geosciences

Review

Coastal Karst Groundwater in the Mediterranean: A Resource to Be Preferably Exploited Onshore, Not from Karst Submarine Springs

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Abstract: Coastal karst aquifers are common in the Mediterranean basin. With their significant potential storage capacity, they are an attractive groundwater resource in areas where the water demand is the most important. They discharge either at the coastal zone or directly into the sea at karst submarine springs (KSMS). Decision makers take an interest in this unconventional groundwater resource and are convinced by companies and research consultancies that KSMS's should be exploited because they would discharge huge amount of fresh water. Being now well documented, the occurrence of KSMS's along the Mediterranean coast is discussed in the light of recent geological history favourable to the development of karst. Conduit flow conditions are common, inherited from an intense phase of karstification during the Messinian Crisis of Salinity at the end of Miocene, when the sea level was 1500 to 2500 m below present sea level. From investigations carried out along the coasts of France and the Levant, compared with studies done along other Mediterranean coastlines, it appears that capturing groundwater discharged at KSMS raises different problems which make the operation dicey and expansive.

Keywords: coastal karst aquifer; submarine spring; Mediterranean; groundwater resources; exploitation

1. Introduction

According to UN data [1–3], water resources in countries of the Mediterranean basin are limited and unevenly shared out. The southern countries have only 13% of the total. By the year 2025, five countries (Egypt, Lebanon, Morocco, Syria and Turkey) among 21 will get less than 1000 m^3 per person per year, what means that their economic development will be impacted. For five others (Algeria, Israel, Libya, Malta and Tunisia) the water resource will be below 500 m^3/year, what will be a drastic constraint for life. The population growth and the economic development strongly weigh on water resources, what jeopardizes the public health and the environment conservation. Water uses, shared between agriculture (67%), water supply (21%) and industry (12%) are more and more competing [4], what leads to conflicts for sharing water resources. The situation will get worse because most of the population will live along the coasts and the climate change will impact water resource.

Consequently, this severe water scarcity in the Mediterranean basin forecast at short term encourages the authorities to find solutions for meeting the demand. One of these solutions is to look for new water resources, known as unconventional. One of them is related to submarine groundwater discharge, which is particularly common along the Mediterranean coastline. Since the 2000′s several private European companies were created with the object of capturing fresh water discharged at submarine springs, in order to sell it to local authorities for water supply. At first glance, it looked a very interesting resource to be exploited, because in the 1960s and 1970s several papers and reports forecast huge flow rates, sometimes of several millions m^3 per day of fresh water [5,6]. Recent advances in submarine works allow considering capturing this unconventional resource which could be a serious challenge to desalination and treated waste water reuse. Investigations carried out during the last 20 years on Mediterranean karst coastal aquifers and submarine springs allow discussing the possibility of capturing karst submarine springs and proposing alternative approaches.

2. Diffuse Versus Concentrated Submarine Groundwater Discharge

Most of the coastal aquifers discharge at least a part of their resource directly into the sea. Many researchers study submarine groundwater discharge (SGD), because this is a contribution to aquatic biodiversity [7] as well as an unknown part of the groundwater balance. However, most works consider only diffuse SGD from porous or fissure aquifers because this is the most common SGD along the world's coasts.

A global assessment [8] showed that concentrated SGD's occur along coastal volcanic and karst aquifers. Among them, karst submarine springs (KSMS) are the most common and are known everywhere offshore carbonate rock formations, especially along the coasts of Florida (see e.g., [9,10]) and of Yucatan [11,12]. However according to [8], more than 90% of them occur along the Mediterranean coasts (Figure 1) where the most spectacular ones are described. They are related to carbonate formations which outcrop all around the Mediterranean, up to 500,000 km^2 of the Mediterranean watershed [13]. We will discuss below why KSMS are mainly concentrated along the Mediterranean coasts.

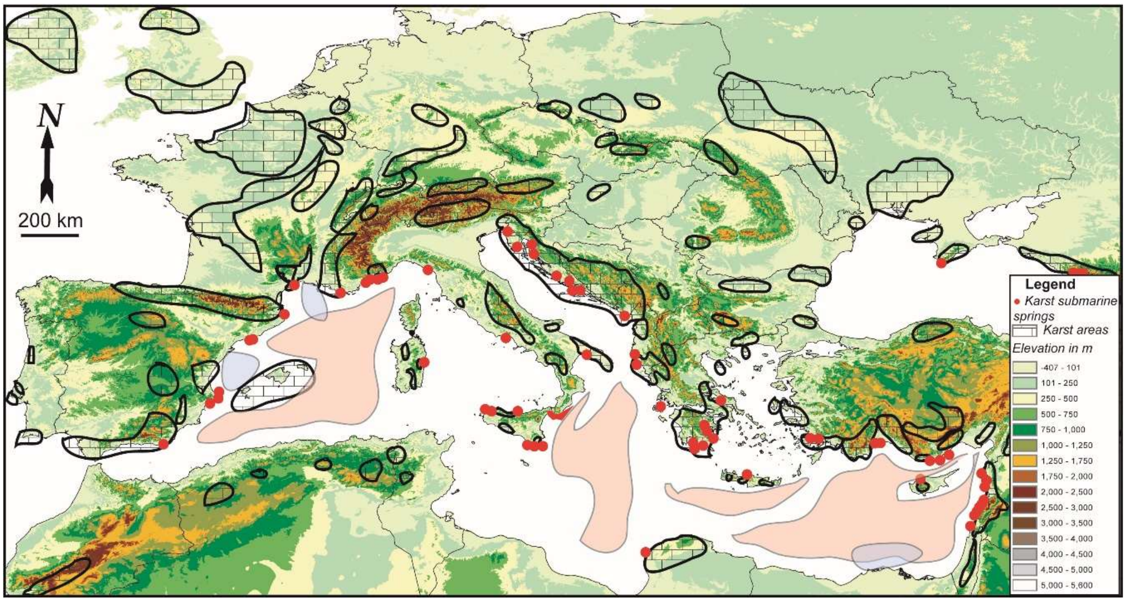

Figure 1. Schematic map of karst areas around the Mediterranean with the location of the main known karst submarine springs (adapted from [14]). The three main remaining hypersaline basins at the Messinian low stage are shown in pink with the main post-Messinian fluvial fans in grey (adapted from [15]).

Mediterranean karst aquifers provide essential water resources at the origin of ancient civilizations, having enabled the settlements and the development of numerous cities, linked with the technology for exploiting the water resources. Presently, the main development occurs along the coasts, what means that they are put under pressure by risks of overexploitation, sea water intrusion and pollution. All the means must be implemented in order to avoid a major water crisis, all the more so since karst aquifers are very complex, unpredictable and consequently particularly difficult to manage and protect [16].

During the last decades, several European projects focused on karst management and protection, in particular COST 65 [17], COST 620 [18], COST 621 [19,20]] and. All of them attempted to summarize the major points of knowledge, techniques and gaps concerning the karst groundwater resources in all the Mediterranean countries. Concerning coastal karst aquifers, the lack of data and geological knowledge was the main obstacle. Mijatovic [21] made a first approach, however, using the results of old field studies based on dated concepts and geological knowledge. All these karst aquifers underwent a complex, recent geological evolution, driven by tectonics with uplifts and subsidences. They all undergo to a typical climate with two opposite hydrological seasons, the humid one, short and severe; the dry one, very long and warm. These conditions of development of karst in carbonate formations are shared with all carbonate rocks around the world [22]. Nevertheless, the Mediterranean karst aquifers and especially the coastal ones were subject to a particular geological event which made them very different from other world's karst aquifers.

3. The Messinian Crisis of Salinity, A Major Geological Event

Until the end of the last century, it was considered that KSMS's were inherited from the last glaciation when the global ocean level was 130 m below the present sea level [21]. This particular situation for the Mediterranean basin cannot explain the occurrence of KSMS's much more frequent in the Mediterranean basin than elsewhere in the world. Moreover, some of them discharge the most important known flow rate according to several evaluations [6,21].

In fact, since the 1970′s geological investigations showed that the Mediterranean basin was subject to a special event at the end of Miocene, the Messinian crisis. It was definitely understood and accepted that this crisis was the consequence of the closure of the strait between the Atlantic Ocean and the Mediterranean Sea caused by the northward movement of the African plate occurring at the end of Miocene around 6 Ma and probably during similar events during upper Miocene [23]. The isolation of the basin was followed by a radical change in its water budget, because the fresh water inflow was—and is still—lower than the evaporation. Before the closure, the difference was offset by an inflow of Atlantic water, as it occurs presently. Without this inflow, the sea level decreased in the same way as presently in the Dead Sea basin. At the maximum of desiccation there was only three remaining hypersaline basins and large evaporite deposits everywhere (Figure 1). For that reason, this major event is named the Messinian Crisis of Salinity (MCS).

Beginning at 7.2 Ma, the MCS was first a long sea level decreasing up to 1500–2500 m below the present sea level (b.s.l.), depending on the basins. The minimum was reached around 6.8 Ma and lasted about 500,000 years. The main river valleys were forced to deeply entrench the continent and groundwater invaded carbonate rocks, developing karst at depth and reaching very low base levels, generally at the bottom of the carbonate formations. The erosion along the river valleys and the emptying of the basin as well as its flooding at the end of the MCS caused isostatic responses [24], fracturing rocks and increasing the relief. All these geological events strongly contributed to favour the development of karst. Rias and rocky inlets—named "calanques" in French—were created during this phase of erosion. Huge karst springs discharged at the foot of carbonate formations developing pocket valleys as shown by investigations along the French coast [25] and now completely plugged with Pliocene and Quaternary formations.

The MCS ended with the opening of the strait of Gibraltar around 5.3 Ma. The basin and the river valleys were then flooded probably in less than 30 years [26]. For instance, the Nile River valley was flooded up to Aswan; and the Rhone River valley up to Lyon. The main rivers supplied a huge clayey sedimentation, the Pliocene (Zanclean) marine blue clays crowned with deltaic and alluvial formations, the Pliocene and Quaternary detrital sediments known as Villafranchian in the South of France.

4. Main Consequences on Karst Aquifers

In areas where the impermeable marine sediments occur, for instance along the Rhone River valley, the Messinian karst systems were blocked in their downstream part and flooded with fresh water still recharging them. The mains consequences are as follows:

- The widening of the recharge area, caused by the connections between adjoining Messinian karst systems, created during the Pliocene flooding. The Vaucluse spring karst system is the best-known example [27]. These karst systems offer a large groundwater resource.
- The increasing of the storage capacity because of the development of karst features at depth during the MCS, creating often huge reserves of groundwater, in the same way as it occurs in intracontinental basins [28].

However, the Pliocene marine clays are not present far from the most important estuaries. Therefore, Messinian surface features are flooded but not fossilized by thick impermeable sediments. In areas where carbonate rocks are predominant, surface karst features such as dolines, sinkholes, dry valleys and karrens are directly open to the sea, what allows sea water to inflow into or fresh water to outflow from conduits and open fractures, according to the water head relationship between sea water and fresh water in the conduits. The main consequences are as follows:

- The occurrence of KSMS's, due to groundwater discharge from flooded karst features, sometimes far from the coastline.
- The natural inflow of sea water into karst aquifers from flooded karst features, what is the cause for inland brackish springs such as Fontestramar in France [29] or Almyros of Heraklion in Crete [30].

According to this situation and because the karst conduits are not plugged, the coastal karst systems present a typical karst functioning, with large hydraulic variations, increased by the strongly contrasted Mediterranean climate. During the rainy season, the high flow produces high fresh water heads in conduits and as a consequence the discharge at seasonal KSMS. During the dry season, low flow and low fresh water heads are prevailing, what results in sea water intrusion into the conduits and as a consequence a low discharge of frequently brackish water.

However, compared to continental karst systems, the functioning of these coastal karst aquifers is quite different because their outlets are not the natural outlets where the conduit system ended originally. The present outlets are either ancient surface features initially acting as input points—swallow hole, abandoned cave, pothole—or fractures progressively enlarged by solution since the flooding of the lower part of the system. This situation creates new conditions for conduit flow, with local high head losses that favour the functioning of seasonal KSMS at greater depths.

5. A Case Study: The Chekka Karst Aquifer and Its KSMS's

Along the northern coast of Lebanon, the Chekka karst system was considered for discharging the highest flow rate directly into the sea from several KSMS [5,21]. For that reason, it was studied by El-Hajj [31] for his Ph.D. under my supervision. This is presently a well-studied example of coastal karst aquifer with several permanent and seasonal KSMS's. The coastal part of this 250-km^2 karst system is shown Figure 2.

The nahr El Asfour River presents a seasonal flow fed in its downstream part by surface flow on the thick, impermeable chalky Senonian marl. The surface water is diffusely swallowed in the narrow valley. However, in its upstream course the river is swallowed at several locations as well as another river located at South, the nahr El Jawz River. These point recharges and the diffuse infiltration into the Cenomanian and Turonian limestone composes the recharge area of the Chekka karst system, discharging in the Chekka Bay.

The discharge system (Figure 2) is composed of several small permanent coastal springs (S7 and S8), a group of permanent submarine springs, S2, S3 and S5, around 22 m b.s.l., all discharging brackish water a part of the year and several seasonal springs functioning only during floods, onshore (blue stars, Figure 2) and offshore (S6, S12 and S13) up to 110 m b.s.l., discharging fresh water. The geological conditions are different from what was described by [5,21] who considered that the carbonate aquifer is confined by an impermeable formation, the Senonian marls, protecting groundwater from sea water intrusion. In fact, as shown by submarine geological investigations, the submarine part of the carbonate aquifer developed in the Cenomanian and Turonian limestone is not protected by the marls which were eroded along the valley before its submersion, that is, the Asfour paleovalley (Figure 2). The bottom of the paleovalley is lined by karstic features such as close depressions and the deep pothole S12 opening at 60 m b.s.l. with its bottom at 110 m b.s.l., where a large unexplored conduit opens. Another submerged pothole S13 remains unexplored.

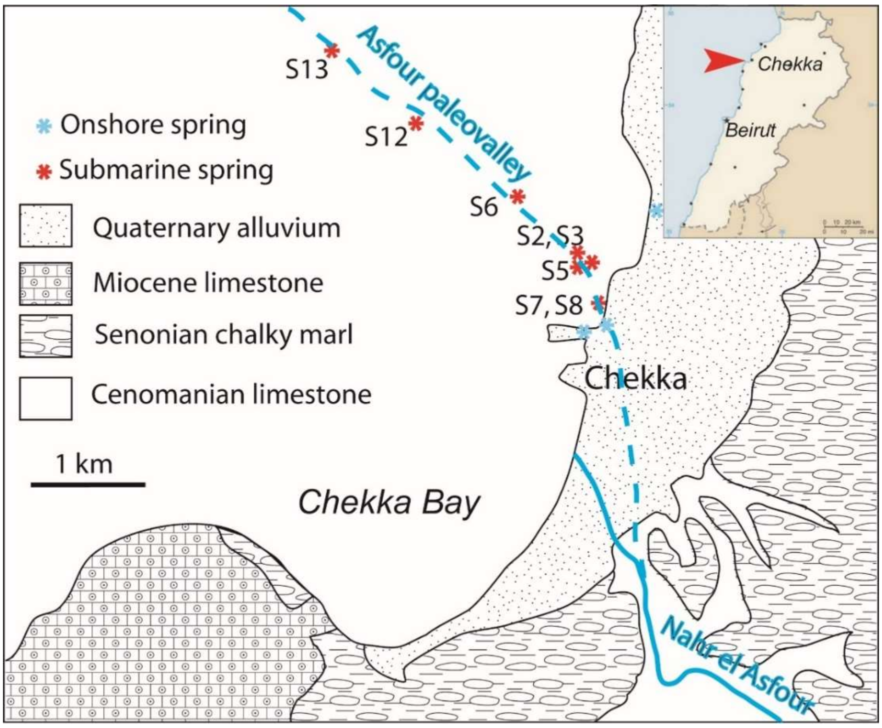

Figure 2. Hydrogeological settings of the Chekka submarine springs. Karst submarine springs (KSMS) (red stars) S6, S12 and S13 are seasonal; S2, S3, S5, S7 and S8 are permanent; other small onshore springs (blue stars) generally discharge brackish water.

The cross section (Figure 3) shows the functioning of the KSMS's in different hydrological conditions:

- the very high flow stage, when S13 and S12 discharge fresh water, that is, when the water head in the conduits is maximal;
- the mean flow stage, when the group of permanent KSMS's only works, probably with some discharge of brackish water at S12;
- the low flow stage, occurring during summer and autumn.

The permanent submarine springs S2 and S3 were tapped for measuring the flow rate, the temperature and the salinity of the groundwater discharged directly into the sea. When Kareh [5] estimated the low flow rate to about 2 m^3/s of supposed fresh water, El-Hajj [31] measured only around 0.1 m^3/s of brackish water at 35% of sea water. During the 2007 dry season—June to October—the total flow rate varied in the range 25–35 L/s, depending mainly on the sea level, when the salinity varied between 33 and 36 mS/cm (50 to 80% of sea water), indicating a fresh groundwater discharge between 10 and 15 L/s.

The seasonal variation of the conductivity of the water discharged at S2 (Figure 4) shows almost instantaneous abrupt change while the groundwater head in the conduits varies quietly. It means that when the water head reaches a threshold value, water flows back in the lower part of the discharge system, either swallowing sea water—the conductivity increases, or discharging fresh groundwater—the conductivity decreases. This is typical of conduit flow conditions, that is, of a well karstified aquifer.

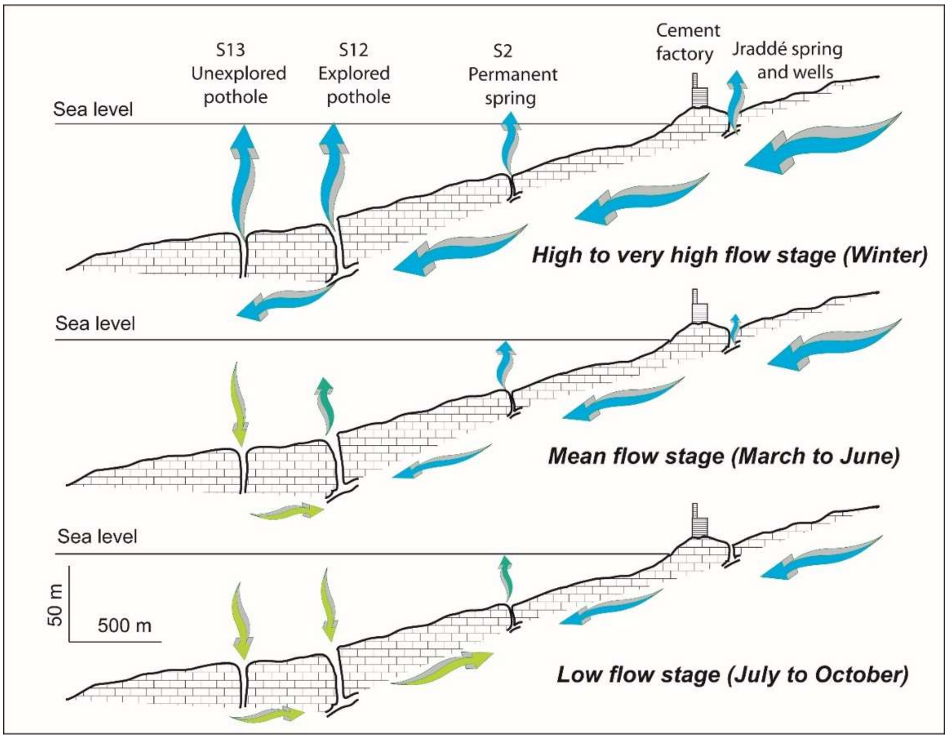

Figure 3. Cross section along the Nahr el Asfour River paleo-valley, North Lebanon. The Chekka submarine springs discharge groundwater of a 250 km^2 recharge area in Mount Lebanon. The deepest flooded karst features swallow sea water during low flow stage. The permanent spring S2 discharges brackish water (modified from [31]). Blue arrows: fresh water flow; green arrows: sea water flow; blue green arrows: brackish water.

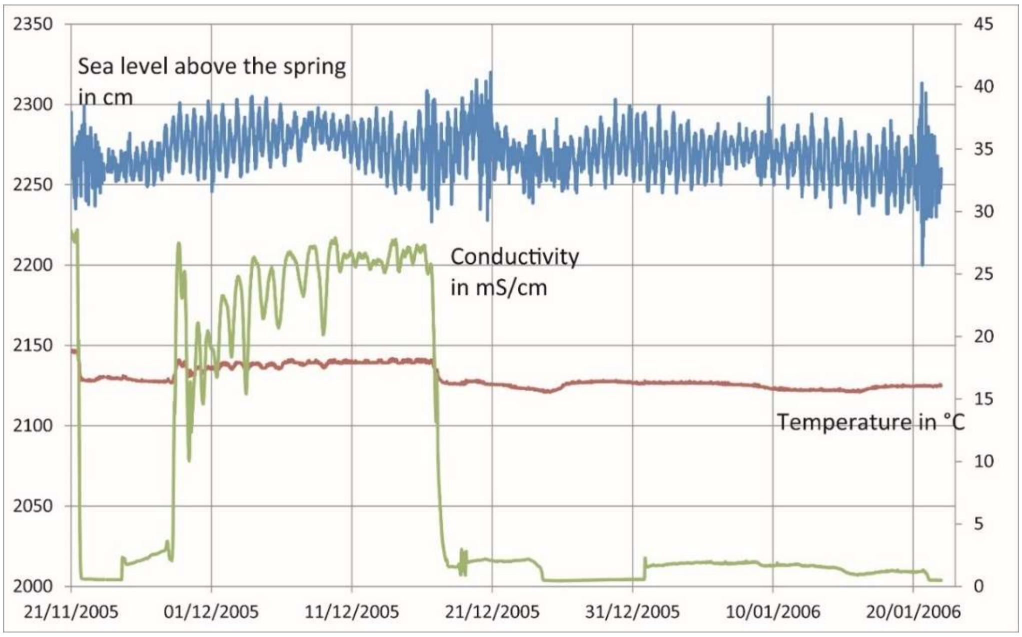

Figure 4. Seasonal variation of conductivity and temperature at S2, compared to sea level. During floods at the end of November and after December 21, the conductivity is low, indicating no sea water intrusion. At the beginning of December, the flow regime not modified by floods is obviously influenced by sea water intrusion occurring in S12 and S13. Therefore, the effect of tide controls the conductivity.

6. The Mechanism of Natural Sea Water Intrusion in Coastal Karst Aquifers

These hydraulic conditions are driven by (1) the difference in water density between fresh water and sea water and (2) the fresh water head in the conduits and the sea water level. Considering the sea water–fresh water relationships studied by Ghyben and Herzberg [32], it becomes possible to define two domains separated by the line of density equilibrium between fresh water h_{fw} and sea water h_{sw}:

$$h_{fw} = 1.025\ h_{sw} \quad (1)$$

In domain 1 (Figure 5) the hydraulic head in the conduit is high enough to overcome the column of sea water and to flow out from any void open to the sea, creating a KSMS, what is impossible in domain 2. For instance, for a conduit discharging groundwater at 100 m b.s.l., the fresh water head in the conduit must be at least 2.5 m above sea level to discharge fresh groundwater. These values are underestimated because the head losses in the conduits are neglected.

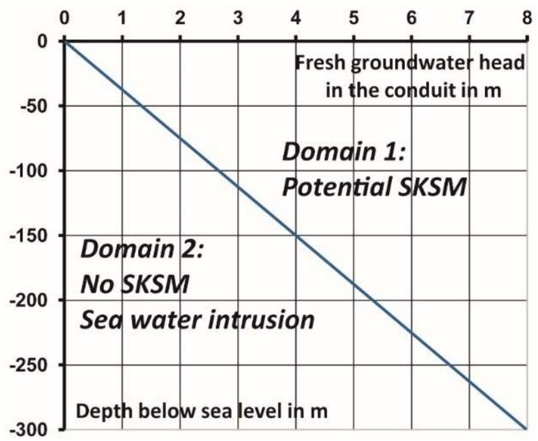

Figure 5. Diagram showing the depth below sea level at which a KSMS may discharge, depending on the fresh water head in the conduit discharging at the spring.

According to the lowest water head in the conduit during the year, the KSMS discharges groundwater permanently or only seasonally. Equation (1) says also that in domain 2 sea water may be swallowed in open conduits or fissures, because the sea water head is higher than the fresh water head. Then a seasonal KSMS generally works as a "swallow hole" swallowing sea water when groundwater head is low, that is, the representative point is located in domain 2 of Figure 5. For instance, a seasonal KSMS located at 50 m b.s.l. means that the fresh water head in the conduit is less than 1 m, what is common in karst conduits where the hydraulic gradient is very low during the low stage. Contrarily to what some authors thought (see [8]), it is not necessary to invoke a special shape of the conduit such as a Venturi to explain the natural intrusion of sea water.

As shown by many studies, the natural sea water intrusion is typical of the functioning of many coastal karst aquifers. The sea water intrusion is due to (1) the presence of surface karst features now flooded and not plugged by impermeable sediments, (2) conduit flow conditions and (3) changes in the water head inside the conduits and in the sea level. The natural intrusion is obviously increased by onshore pumping, which decreases the water head in the conduits. The sea water intrusion may occur sometimes several kilometres away from the coastline and at great depth below sea level [33,34].

7. The Issue of Offshore Fresh Groundwater Capturing

At Port-Miou, a "calanque" near Marseille, France, where a large flooded conduit discharges brackish water at around 10 m b.s.l., as well as at Fontestramar near Perpignan, France, two main brackish coastal karst springs, the origin of salts was first assumed to be due to local geological settings, for instance the presence of Triassic evaporates known in the presumed recharge area. This assumption was abandoned with the development of isotopic and geochemical analyses which showed the marine origin of the salinity.

The capture of a KSMS was then attempted in the 1960's by increasing the water head in the conduit in order to decrease the salinity. The most famous experiment was done at Port-Miou [35] by the French Geological Survey (BRGM) together with the Marseille Water Company (Eaux de Marseille). The aim of the project was to strengthen the water supply of Marseille.

A partial dam, that is, not fully baring the conduit, was built inside the flooded conduit at 10 m b.s.l., from an onshore enlarged natural pit. The goal was to avoid the sea water intrusion into the conduit itself [35]. Because the groundwater salinity did not change after completion, the dam was completed in order to increase the water head in the conduit, what did not change significantly the salinity. However, at that moment, the real geological settings related to the MCS were totally ignored and nobody could assume that sea water intrusion may occur at great depth as it was showed later for the brackish karst spring Almyros of Heraklion, Crete [30] or Port-Miou [36].

Another experiment was done at the Vise (or Abysse) KSMS, discharging at 30 m b.s.l. from the bottom of a natural cone, in the Thau lagoon, near Montpellier, France [37,38]. The spring was capped with a large reversed funnel. The salinity of water did not change. The capturing system allows the observation of an inversion of the flow during several months, what was referred to the "inversac" feature [39,40], from the name of a local coastal karst spring where the phenomenon was known for long. It was shown as the consequence of intense pumping in a bauxite mine at few kilometres from there [38,41]. After the closure of the mine, the Vise spring worked again normally, discharging brackish water [42]. But the capturing system was abandoned because it was supposed to act upon the quality of the nearby thermal spring of Balaruc.

During the last decades, offshore and submarine works did a lot of progress what pushes some companies to undertake the capture of fresh water directly offshore at the opening of karst conduits. In the early 2000′s an experiment done by Nymphea Water Company showed that with a kind of submarine umbrella above a KSMS, the fresh water could be stored inside the umbrella and then drained out with a pipe [14]. This experiment gave the simple idea that capturing a submarine spring could be easy. A prototype of capturing system was developed by Nymphea Water and built for the Mortola KSMS, offshore Menton, France, close to the Italian border [43].

Several obstacles appeared during the development phase. At first the design of the system imposes to correctly assess the natural flow rate. The different methods (IR thermography of the sea surface, flow velocity assessment or measurement, modelling) used previously by scientists and divers for estimating the flow rate were checked. The results showed that they all largely overestimate by 10 to 100 times the actual flow rate measured with a flow meter in a pipe capturing the total flow [14,31]. This large overestimation can make the project not viable economically.

The second difficulty is related to the salinity of the water. Most of the time the discharged groundwater is not fresh but more or less brackish, that is, not drinkable, what also makes the project not viable economically. Moreover, because the flow rate is highly variable seasonally as well as its degree of salinity, it is difficult if not impossible to adapt a capturing system controlling the flow. Despite that, Breznik and Steinman [44] consider that water from KSMS could be desalinated, the variable salinity makes very difficult, or even impossible the connection to a desalination plant, which requires a relatively constant salinity.

At last, the capturing system lowers the water head over the KSMS by isolating the fresh to brackish water column from the sea water head. When the water head above the KSMS decreases, the inflow of sea water swallowed into the conduits from flooded fractures or karst features increases what increases the salinity of the discharged water.

Because the sea level is always changing with tides and head losses are low in conduit flow conditions, the swallowing regime varies in the same way. Despite that the tide amplitude is low in the Mediterranean, commonly around 1 m or less, the effect during low stage flow is remarkable as shown at Chekka KSMS (Figure 6) when the tide amplitude is around 0.50 m. During high water the sea water intrusion should be maximal while minimal during low water. However, the conductivity of water at the KSMS is higher during low water than during high water, what shows the mechanism of sea water intrusion and transport to the permanent KSMS 1 km away from the main intrusion point is complex and not yet fully understood.

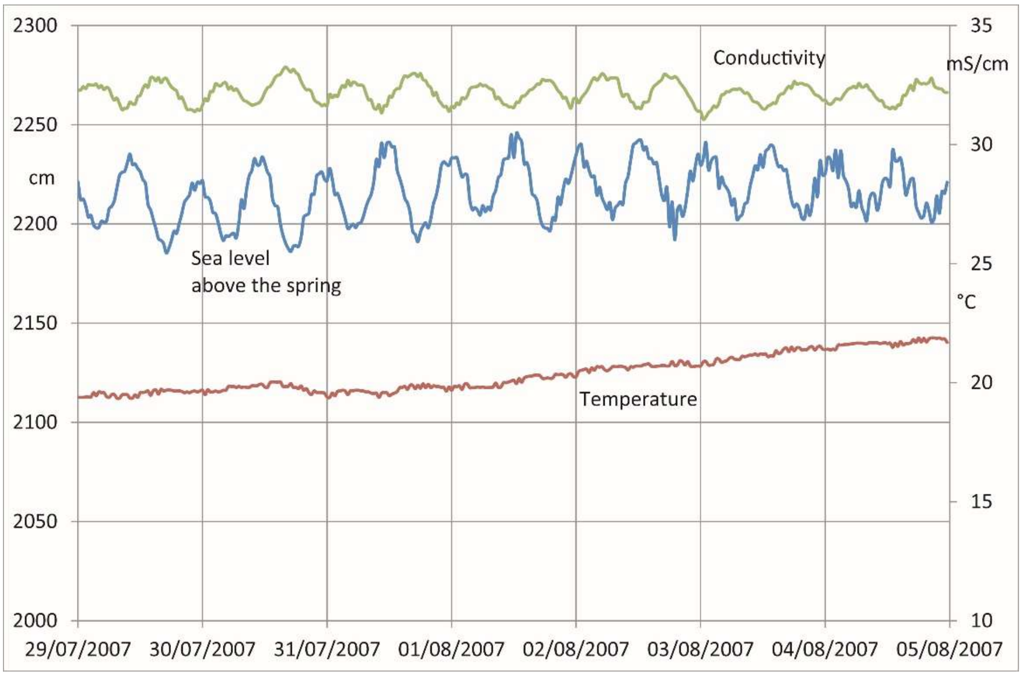

Figure 6. Variation of groundwater conductivity and temperature at Chekka KSMS during low stage, compared to sea level above the spring. The 50 cm range tide effect is at the opposite of the salinity variation, an increase of the sea level being related to a decrease of salinity.

From the studies and experiments done in Lebanon and Syria [20,45–47], the functioning of these coastal karst aquifers discharging offshore is now well but not yet fully understood. Concerning their exploitation, it appears very dicey to attempt the capture of groundwater offshore directly at a KSMS. Karst features developed before the submersion of the continental shelf are very common offshore, what allows natural sea water intrusion into the coastal karst aquifers. Most KSMS are brackish during several months.

However, the Baniyas aquifer in Syria is probably an exception [20]. The lower part of the aquifer and its submerged part are covered by Pliocene and Quaternary basalts which confine groundwater and create high water heads in the Messinian conduit system at depth. In its coastal part, this aquifer is protected from natural sea water intrusion, although it discharges at several submarine springs through the fractured basalt at 10 or 20 m b.s.l. Groundwater is exploited onshore from boreholes from which the nearest of the coast are artesian and gushing several tens L/s. The question of capturing the small KSMS is there of no relevance.

8. Is Groundwater from Coastal Karst Aquifers Exploitable Despite Everything?

The general unfavourable conditions met at most Mediterranean KSMS should encourage exploiting and managing groundwater onshore from wells and from seasonal overflow springs when present. Digging a well onshore in limestone aquifers remains a challenge. The recent improvements of boring techniques and geophysics in karst aquifers allow considering much better success rate than in the past, especially at relatively low depth.

However, a strict monitoring of groundwater must be done in order to control the possible spread of the salinity because of sea water intrusion increasing under the effect of withdrawals decreasing the water head in the conduits. The monitoring may be done at piezometers located between the pumping stations and the coast, as it is done by IGME, the Greek Geological Survey, near Agios Nikolaos in Crete [48]. The pumping regime is driven in function of the salinity in the piezometers.

Another way is to monitor the permanent KSMS for temperature, salinity and pressure. When the water head in the conduit becomes low because of overpumping, the flow at the submarine spring is reversed and sea water is swallowed. This is certainly the most efficient monitoring; it needs to build a simple capturing system at the KSMS which does not need to be completely sealed and would allow some leakage. Remote control equipment allows making such kind of monitoring. At last in coastal karst aquifers wells and their pumping rates should be strictly authorized and controlled in order to avoid overexploitation and sea water intrusion.

9. Conclusions

As a consequence of the MCS, submarine and brackish coastal karst springs are particularly more abundant along the Mediterranean coasts than everywhere else in the world. Investigations of the consequences of the MCS on karst development around the Mediterranean are at their early beginning in the western part of the basin (Italy, France and Spain) and badly known elsewhere especially along the coasts of Croatia, Greece and Italy. The study of KSMS and their recharge area are also at their early beginning. However, we know that karst conduits developed at great depth below present sea level may be often largely open to the sea, allowing natural sea water intrusion.

The hydraulic relationship between fresh groundwater and sea water through karst conduits creates a kind of fragile balance which is upset by the changes of sea level and/or water head in conduits. The sea water intrusion is then the major risk which jeopardizes the karst coastal groundwater resources. When it occurs, there is no mean to get back to the initial situation of fresh groundwater. The exploitation of karst coastal aquifers is consequently very difficult and requires strict conditions of management and monitoring including pumping rates, discharge at KSMS and salinity of groundwater in monitoring wells. The salinization of groundwater, not only of karstic origin, in many regions of the world appears to be a long-term process somewhere irreversible, what should encourage the decision makers in applying strict regulations and control procedures for exploiting this water resource essential for maintaining the economic activities in the most populated part of the world.

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