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ORIGINAL ARTICLE

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The groundwater discharge in the Mediterranean karst coastal zones and freshwater tapping: set problems and adopted solutions. Case studies

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Abstract In the karstic regions of the Mediterranean coastal zones the groundwater discharge and its outcrops—the coastal and submarine springs—represent the most typical natural phenomena of littoral karst, the economic potential of which is significant. The case studies discussed in this paper concern the problems of freshwater tapping in karst coastal zones along the Mediterranean littoral. Owing to the geological and hydrogeological approach, the set problems and adopted solutions involve two most important tasks: (1) the regulation of groundwater flow in the tapping facilities and (2) the control system of saltwater encroachment in a larger protection zone, between the coast and the site of tapping facilities.

Keywords Mediterranean basin · Coastal zone · Submarine karst · Mediterranean

Geotectonic and hydrogeological framework of Mediterranean

Mediterranean basin, with its main geological structures along the coastal zones, consists of very heterogeneous and disrupted Perimediterranean alpine chains. It also includes mountain ranges such as Dinarides, Hellenides and Taurides. These chains are particularly well known by very large development of carbonate formations (especially limestones and dolomites) that are responsible for the creation of the famous karst sceneries, the biggest and unsurpassed in the crust of the Earth.

Except for this geomorphologic phenomenon, the Perimediterranean alpine chains (Fig. 1) are built of two important mountain branches: one Alpidic that is thrust over the European continental margin and one Dinaric that is thrust over the African continental margin. Between these two branches a Tethysian ophiolitic suture appears with the limit on the Skadar-Peć transverse zone (Aubouin and Debelmas 1980).

Plio-Quaternary tectonics gives Mediterranean global unity through the birth of the neo-oceanic crust (Aubouin and Debelmas 1980). In connection with such circumstances, for the whole Mediterranean, it is important to emphasize the relationship between global climate change and consequently global modifications of groundwater discharge in coastal zones. Sea level fluctuation has had a very important role in the coastal areas. During the last two climatic extremes of the Quaternary period, a maximum sea level rise occurred from 19,500 to 16,100 ^{14}C yr BP and an optimum lower sea level occurred from 9,000 to 7,000 ^{14}C yr BP (sea levels adapted from Map 1 and Map 2, CGMW, prepared with the support of ANDRA and INQUA, 2004).

The Mediterranean sea level is first of all lowered more than 100 m during the last glacial maximum. But in the subsequent Holocene optimum climate period, the sea level rose around 120–150 m, creating the biggest effects of the submarine karst along the coastal zones. In the present, this is confirmed by the evidence of the numerous submarine springs in wide open Mediterranean littoral areas. This fact, however, proves that general erosion base of groundwater discharge is between 100 and 150 m below actual sea level in the Mediterranean.

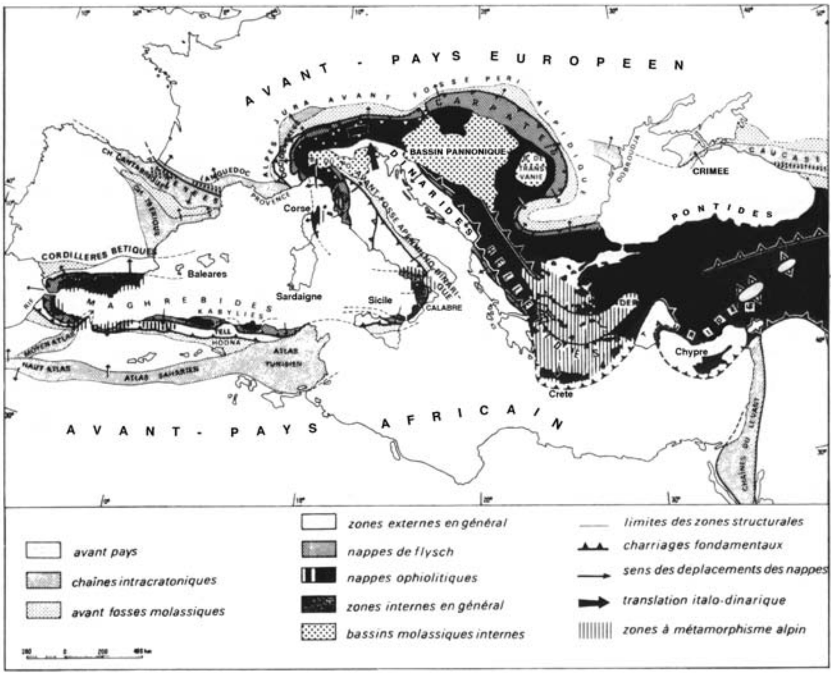

Fig. 1 Structural scheme of Perimediterranean chains (adapted from J. Aubouin and M. Durand-Delga 1971)

It is important to mention that the oxygen isotope proves that the most recent cold phase peaks at around 18000 yr BP, when sea-level was at its lowest, and is referred to here as the ''last glacial maximum''. The ''present interglacial'' began around 10,000 yr BP. The Holocene optimum is 9,000–7,000 ^{14}C yr BP.

Environmental impact on groundwater karstic flows in coastal aquifers

In the karstic areas of the Mediterranean coastal zones, vast quantities of groundwater flows through the carbonate formations and finally reaches the sea (Fig. 2). This groundwater discharge and its outcrops—the coastal and submarine springs—represent the most typical and common natural phenomena of littoral karst and have been discovered along the coast of Turkey, Syria, Lebanon, Israel, Greece, former Yugoslavia, Italy, France, Spain, Algeria, Tunisia, Libya. The economic value of such flows is significant. According to estimates, the annual groundwater discharge flux is between 25 km^3/year (Margat and Forkasiewicz 1981) and 68 km^3/year (Zekster et al. 1984). However, in spite of their great frequency in the Mediterranean basin, there are only a few successfully realized freshwater tapping projects along the karst coastal zones. There are a few exceptions, such as the record from antique time regarding Fenician who drew freshwater up from a submarine spring by lead funnels linked to leather pipes

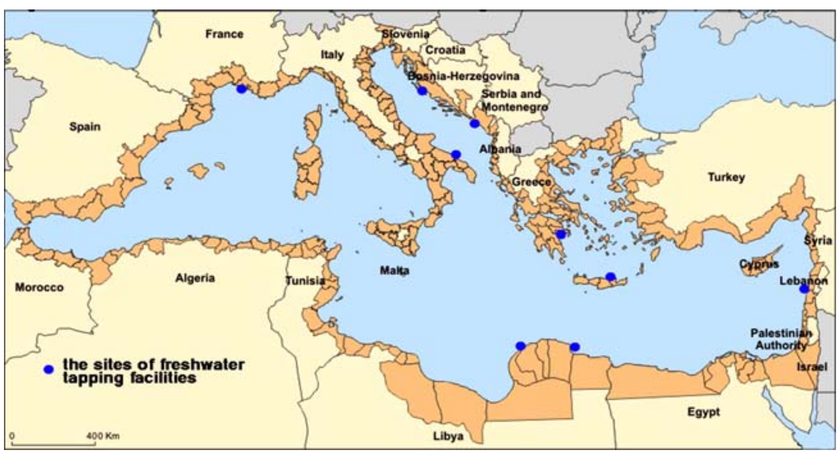

Fig. 2 The Mediterranean countries and their coastal regions

near the town Tyr, then the "Sorgenti d'Aurisina" at Trieste Bay and the famous one at Ayios Georgios Kiveri at the Argolides Bay in Peloponese, constructed in the shape of semicylindrical dam in the sea during the year 1970. This spectacular freshwater tapping into the sea itself proves that hydrogeological karstic phenomenon in the Mediterranean coastal zones can always provide new surprises.

Some unsuccessful attempts have been made to exploit the coastal springs, the number of which increased during last decades of the last century. The submarine springs of Port Miou near Marseille, the Scurda and Gurdic springs in the Bay of Kotor, Chekka in North Lebanon coast, Almiros spring near Iraklion in Crete, Ain Zayana near Benghazi in Libya, etc., reveal the complexity of relationships between the coastal aquifers as groundwater reservoirs and their erosion base regarding sea level, which controls the level of groundwater flow.

Many problems concerning freshwater tapping still remain to be solved because the hydrogeological frameworks of the groundwater protection zones in a karst environment are frequently poorly understood, especially freshwater/saltwater exchanges, which are caused by hydrodynamic behavior related to the structure of the three-dimensional karstic network responsible for unsteady flow. This phenomenon implicates its effects on marine intrusion into freshwater body, e.g., the phenomenon of hydraulic gradient inversion at interface freshwater/saltwater caused by their differences of density.

To improve this situation, a multi-criteria method for a new protection strategy in coastal karst environment for outlining the groundwater protective zones around freshwater tapping sites has been developed. Several case studies discussed represent typical examples of geological mining facilities for artificial improvements of groundwater tapping in Mediterranean coastal zones. The method for increasing the volume of stored water and for controlling discharge with better yield involves underground dams, grout curtains and particularly drainage galleries. A coastal management plan according to available monitoring data for steering special research in the discharge zone should be classified based on (1) preventive protection and (2) remedial measures or consequent protection.

Case studies: generality

Along the Mediterranean coastal zones, the presence of well-developed submarine karst makes illusory any attempts of freshwater tapping in the coastal area if the geological conditions do not prevent saltwater encroachment into aquifers. In karstic areas of that kind, the submarine connection of deep channels and cavities are regularly open to the sea along a belt whose depth is over 100 m below the sea level. It is practically impossible to locate the saltwater cone affecting a freshwater tapping facility. In such a case, nothing can be gained by tapping those coastal karstic springs, as some deeper channels always remain open whose effects are even greater. To isolate all channel connections around the system would be impossible.

The exploration of costal karst at various Mediterranean regions by speleodiving has made evident the existence of caves, channels and galleries of large dimensions that are easily accessible to depths of − 45 m in Port Miou, − 51 m in Gurdic estavelle in Kotor, − 120 m in Ljuta spring of Kotor gulf. Numerous boreholes have discovered circulation zones of saltwater at depths of several hundreds of meters below the sea level. The case of saltwater pollution of the famous spring Almiros (Crete Island, near Iraklion) is characteristic for explanation of the saltwater mechanism and its consequences on freshwater quality (Fig. 3). Because

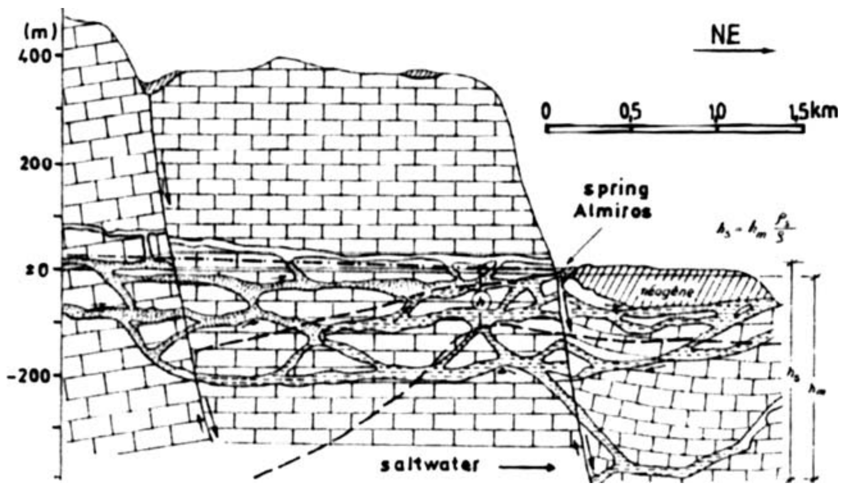

Fig. 3 Hydrogeological cross-section from carbonate massif of the Keri Mountain to the plain of Iraklion and the spring Almiros (Monopolis and Mastopis 1969)

of considerable neotectonic movement of lower carbonate blocks of the north part of the island, the paleokarstic outcrops are activated at the depths of 300 and 400 m below sea level. Some parts of karstified blocks can be dislocated at the depths of 600 m or even 1,200 m. In such conditions, it is evident that during dry periods, the shoreward movement of saltwater to the spring occurs.

Available methodology of freshwater tapping

As geological conditions play such an important role affecting the hydrogeological features of the karst coastal aquifers and their hydraulic behavior, the possibilities of freshwater tapping are widely different from one area to another. Depending on the locality and size of the interface between the aquifer and the sea, various types of tapping occur. Consequently, the mode of tapping is particularly relevant. The proper choices of tapping are: (1) the vertical well and (2) the horizontal drainage gallery.

The freshwater tapping in the coastal zone, with its large-size cavities and preferred directions of groundwater flows, involves many risks concerning both capacity and water quality if the groundwater tapping is based on a system of wells. On the other hand, tapping of the horizontal gallery has proven to be reasonably efficient under such conditions. Maximum capacity is obtained through cavities with preferred direction of groundwater flows; horizontal galleries also reduce the effect of saltwater encroachment during withdrawal of freshwater. The balance can be obtained by regulation of pumping or by constructed intervention in the karstified zones (building an artificial barrier across the direction of water flow).

Horizontal drainage galleries have played a positive role at several sites in the coastal karst regions. Table 1 provides some basic information concerning the tapping facilities in the Dalmatian littoral (Croatia) and the largest facility located in the Libyan littoral (Mijatović 1996).

Exploration of the confined karstic aquifer discharging trough submarine springs (Lebanese coast)

In the Chekka region of North Lebanon, considerable discharge of freshwater (6 m^3/s in dry period and over 50 m^3/s in winter) sprouts up in the Mediterranean Sea from a number of submarine springs lying between 20 and 2,000 m off shore (Fig. 4).

There are two main problems for collection: the first is the circumstances of seawater encroachment into the aquifer by the submarine springs; the second is the possibility of freshwater tapping on the coast at points where groundwater flow and the freshwater head (hydraulic potential) are suitable. The conclusion of complex studies by UNDP was monitored by pumping tests (14 September–2 October 1966) in boreholes cutting trough fissures in the Senonian marls and communicating with Cenomanian limestones. Preliminary results of pumping tests showed that a capacity of 150 l/s of freshwater could be obtained at Crevasse C.

Sidi-Mansur freshwater tapping facility in Libyan coast

The main purpose of the groundwater tapping project at Sidi-Mansur near the Jebel Akhdar escarpment and Benghazi town (11 km from the coast) consisted of mining excavation of the vertical shaft (82 m deep) and horizontal drainage gallery (500 m length) perpendicular to the groundwater flow. This channel is tectonically predisposed on direction from Sidi-Mansur to coastal spring Ain-Zeina (Lagoon Blue) (Fig. 5). On the basis of complex hydrogeological research, two important facts were established: (1) the minimum level of groundwater in the site of drainage gallery is at + 3.5 m and because of that the bottom of the gallery is seated at + 1.90 m; (2) the width of the groundwater brackish zone from the coastal spring Ain-Zeina, whose minimum yield reaches more than 1.0 m^3/s of brackish water, is measured to more than 1 km by well network observation; therefore, the gallery length must be 500 m (Mijatović 1996.). The

Table 1 Tapping facilities on the Dalmatian and Libyan littoral

Locality	Distance from the sea (km)	Depth of shaft (m)	Length of gallery (m)	Minimum capacity (l/s)	Cl content, ppm (mg/l)
Dubrava 1	3.0	28	110	35	35
Dubrava 2	3.7	40	150	15	50
Kovca	4.0	70	50	25	30
Roman well	2.0	82	270	100–120	250–300
K1, Brac	0.8	18	20	1	400–500
K2, Brac	1.8	52	400	5	300–400
Zuljana	1.0	18	30	10	300–400
Marina	3.0	33	400	45	200–250
Sidi-Mansur, Libya	11.0	80	500	400	250–300

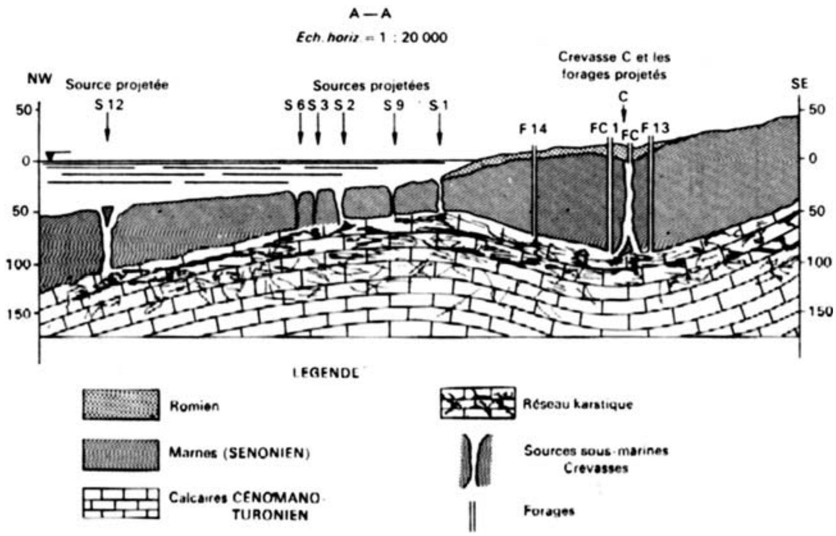

Fig. 4 Hydrogeological profile across discharging submarine zone in the Chekka coastal region

total pumping capacity is 400 l/s with average salinity of 300–350 ppm.

Unfortunately, a monitoring system for saltwater encroachment control was never established. This situation resulted in serious deterioration of freshwater quality (1,500 ppm) after 15 years of freshwater supply by the Sidi-Mansur facility. This facility was the first horizontal type intake structure for water supply constructed in North Africa in modern times.

Fig. 5 The spring Ain-Zeina (Lagoon Blue)

Conclusion

Experiences obtained in research and the use of coastal karst aquifers reveal an ample diversity of relationships between these system and the sea. Although the vulnerability of tapping facilities on external hazardous waste from catchment areas is evident, both problems regarding water capacity and water quality are always closely linked with the phenomenon of seawater encroachment. This phenomenon is still insufficiently defined in the scale of current tapping facilities. Analyses and tests of the chemical and physical processes which regulate contamination of the freshwater are usually approximate. Unfortunately, reliable experiences regarding monitoring and interpreting data for indicating the zones subjected to saltwater intrusion are insufficient. It is not possible to efficiently protect a tapping facility without a well-designed and functioning groundwater–seawater control system, accompanied by continuous monitoring of brackish and saltwater in a wide zone of influence, as well as simultaneous control of pumping capacity to assure the quality of freshwater produced.

Two examples of successful operation of such control systems are the tapping facility near Pantan spring on the Dalmatian coast and the system on Skurda-Gurdic springs-estavelle in the Gulf of Kotor, where the direction of saltwater encroachment toward the tapping facility have been determined by precise monitoring of hydraulic potential.

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