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Significance and origin of very large regulating power of some karst aquifers in the Middle East. Implication on karst aquifer classification

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Summary Karst aquifers are the main groundwater resource in Lebanon as well as in most Mediterranean countries. Most of them are not exploited in a sustainable way, partly because their characteristics remain unknown. Karst aquifers are so complex that the assessment of their resource and their exploitable storage requires an analysis of their whole functioning, particularly by analysing the spring hydrograph. Among all various methods, the method proposed by Mangin aims to characterize at the same time the recharge conditions and the storage and recession of the saturated zone by analyzing the spring hydrograph. This method defines two parameters, the infiltration delay ***i***, and the regulating power ***k*** which are the roots of a classification of karst systems. This classification makes the distinction between karst and porous aquifers considering the value of the regulating power. ***k*** is assumed to be lower than 0.5 in karst, and between 0.5 and 1 for all other aquifers, 1 being the upper limit.

The study of karst aquifers in Lebanon shows values of ***k*** > 0.5, and even 1; former data from the literature show that other karst springs in Middle East have comparable characteristics. In fact, what is not considered by Mangin and others, ***k*** is equivalent to a mean residence time in years of water in the saturated zone. So long residence times are normally observed in poorly karstified aquifers, or containing abandoned, not functioning karstification. The geological framework in which the studied springs are located in fact shows that these aquifers have been subject to a long, complex evolution, as a consequence of the base level rising. This rising produced the flooding of the successive karst drainage network, which does not really function anymore and provides a large storage capacity to the aquifer. The very interesting properties of these aquifers make them prime targets for fulfilling the increasing needs of water.

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As it occurs in most Mediterranean countries, carbonate rocks, mainly karstified, offer the main groundwater resources in Middle East. These resources are exploited for several millenniums as it is proved by ancient water works on karst springs, e.g. in Palestine (Nordon, 1991), Lebanon (Bakalowicz et al., 2002), and Syria (Kattan, 1997). Nowadays thanks to technical progress their exploitation is more intensive. The main consequences are their pollution and/or their overexploitation. For instance the spring of Khabour River, Khabour, or Jezireh Ras el Äin is presently dry a part of the year while it was one of the largest karst spring in the world with a mean annual discharge measured around 38 m^3/s in the 40s and 50s (Burdon and Safadi, 1963, 1964).

In Lebanon and in Syria it exists several karst springs presenting large average annual discharge with relatively weak seasonal variations. Previous studies (Burdon and Safadi, 1963, 1964; Abd-el-Al, 1967; Kattan, 1997) indicate that some of these springs discharge groundwater from aquifers owing large to very large storage capacity and long residence time. These characteristics are obviously not typical of truly karstic aquifers, which show low storage capacity, residence time shorter than 1 year, and highly variable discharge and chemical and isotope contents.

Recent studies of karst systems in Lebanon showed that the functioning of some of them is not typically karstic. Moreover, some results showed that the implemented investigation methodology, now recognized as well adapted to karst hydrological functioning (Ford and Williams, 1989; Bakalowicz, 2005), although needing some improvement, allows a fine characterization of such particular karst systems.

In this paper, we will (1) briefly describe and discuss the basic method; (2) present the case studies and the characteristics of the karst systems; (3) discuss the results; and (4) attempt an interpretation from previous results and the geological settings of the karst aquifers.

Method for analyzing karst system functioning

Several methods aim to determine the hydrodynamic functioning of carbonate aquifers from spring hydrograph analysis in order to characterize the role of karst structure development. The classical methods aim at identifying an experimental law in (a part of) the hydrograph. They were discussed, criticized and supplemented by Mangin (1975) who proposed a method which characterizes separately the infiltration conditions and the phreatic zone, and identifies the degree of karst development. Despite the fact that some recent works ignore or do not account for Mangin's critical analysis (see for instance Grasso and Jeannin, 1994; Bonacci, 1987, 1995) or attempt to improve it (Dewandel et al., 2003), this method, tested and complemented by Marsaud (1997), appears as the easiest to use and the most appropriate for identifying the karst efficiency in carbonate aquifer functioning. Consequently, it is commonly used in academic as well as practical studies (Soulios, 1991; Samani and Ebrahimi, 1996; Bouchaou et al., 1996; Crochet and Marsaud, 1997; Andreo et al., 2002). Other recent approaches attempt to model spring hydrographs by different ways for characterizing the role of karst in the aquifer functioning (Jeannin and Sauter, 1998; Grasso and Jeannin, 2002; Cornaton and Perrochet, 2002; Grasso et al., 2003; Kovacs et al., 2005).

In a holistic approach, the hydrodynamic functioning of carbonate aquifers is dependent upon (1) the state of development of the karst conduit network, both in their infiltration and phreatic zones, (2) the partitioning of infiltration in fast, slow and delayed conditions, and (3) the storage capacity of the phreatic zone. These characteristics may be identified with parameters or simple representations in order to compare and choose the appropriate methods to study these aquifers, and particularly to evaluate the groundwater resources and to define the best methods for exploiting and managing them (Mangin, 1994; Bakalowicz, 2005).

Several methods were proposed for classifying karstic aquifers, from hydrodynamic information (Mangin, 1975; Smith and Atkinson, 1976; Bakalowicz and Mangin, 1980) and water geochemistry (Shuster and White, 1971; Smith and Atkinson, 1976; Bakalowicz, 1977). Contrary to geomorphological classifications which are concerned with the results of karst processes expressed by landforms, these classifications are based only on hydrological functioning criteria.

The classification method proposed by Mangin (1975) and detailed by Marsaud (1997) is certainly the most achieved because it is based on a quantitative characterization of infiltration and storage in the karst phreatic zone. This classification refers to two criteria provided by the analysis of spring flood hydrographs, i.e. the recession curve analysis, one related to the infiltration conditions, and the second to the storage capacity of the phreatic zone.

Used for many years in hydrological studies, particularly in France and Spain, this classification is strengthened by all these studies. However, investigations on karst aquifers in Lebanon lead us to analyze and discuss the basics and interest of this method.

Mangin's method for analyzing the spring hydrograph

Mangin (1975) referred to the spring hydrograph recession, considering that it informs on both infiltration processes and storage in the phreatic zone. Based upon considerations for rightly rejecting the other methods (Mangin, 1970), that method (see Ford and Williams, 1989, p. 200 et sq.) is used for deciphering the recession, i.e. the decreasing part of the flood spring hydrograph, in two parts:

- the falling stage, translating the effect of the recharge to the spring,
- the baseflow stage, relating to the phreatic zone during its emptying without any recharge, i.e. not influenced by rainfall.

The total flow is then split up as follows:

$$Q_{spring} = \psi(t) + \varphi(t) \quad (1)$$

in which $\psi(t)$ is the infiltration function and $\varphi(t)$ the baseflow recession.

The baseflow recession classically follows Maillet's expression:

$$\varphi(t) = Q_0 * e^{-\alpha t} \quad (2)$$

in which Q_0 is the discharge at the beginning of baseflow recession at $t = t_i$, t_i in days being the time when the infiltration becomes negligible; and α being the baseflow coefficient in day^{-1}. The dynamic volume V_{dyn} is calculated by integrating the baseflow function from the flood peak time t_0

$$V_{dyn} = c\frac{Q_{R0}}{\alpha}, \tag{3}$$

V_{dyn} in m^3, with c = 86,400 when Q_{R0} is in m^3/s and α in day^{-1}. Therefore, V_{dyn} gives an estimate of the storage extent, lower than the total volume stored in the phreatic zone, as shown by Marsaud (1997).

Assuming that Maillet's expression may be extrapolated to the flood peak, Mangin deducted the phreatic flow from the falling stage in order to obtain the infiltration part. In order to characterize the infiltration by a function, Mangin proposes to use the following homographic function:

$$\psi(t) = q_0\frac{(1-\eta t)}{(1+\varepsilon t)}, \tag{4}$$

with q_0 the initial infiltration flow rate, ε the flow heterogeneity in day^{-1} and η the infiltration velocity in day^{-1}. Mangin chose that function because it fits well to all observed falling stage curves. $\psi(t)$ is obtained from the spring hydrograph according to the following procedure. $\varphi(t)$ is extrapolated for $t < t_i$, assuming that Maillet's law is available. At time t_0, i.e. at the flood peak, the initial discharge of infiltration q_0 is given by the difference between the total discharge Q at t_0 and Q_{R0} the initial discharge of the phreatic zone at t_0, from the extrapolation. Then experimental $\psi(t)$ is calculated according to Eq. (1) for $t_0 < t \leqslant t_i$, $q0$. Finally ε and η are obtained by fitting $\psi(t)$. From Eq. (4), it comes:

- $\eta = 1/t_i$, i.e. η is given in day^{-1}. η is related to the velocity of infiltration: the lower η, the slower the infiltration.
- ε, also in day^{-1}, controls the shape of the infiltration hydrograph. The more concave the hydrograph, the higher ε, the more prevailing the fast infiltration. $10 > \varepsilon > 1$ indicates that fast infiltration is dominant.

From studied examples, Mangin observed that a poorly developed conduit system or a sedimentary cover on carbonate rocks is responsible for a slow or delayed infiltration, η and ε being small, lower than 0.1. The snow cover acting in the same way as a sediment cover delays the infiltration. Many case studies confirmed this interpretation (see for example Marsaud, 1997).

Mangin's classification of karst aquifers

In his classification of karst systems, Mangin considered two indices, ***k*** defining the extent of the karst phreatic zone, and ***i*** characterizing the infiltration conditions.

The larger the phreatic storage V_{dyn}, the more efficient the regulation of the discharge. V_{dyn} is then compared with the average annual transit volume, V_{trans}, corresponding to the integral of the instantaneous discharge over the time period of record normalized to one water year. Then ***k*** is the ratio:

$$k = \frac{V_{dyn}}{V_{trans}}. \tag{5}$$

k highlights the regulating power of the phreatic zone of the aquifer. It is calculated by taking the maximum value of V_{dyn} observed during a long-term time series and V_{trans} the mean annual volume flowing through the phreatic zone during the same time series. Mangin (1975) and Marsaud (1997) considered that karst aquifers must present ***k*** values lower than 0.5, while in porous and fractured aquifers ***k*** should be in the range 0.5–1, 1 being the upper limit.

Mangin considered the variable ***y***

$$y = \frac{(1-\eta t)}{(1+\varepsilon t)}, \tag{6}$$

and proposed to keep as ***i*** index the value of y at t = 2 days. Index ***i*** is named the ''infiltration delay''. Then being in the range 0–1, ***i*** allows easily making a distinction between systems characterized by a mainly fast infiltration – ***i*** tending towards 0 – from those recharged by a slow or delayed infiltration – ***i*** tending towards 1.

Mangin (1975) defined five fields within the space defined by ***i*** and ***k***. Each field is designed according to data and ***i*** and ***k*** values from well known karst systems, from Europe, considered as references (Fig. 1). These fields are the following:

1. $k < 0.5$ and $i > 0.5$: domain of complex karst systems, largely extended and made up of several sub-systems;
2. $k < 0.5$ and $0.25 < i < 0.5$: systems with a karst conduit system more developed in their upper part than in parts close to their spring, and characterized by a delayed recharge because of either non-karstic terrains or snow, or sediment cover;
3. $k < 0.1$ and $0 < i < 0.25$: intensely karstified systems in both infiltration and phreatic zones, with a well developed conduit system directly connected to the spring;

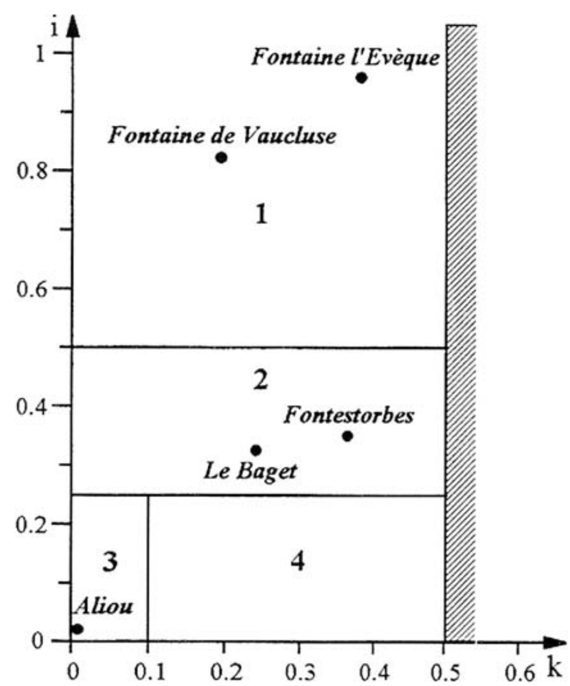

Figure 1 Classification of karst systems based on indices from the recession analysis (Mangin, 1975, in Marsaud, 1997).

4. 0.1 < *k* < 0.5 and 0.1 < *i* < 0.25: systems with a well karstified infiltration zone and an extended conduit network ending into a flooded phreatic zone;
5. k > 0.5: porous and fissured aquifers.

The reference karst systems considered by Mangin (1975) are three systems in the French Pyrenees — Baget, Aliou and Fontestorbes —, and two large systems in the French Mediterranean Alps, Fontaine de Vaucluse and Fontaine l'Évêque. Various European karst systems from France, Switzerland, Spain and Morocco were input in this classification, validating it.

Discussion

However Ford and Williams (1989), quoting Ecock's studies on karst hydrology in Vancouver Island, Canada, consider that the ***i*** index does not allow taking in consideration karst systems of North America characterized by a very rapid flow resulting in an intense development of karst. In fact, these results, locating these karst systems in domain 3, drive Ford and Williams to look for a more detailed classification, what is not the Mangin's aim.

Moreover, we noted that this classification is also incapable to take into consideration karst systems characterized by very long residence times. Mangin and Marsaud consider that ***k*** index is dimensionless. However, ***k*** is time equivalent because when dividing V_{dyn} in m^3 by V_{trans} in m^3/year, ***k*** is an integrative parameter, equivalent to the water residence time given in years, averaging the high heterogeneity of flow velocities occurring in the karst phreatic zone. Consequently, Mangin implicitly considered that the average water residence time in karst systems is shorter than 6 months (0.5 year). In fact, there is no theoretical reason for limiting ***k*** to 1 year, as we now show from some karst systems in the Middle East.

Karst systems in Lebanon

Carbonate rocks outcrop over more than 66% of Lebanon territory. Because karst processes occur at least since the upper Miocene, carbonate rocks are karstified, constituting the main aquifers in Lebanon, presenting the main groundwater resource and permanent flow. The detailed study of the main springs is a prerequisite to a sustainable exploitation of the water resource. Four main karst systems were studied by means of spring hydrograph analysis, supplemented by discharge time series analysis, and chemical or isotope natural tracing, depending on the individual case.

Anjar and Chamsine springs and their recharge areas in the central Bekaa (El-Hakim, 2005) drain out a large aquifer developing in the west side of Mont Anti-Lebanon. The hydrograph analysis of these springs is at the root of this work. The data are complemented by those previously got by Maalouf (1999) on Ain ez Zarka, the spring of Orontes River, discharging in the Northern Bekaa, and by Azar (2000) on Afka spring, the main spring of Nahr Ibrahim, in Mont Lebanon.

Climate and hydrology

Among all the countries in the Middle-East, Lebanon and Syria present a large range of climate and hydrology conditions. The aridity gradually changes from the Mediterranean littoral towards the interior, supported by the coastal mountains which intercept moisture and form a screen preventing it from reaching the inner regions. The Mediterranean climate changes thus by the various varieties of transition to the desert climate by the attenuation of the Mediterranean moderating influence. As a whole, the climate is excessive; two major seasons occur: a long dry season, from April to November, with large thermal amplitudes immediately behind the coastal ridge; and a short humid season, from December to April, often with violent rainfalls and storms on the coastal ridge. Above 1000 m above sea level (asl), snow predominates and forms a thick cover which melts from February to June. Snow melting constitutes the major recharge process.

The studied karst systems are subject to different climate conditions (Table 1). Afka system, located in the western side of Mount Lebanon, receives high precipitation, mainly snow which provides high yields when melting (representative rainfall at Qartaba station, Table 1). Anjar — Chamsine and Zarka karst systems are located in the Bekaa plain behind Mount Lebanon and then receive lower rainfalls. Anjar system extends in a continental semi arid climate (Anjar station, Table 1) and Zarka system partly in an arid climate where rainfall rarely exceeds 250 mm/year (Hermel station, Table 1). Their main hydrologic data are presented in Table 2.

Geology and hydrogeology settings

It exists two widely extended carbonate formations, separated by the lower Cretaceous complex aquiclude, composed of sandstones, basalt, limestone and marls, 600—800 m thick: (1) upper Jurassic limestones and dolomites, more than 1000 m thick and (2) upper Cretaceous, Cenomanian and Turonian, limestones, 600 m thick. The upper Cretaceous (Senonian) and Palaeocene marls, 400—600 m thick, end the series.

Table 1 Mean annual rainfall at stations representative of the studied karst systems, for the period 1931—1960, with the part fallen during the humid season

Station	Location	Altitude (m)	Range of variation of the annual rainfall (mm)	Mean annual rainfall (mm)	Rainfall from December to March (mm)
Anjar	Near Anjar spring	880	457—969	510	418 (82%)
Hermel	Near Aïn ez Zarka	750	—	240	170 (71%)
Qartaba	Near Afka spring	1140	914—2221	1396	1072 (77%)

From Service Météorologique du Liban (1977).

Table 2 Main hydrologic characteristics of the studied springs

	Period of observation	Mean annual discharge	Range of variation	Minimum discharge	Maximum discharge
Afka spring	1966–1972	4.02	2.72–6.08	0.5	56.7 (1971)
Anjar spring	1962–1972	2.35	1.50–3.75	0.6	9.3 (1963)
Aïn ez Zarka	1956–1972	12.9	11.00–16.30	5.5	26.0 (1971)

Discharge is given in m^3/s.

Wide asymmetric folds oriented NE-SW constitute the regional geological framework, organized in two anticline structures, Mont Lebanon ridge at West, and Mont Anti-Lebanon ridge at East, separated by a large syncline structure, occupied by the Bekaa plain (Fig. 2). Bekaa plain is edged by the Yammouneh fault, a major strike-slip fault, at West. Bekaa plain is a part of the rift extending from the Rhab plain, at North, in Syria, to the Dead Sea at South. This geological structure organizes the main regional aquifer systems as following: (1) the coastal plains, (2) the western flank of Mont Lebanon, (3) the eastern flank of Mont Lebanon, oriented to the Bekaa plain, (4) the Bekaa plain, and (5) the western flank of Mont Anti-Lebanon. Anjar – Chamsine system belongs to domain 5; Zarka system to domains 4 and 3; Afqa system to domain 2. They all develop in upper Cretaceous limestone, which is karstified.

The Anjar spring

Eight recessions, between 1962 and 1971, were analyzed, giving the main parameters characterizing the infiltration and phreatic zones (Table 3).

The index $\boldsymbol{i}$, included between 0.71 and 0.94, means that low infiltration is predominant. The snow cover may be considered as the principal cause for the long delay in infiltration, in the absence of any soil or sediment cover on the karst surface. In the Anti-Lebanon, the recharge is provided by snow melting at the end of winter and during spring. The mean value $\boldsymbol{i} = 0.83$ for the seven recessions is accepted.

For the same period (4383 days), the annual mean flow is $V_{trans} = 66 \times 10^6\ m^3$ and the largest observed dynamic storage is $V_{dyn} = 107 \times 10^6\ m^3$, what gives $\boldsymbol{k} = 1.635$ year.

The Chamsine spring

Three recessions between 1966 and 1968 are considered, the following ones being discarded because of the bad quality of data (Table 4). The index $\boldsymbol{i}$, included between 0.80 and 0.94 (average 0.90), corresponds to a mainly low infiltration, controlled by a long delay probably due to snow cover.

The highest V_{dyn} value is $39 \times 10^6\ m^3$, and the mean annual V_{trans} is $23.0 \times 10^6\ m^3$, what gives $\boldsymbol{k} = 3.0$ years.

Anjar and Chamsine systems present similar characteristics, being controlled by the same geologic and climatic conditions. They are possibly hydraulically linked, what is being studied.

The Afka spring

The Afka spring is the main spring of Nahr Ibrahim, which catchment area extents over a large part of the Northern Mont Lebanon. Its mean flow (Azar, 2000) is about $4\ m^3/s$ for the 1965–1971 period. Table 5 summarized the main data. The infiltration at the system scale presents the same character, mainly slow and delayed, as Anjar and Chamsine karst systems: $\boldsymbol{i}$ in the range 0.63–0.92 (average 0.83) should be also related to the recharge by the snow cover melting.

However, the phreatic zone shows characteristics different from those of Anjar and Chamsine systems: the dynamic storage is comparatively smaller, around $27 \times 10^6\ m^3$, accounting for a mean annual discharge $127 \times 10^6\ m^3$, what gives $\boldsymbol{k} = 0.21$ year (2.5 months). Therefore, the Afka system takes place within the domain 1 of the complex systems, with delayed infiltration.

Ain ez Zarka, the spring of Orontes river

The Zarka karst system has one of the largest springs in the Middle East, Ain ez Zarka, which mean flow is about $13\ m^3/s$, i.e. a mean annual flow of $410 \times 10^9\ m^3$/an. This is the permanent spring of the Orontes River, Nahr el Assi. It drains a large recharge area extended in the Northern Bekaa plain and Mont Lebanon, which area and limits remain unknown. The spring discharges through the thick, poorly permeable Neogene and Quaternary detrital sediment cover, which is supposed to confine the lowest part of the phreatic zone and to partly plug the spring. Table 6 gives the characteristics of several recessions (Maalouf, 1999).

The indices **i** and **k** are, respectively, 0.98 and 66 years. Even if we ignore the huge value of the dynamic storage calculated for 1967–1968 hydrological year ($27 \times 10^9\ m^3$), **k** remains very high, with 24 years. The Zarka spring drains a very large system, which functioning looks non-karstic, with a predominant long and slow infiltration and a large regulating power.

Discussion

Carbonate aquifers with such large storage capacities in their phreatic zone, responsible for residence times of some years, much longer than in active karst aquifers, are not common. Referring to several authors, Ford and Williams (1989) consider that karst processes develop mainly the karst porosity in the shallow phreatic zone, what favors its horizontal development rather than vertical. The only explanation for so large storage should be looked for a development of karst features deeply below the spring level. Deep karst development should be related to the rising of the karst base level which should have constrained superposed karst drainage structures to developing and flooding them as paleokarst in the present phreatic zone (Bakalowicz, 2004).

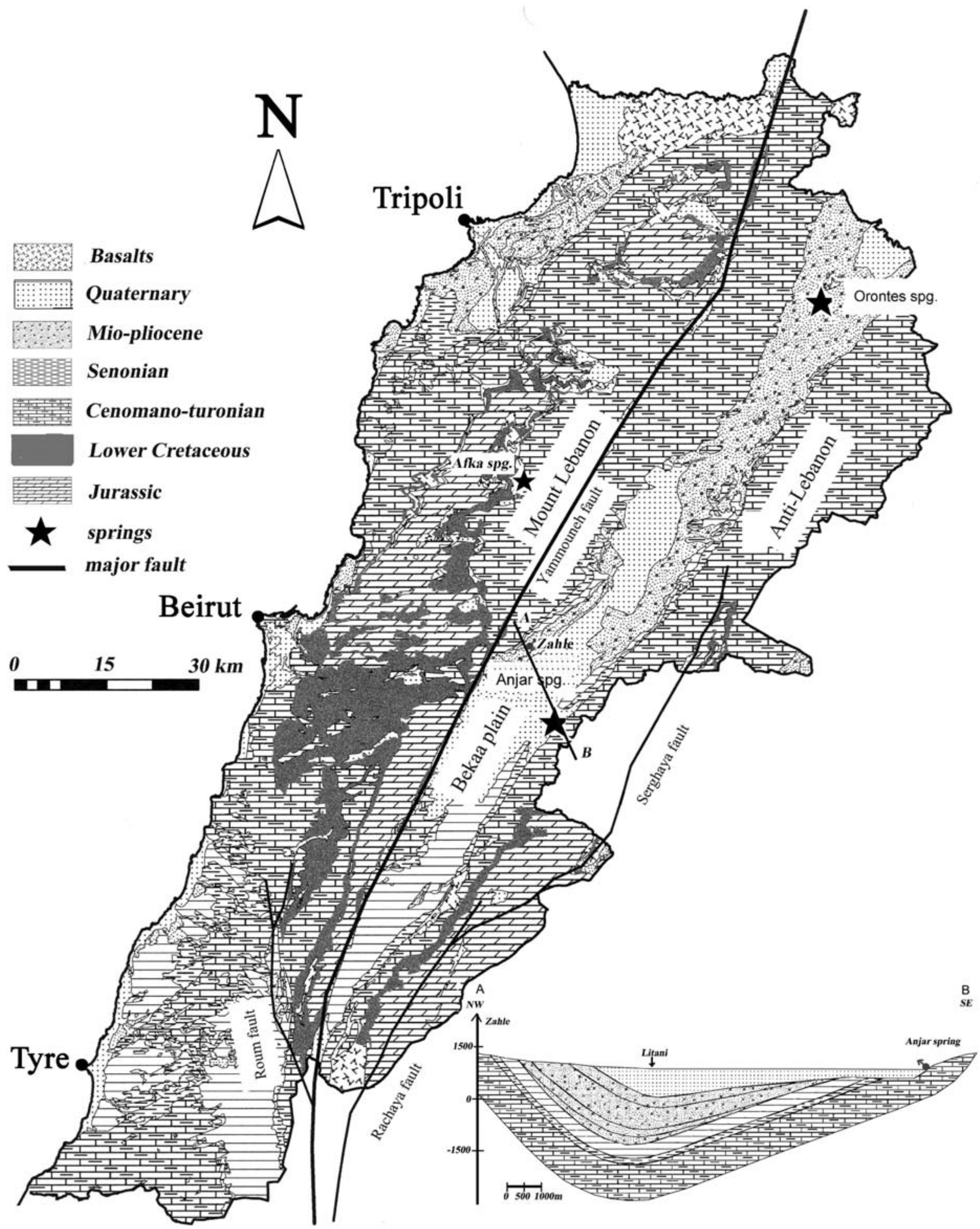

Figure 2 Geological map of Lebanon with the location of the studied karst springs. A cross-section of the Bekaa plain shows the extension of Anjar — Chamsine aquifer at depth, which is comparable to Zarka aquifer.

These important values of the dynamic storage are comparable to those reported by Abd-el-Al (1967), from karst springs located in Lebanon and Syria (Fig. 3). This author analyzed the baseflow recession of several springs in the Middle East, for hydrological years before 1953. His fitting method of the baseflow recession is the hyperbolic method which generally gives results comparable to the Maillet's law. The results (Table 7) led him to conclude that it exists in Lebanon and Syria limestone aquifers with huge baseflow storage. From Abd-el-Al's data it is possible to estimate a value of **k** index, from the ratio of the baseflow volume to the mean annual discharge en m^3/year. The storage in Anjar aquifer

Table 3 Characteristics of infiltration and baseflow of Anjar system

	Parameters of the infiltration function $\psi(t)$					Parameters of the Maillet's function $\phi(t)$		
	q_0 (m^3/s)	t_i (day)	η (day^{-1})	ε (day^{-1})	i	Q_{R0} (m^3/s)	α (day^{-1})	V_{dyn} (10^6 m^3)
20/2 to 12/10/1962	5.8	95	0.011	0.15	0.75	1.3	0.0025	44.9
24/2 to 19/11/1964	6.6	108	0.0093	0.023	0.94	1.75	0.0023	65.7
27/3 to 15/12/1966	5.3	90	0.011	0.19	0.71	1.4	0.0025	48.4
27/3 to 29/09/1967	6.3	82	0.0122	0.024	0.93	2.6	0.0025	89.9
19/2 to 02/12/1968	4.7	90	0.011	0.012	0.79	3.5	0.004	75.6
24/3 to 07/12/1969	5.9	109	0.0092	0.069	0.91	3.1	0.0025	107.1
24/3/1970 to 15/01/1971	4.8	90	0.011	0.12	0.73	1.7	0.0021	69.9
21/04 to 10/12/1971	7.1	110	0.009	0.12	0.79	1.8	0.0022	70.1

Table 4 Characteristics of infiltration and baseflow of Chamsine system

Recession period	Parameters of the infiltration function $\psi(t)$					Parameters of the Maillet's function $\phi(t)$		
	q_0 (m^3/s)	t_i (day)	η (day^{-1})	ε (day^{-1})	i	Q_{R0} (m^3/s)	α (day^{-1})	V_{dyn} (10^6 m^3)
28/3/ to 18/12/1966	0.123	50	0.02	0.10	0.80	0.43	0.0021	17.7
27/03 to 17/12/1967	0.429	67	0.0149	0.015	0.94	0.565	0.00125	39.1
21/2 to 23/9/1968	0.417	72	0.0139	0.028	0.92	0.55	0.0015	31.7

Table 5 Characteristics of infiltration and baseflow of Afka system

Recession period	Parameters of the infiltration function $\psi(t)$					Parameters of the Maillet's function $\phi(t)$		
	Q_0 (m^3/s)	t_i (day)	η (day^{-1})	ε (day^{-1})	i	Q_{R0} (m^3/s)	α (day^{-1})	V_{dyn} (10^6 m^3)
1965	8.5	118	0.008	0.274	0.635	0.7	0.003	22
1966	23.0	126	0.008	0.036	0.919	0.9	0.003	27
1967	26.0	139	0.007	0.063	0.875	1.3	0.006	18
1968	20.3	112	0.009	0.075	0.854	1.6	0.007	19
1969	10.9	99	0.010	0.071	0.858	0.7	0.003	19
1970	14.0	123	0.008	0.060	0.878	1.0	0.006	14
1971	30.5	81	0.012	0.134	0.769	1.4	0.009	14

Table 6 Characteristics of infiltration and baseflow of Zarka system

Recession period	Parameters of the infiltration function $\psi(t)$					Parameters of the Maillet's function $\phi(t)$		
	q_0 (m^3/s)	t_i (day)	η (day^{-1})	ε (day^{-1})	i	Q_{R0} (m^3/s)	α (day^{-1})	V_{dyn} (10^6 m^3)
27/06/1957 to 3/1/1958	15.62	133	0.0075	0.001	0.98	11.05	0.001	830
21/5/1959 to 24/3/1960	13.52	115	0.0087	0.001	0.98	8.3	0.0002	3680
27/5/1966 to 17/12/1966	14.58	131	0.0076	0.003	0.98	9.05	0.0007	1050
6/7/1967 to 5/2/1968	19.77	145	0.0069	0.002	0.98	15.11	0.00005	27000
14/11/1969 to 4/7/1970	20.38	122	0.0082	0.002	0.98	12.53	0.00014	9930

according to Abd-el-Al, is a little smaller (48×10^6 m^3) than V_{dyn} that we have calculated (average: 71.4×10^6 m^3), but remains in the range of this study, 45– 107×10^6 m^3 (Table 3).

Three groups of springs may be considered:

- ***k*** < 0.5. Only one spring, Nabaa el Assal shows a relatively low value (k = 0.21 year). It discharges groundwater from a karst system developed in upper Cretaceous limestone of Mont Sannine, northern Mont Lebanon. In the same hydrogeological situation as Afka spring, it presents comparable characteristics.
- ***k*** ≈ 0.5. This group brings together three springs emerging from Mont Lebanon, from the Barouk massif (Barouk, Safa and Khouraïzat), as well as Anjar and Barada springs discharging aquifers of the Mont Anti-Lebanon, on both sides in Lebanon and Syria. They all show a

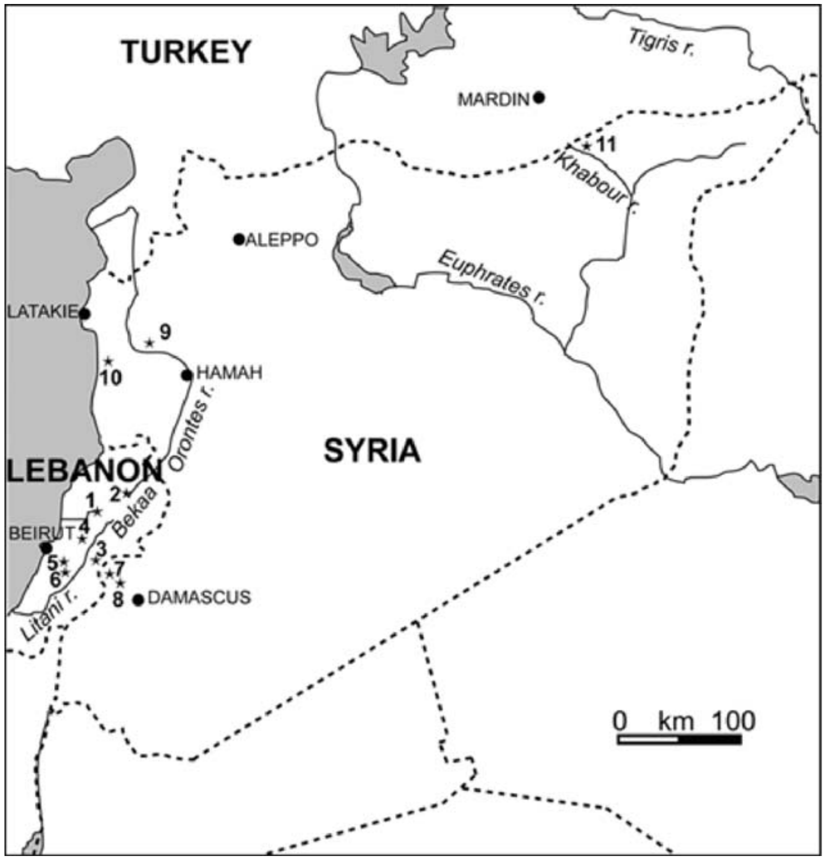

Figure 3 Location map of the studied karst systems in the Middle East. Stars design the karst springs cited. 1: Afka spring; 2: Aïn ez Zarka; 3: Anjar and Chamsine springs; 4: Nabaa el Assal; 5: Barouk and Safa springs; 6: Khouraïzat spring; 7: Barada spring; 8: Figeh spring; 9: Tell Ayoun spring; 10: Nahr Sene spring; 11: Khabour Ras el Aïn.

Table 7 Main characteristics of the karst springs studied by Abd-el-Al (1967)

Springs	Location	Mean annual discharge (m^3/s)	Baseflow volume (10^6 m^3)	Estimate of index *k* in year
Barouk	Mont Lebanon	1.7	27.2	0.51
Khouraïzat	Mont Lebanon	0.4	6.4	0.51
Safa	Mont Lebanon	1.9	30.4	0.51
Nabaa el Assal	Mont Lebanon, Sannine	2	13.3	0.21
Anjar	Mont Anti-Lebanon, Bekaa	3	48	0.51
Aïn ez Zarka	North Bekaa	17	734	1.37
Barada	Mont Anti-Lebanon, Syria	5	80	0.51
Tell Ayoun	Djebel Zawiye, Ghab, Northwestern Syria	5.3	229	1.37
Nahr Sene	Mediterranean coast, Northwestern Syria	14	737	1.67
Khabour Ras el Aïn	Northern Syria, south of Mardine, Turkish border	40	2500	1.98

Index ***k*** is calculated from Abd-el-Al's data.

value of $k = 0.51$ year, i.e. around a 6-month residence time in the saturated zone, what is not usually considered as karstic.

– ***k*** > 1. This is the group of the springs with lowly variable and high discharge: Aïn ez Zarka in Lebanon, and Tell Ayoun, Nahr Sene and Khabour Ras el Aïn in Syria. All these springs discharge groundwater from thick, large carbonate aquifers developing at depth below thick sediment cover.

All the springs with an estimated $\boldsymbol{k} \geqslant 0.5$ present some common hydrogeological characteristics, comparable to that of Anjar, Chamsine and Zarka karst systems. Two groups may be considered from their hydrogeological characteristics:

- The springs of Mont Lebanon, Barouk, Safa and Khouraïzat, are the point discharge of large carbonate aquifers; their flow is seasonally variable in regime and chemical content. They drain out a thick aquifer developing in Jurassic carbonate rocks, which are the known basement of the mountain ridge, partly confined under the thick impermeable series of the lower Cretaceous clayey sandstones. Karst features are particularly abundant in the Jurassic limestone at the contact with the basal Cretaceous, probably because of a karst development phase at the end of Jurassic. Recently identified, that past karstification phase is being investigated. The high storage capacity of the Jurassic carbonate aquifers is likely inherited from that paleokarst of Jurassic or lower Cretaceous age.

- All the other springs, Anjar and Barada on both sides of the Mont Anti-Lebanon, Aïn ez Zarka in Lebanon, and Tell Ayoun, Nahr Sene and Khabour Ras el Aïn in Syria, are located at the contact of extensive basins filled with thick Neogene and Quaternary detrital sediments. They discharge groundwater from large carbonate aquifers developing at the margin and underneath the thick, low permeable basin infilling.

— Some of these basins belong to the Dead Sea Rift, such as the Bekaa plain and the Ghab plain, into which Anjar, Aïn ez Zarka and Tell Ayoun springs discharge. Anjar aquifer develops in the upper Cretaceous limestone dipping westwards underneath the Bekaa plain continental sediment filling; Zarka aquifer, in the upper Cretaceous limestone of both sides of the Bekaa plain and below its thick alluvium filling; Tell Ayoun aquifer, in the upper Cretaceous limestone, partly covered with marly lacustrine Miocene and alluviums of the Orontes River.

— The Barada aquifer develops in the Jurassic limestone and dolomite of the Anti-Lebanon, dipping eastwards underneath the Zebdani plain infilling, of Neogene age, which is the north-western part of the Damascus basin. The hydrogeological settings of Figeh spring, emerging from upper Cretaceous limestone, are comparable to those of Barada aquifer (Kattan, 1997).

— Khabour Ras el Aïn, the main spring of the Khabour River, the main left bank tributary of the Euphrates River, discharges at the contact between an extensive limestone plateau developing mainly in Southern Turkey and an alluvial plain, in a comparable hydrogeological situation. Presently, that spring, one of the major karst springs in the World, is drying up because of the extensive overexploitation of its aquifer from many wells, with neither unadapted or insufficient control nor managing procedure on groundwater resource.

— Nahr Sene spring is a large spring, South of Latakie, presently forming a small lake because of a dam built for feeding irrigation canals, also captured for the water supply of Latakie region. It emerges at the foot of an escarpment of upper Cretaceous limestone, at the contact of the coastal plain made up of thick Pliocene and Quaternary sediments covering the limestone dipping westwards below the sea level. Although nothing is known about ante-Pliocene karst development at depth in Eastern Mediterranean, we assume that karst should have developed at depth during the Messinian salinity crisis, as shown by the recent investigations carried out particularly in France (Bakalowicz et al., 2003; Aunay et al., 2003; Bakalowicz, 2004).

Therefore, the carbonate karst aquifers in Lebanon, showing large regulating power as shown by the hydrodynamic properties of their phreatic zone, are representative of large carbonate aquifers in the Middle East. These aquifers contain in their phreatic zones abundant karst features, inherited from past karst phases, developed in relation with the rising of the karst drainage base level, due to either the formation of basins subsiding since the Neogene in a continental environment, or to the sea level lowering, during the Messinian crisis, followed by the Pliocene flooding.

In order to account for this type of karst aquifers, presenting large regulating power, and for the definition of the index $\boldsymbol{k}$ as a time, we propose to modify Mangin's classification of karst systems (Fig. 4) as follows:

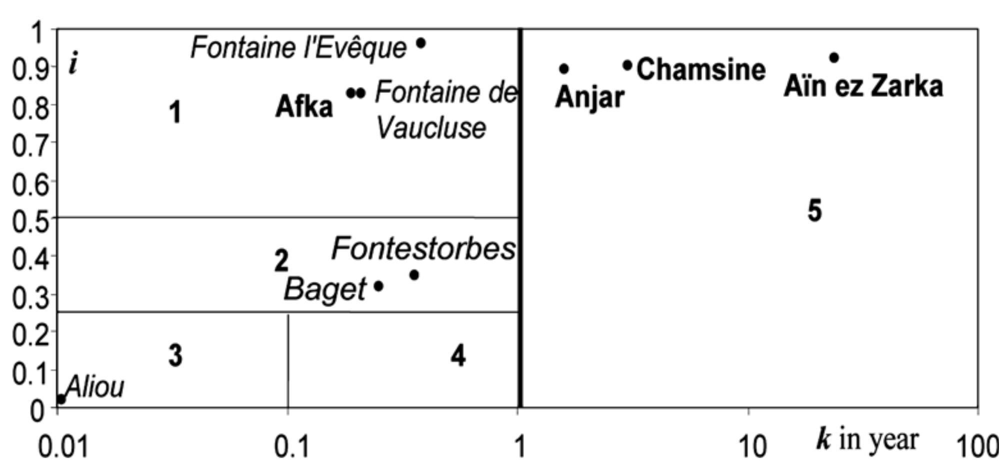

Figure 4 Proposed classification of karst systems from the recession analysis, accounting for karst systems with very long residence times.

(1) The **k** index is the mean groundwater residence time in the phreatic zone, in year, calculated from the ratio between the largest dynamic storage, in m^3, from the analysis of the low stage recession according to Maillet's approach, and the mean annual recharge for the same period, in m^3 per year.
(2) The domain of effective functioning karst aquifers is restricted to $k < 1$ year. Most classical karst systems show that their regulating power is lower than 1 year.
(3) The **k** index is then considered on a logarithmic scale, in order to represent very long residence times related to the storage allocated to paleokarst features in the deeper phreatic zone.
(4) The domain 5 ($k > 1$) for carbonate aquifers should be considered as the domain of karst systems with a deep phreatic zone, partly or totally confined underneath impermeable sediments, and largely karstified during previous karstification phases. According to Marsaud (1997), they are named ''non-functional karst systems''. These karst systems possess a complex drainage structure responsible for very long, multiannual or secular residence times. However, the paleo-conduit networks existing in their phreatic zone remain partly functional.

Conclusion

This hydrogeological situation of karst aquifers relating to the rising of their base level is common in Mediterranean carbonate massifs. Grabbens, formed during the Oligocene and Miocene distension phases were afterwards filled in with continental sediments. The Messinian lowering of the Mediterranean Sea level up to 1500 m below the present sea level also allowed the development of karst followed by a plugging by Plio-Quaternary marine and continental sediments, or by the partial flooding by sea water. Because most of these karst aquifers are partly covered with sediments or sea water, that hydrogeological situation remained ignored, by the lack of data and detailed studies.

Because of their large storage capacity in their phreatic zone and of their easy recharge thanks to karst structures, these aquifers present an important economic interest, particularly in regions of limited water resources and increasing water demand. Their large storage capacity allows an active management of their resources which may provide water supply for important populations. The active management of aquifers (Detay, 1997) consists in exploiting them at a total withdrawal rate close to the mean spring flow, by temporarily depleting the phreatic zone. The depleted part of the storage must be recharged during the following rainy season, what compensates for the natural seasonal flow variation. A large storage capacity and long residence time may allow regulating the total output flow at a multiannual scale, taking into account the secular climatic variations. By the fact of existent karst structures, the storage may be easily restored during the seasonal recharge. Karst aquifers with important storage capacities are the most suitable, provided that the aquifers characteristics and the karts system extension are well known and that the water authorities have at their disposal well documented data bases on groundwater extraction and well fitted decision support systems.

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