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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 Aïn 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:

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

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 infiltra-