploited, possibly with desalination of brackish water.

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