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Describing the Karst Evolution by the Exploitation of Hydrologic Time-Series Data

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Abstract The importance of the groundwater management of karst aquifers relatively to their complexity requires the knowledge of the subsurface flow and storage behavior. In this study, a methodological approach based on the exploitation of daily spring's discharge data was developed and tested. The methodology makes use of the hydrograph recession curves, the correlograms output, and the logarithmically structured duration curves. This methodological approach was applied to the complex karst system of Louros basin. The Louros karst system consists of individual karst units discharged by respective springs which are distributed on three levels and form three easily distinguishable groups. The application results revealed a well organized karst system with conduits of slow and fast flow. It also revealed the uniformity and the complexity of the different units, as well as the properties, such as the storativity and the evolutionary process. This approach demonstrates the benefits of interpreting different methods in a hydrologically meaningful way for the recharge data evaluation.

Keywords Duration curves · Statistical analysis · Springs' discharge data · Cross correlation function · Recession curves · Karst aquifer

1 Introduction

A typical karst aquifer is an extremely heterogeneous organized network of conduits with different diameter, extent and joints. This organization which is related to the evolution of the carbonate rocks results in spatial and temporal variation of the aquifer properties, such as the porosity and hydraulic conductivity. According to White (2003), the hydraulic conductivity

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can be categorized as: 1. the matrix (or granular) permeability of the bedrock itself, 2. the fracture permeability and 3. the conduit permeability.

Because of the high karst heterogeneity no model is yet capable of simulating the whole aquifer system, unless under drastic simplifying assumptions (Groves et al. 1999). Studies on the function and hydrodynamic behavior of karst aquifers have mainly focused on the analysis of the whole karst spring hydrograph (Galabov 1972; Soulios 1991; Bonacci 1993) or the recession curves (Schoeller 1965; Mangin 1975; Padilla et al. 1994). Time series analysis, considering rainfall as an input and spring discharge as an output, has been also employed in karst hydrogeology (Mangin 1981; Mangin and Pulido-Bosch 1983; Mangin 1984; Machkova et al. 1994; Padilla and Pulido-Bosch 1995; Pulido-Bosch et al. 1995; Angelini and Dragoni 1997; Eisenlohr et al. 1997; Larocque et al. 1998; Labat et al. 2000; Lambrakis et al. 2000; Bouchaou et al. 2002; Panagopoulos and Lambrakis 2006; Katsanou et al. 2011; among many). Indeed in many cases, statistical methods were applied to the study of the rainfall trend, as for example the investigation of drought periods and their impact on the springs' discharge (Alexakis and Tsakiris 2010; Tsakiris and Alexakis 2013). Time series data analysis attempts to decode the information of hydrodynamic behavior of karst aquifers.

Each statistical method describes a single characteristic of the karst. For example; the coherency function method is used to investigate the property of linearity that characterizes a highly karstified aquifer when a change in the input function (precipitation) creates a proportional change of the output function (spring's discharge) (Larocque et al. 1998). The gain function expressing the amplification (>1) or attenuation (<1) of the output data in relation to the input signal constitutes an indication of the storage capacity of an aquifer (Padilla and Pulido-Bosch 1995). The use of autocorrelation and cross correlation functions could be practical and efficient in describing the hydrodynamic time series of a karst aquifer (Panagopoulos and Lambrakis 2006).

A method taking into consideration the recession coefficients of hydrographs, the lag time from the application of auto- and cross- correlation functions, and the duration curves constructed on a logarithmic basis could provide very useful information for the complexity, the evolution, and properties of a complex karst system consisting of individual karst units. From a hydrogeological point of view, the recession curve analysis provides information related to properties, such as the karst formation storativity, the lithological types, the degree of fragmentation, and the porosity while the correlogram provides qualitative information on the karstification degree and the amount of groundwater reserves (Mangin 1984; Padilla and Pulido-Bosch 1995; Bouchaou et al. 2002). The duration curves are proved to be useful for the comparison of karst springs in relation to the watersheds that recharge them (Ozis et al. 1993; Florea and Vacher 2006). Moreover, identical duration curves correspond to karst units of similar function (Mangin 1971; Soulios 1985; Florea and Vacher 2006).

This study investigates the evolution of the karst formations and describes the karst properties by means of well-known methodologies which exploit the discharge time series of the springs. For this purpose; the analysis of the recession curves, the study of the auto- and cross- correlation function as well as the duration curves, were carried out. The effectiveness and usefulness of carefully selected and tested methods were demonstrated. These methods were applied to daily discharge data of 11 karst springs located in Louros basin which was extensively investigated using hydrogeological and hydrochemical methods (Katsanou 2012). For these springs, the available sporadic daily measurements within a month and for several years (1982–1987) were completed by the use of simulation codes (Katsanou et al. 2014) and used as representative for the springs' yield. On the same time, daily precipitation data were used for each individual catchment.

2 Methodological Approach

A brief review on the employed methods is considered to be essential for understanding their application and utility in describing the karst system. The citing order is related to the hydrogeological interpretation of the treated data.

It was very early understood that the form of a spring's response (discharges) to a pulse force (precipitation) indicates all the factors that affect its catchment area. Areas with favorable potential groundwater yield, displaying high values of transmissivity and base flow, could be delineated by using base flow as an indicator. Hence the recession curves were considered. The correlograms were also studied as they contain information on the karst evolution and properties. Finally, the form of the duration curves was also taken into consideration so as to evaluate the complexity of the karst and the individual units' interrelation.

The recession curves correspond to the part of the hydrograph which extends between the discharge peak and the point at which the next rising limb starts. Their analysis enables the estimation of the aquifer's hydrogeological properties. Generally, the recession coefficient is proportional to the hydraulic conductivity and inversely proportional to the karst aquifer storativity and extent (Soulios 2008). According to Riggs (1964) and Petras (1986) any changes in the slope of the recession curve are attributed to heterogeneous aquifers. In case that a single exponential term can express the recession curve the aquifer is regarded as uniform in terms of hydraulic conductivity and storativity (Petras 1986). On the other hand, Padilla et al. (1994) claimed that the aquifer is considered to be not uniform if in a semi-logarithmic diagram the recession curve comprises of two components. In this case, the higher slope corresponds to the rapid discharge and the lower slope to the base flow. According to Mangin (1970) the recession curve composes of the falling and the depletion curves that correspond to two terms of the Mangin's recession equation. Coutagne (1968) considered the recession as a response of a single reservoir, the discharge of which obeys a power low of the drained volume.

Mangin (1981) was the first to study and treat the rainfall and the derived discharge time series in statistical terms. Aiming to describe the Pyreneean karst aquifers and their functions he/she obtained further depth in his interpretation (Ford and Williams 2007). The most used ones are autocorrelation, spectral density, cross-correlation, cross-amplitude, gain, coherency and phase functions for which detailed theoretical analysis and mathematical expressions can be found in Mangin (1981), Mangin and Pulido-Bosch (1983), Mangin (1984) Box et al. (1994), Padilla and Pulido-Bosch (1995) and Larocque et al. (1998).

In this paper, the auto and cross correlogram are briefly presented and used to outline the memory and the karstification degree of Louros' individual units. The memory of a karst unit corresponds to the time period which is required so that the initial conditions no longer affect its function. According to Graf and Elbert (1990), the decorrelation time can be obtained as equal to the minimum of time at which the autocorrelation function is equal to zero or to the first local minimum, in case it passes earlier through zero. The values of the autocorrelation function that range between 0.1 and 0.2 correspond to the memory of the karst unit. The cross correlation, which is essentially a bivariate analysis, features the conversion of an input to an output function (e.g., rainfall-discharge functions). It is applied, provided that the daily rainfall, which is used as input stress, is an uncorrelated process and when related to the karst spring discharge values, gives an idea of the system's response (Padilla and Pulido-Bosch 1995; Larocque et al. 1998).

Padila and Pulido-Bosch (1995) applied correlation and cross spectral analysis on precipitation and karst springs discharge data to demonstrate that the age of a karst system, which is associated with its function, can be relatively determined. By this way, a karst system can be classified as "old" displaying the characteristics of two-speed conduits, as "young" displaying the characteristics of the Darcy flow type, or as "intermediate".

In the cross correlation function; the delay, which is the lag time between lag = 0 and the maximum cross-correlation, indicates the karstification degree of the aquifer. It gives an estimation of the pressure pulse transfer and the particle travel time through the aquifer.

The flow-duration is a cumulative frequency curve, which shows the percent of time-specified discharges which are equaled or exceeded during a given period. It combines, in one curve, the flow characteristics of a stream across the full range of discharge, regardless to the sequence of their occurrence (Searcy 1959). The duration curves constitute the signature of a hydrological basin and are used for the fast and direct perception of the infiltration response in a hydrogeological basin (Jothityangkoon et al. 2001).

Yu and Liu (2002) used duration curves' data to predict low flow rates in small rivers without flow recording stations in Taiwan. In a previous similar research, Franchini (1996) proposed a methodology for determining drought periods based on duration curves. The discharge duration curves of a river are important for the design of hydroelectric production projects, especially in constructions with small or without reservoir (Mimikou and Baltas 2012).

The discharge duration curves are also used to investigate karst systems and their distinction into simple, isolated to the adjacent ones and complex (Soulios 1985; 1991).

3 Study Area

The broader area of Louros basin is located on the southern part of Epirus and it is discharged through 11 major springs (Fig. 1). The mountainous part of the basin is developed between 100 and 1200 m. It displays a humid climate with a mean annual precipitation of 1750 mm which can locally reach up to 2500 mm. There are no continuous temperature records within the watershed. Therefore, the mean annual temperature (18 °C) was obtained by a nearby station located at an elevation of 100 m. Geologically, the study area is hosted in the formations of the Ionian geotectonic zone (Katsikatsos 1992) (Fig. 1). The oldest formations consist of evaporitic layers of Early to Middle Triassic age that outcrop at the western and southern mountainous part around Ziros spring and are locally overlain by breccias derived from calcification processes (Karakitsios and Pomoni-Papaioannou 1998). These formations are overlain by a thick sequence of carbonate and clastic rocks reflecting a continuous sedimentation from Late Triassic to Upper Eocene (Skourtis-Coroneou and Solakius 1999) (Fig. 1).

The Pantokrator and Upper Senonian limestones are considered to be permeable. According to Nikolaou and Lagaris (1990) and Nikolaou et al. (2011), the storage coefficient values for the saturated part of these carbonate formations vary between 2 and 3 %. Clastic limestones of Eocene and Vigla limestones are considered of low permeability. The latter formation (Smyrniotis 1991) constitutes the base level of the local aquifer, under which karstification is very low or does not exist, when underlying limestones of high permeability such as the Senonian ones (see geological section in Fig. 1). Dolomites, shales, amonitico rosso limestones and flysch formations are considered either of very low permeability or impermeable. The Neogene and Quaternary deposits mainly comprising of clayey but also sandy beds display low permeability in comparison with the carbonates rocks.

The major tectonic features of the region are folds with their axes trending SW-NE and NNW-SSE directions. The broader area is characterized by the continuous succession of

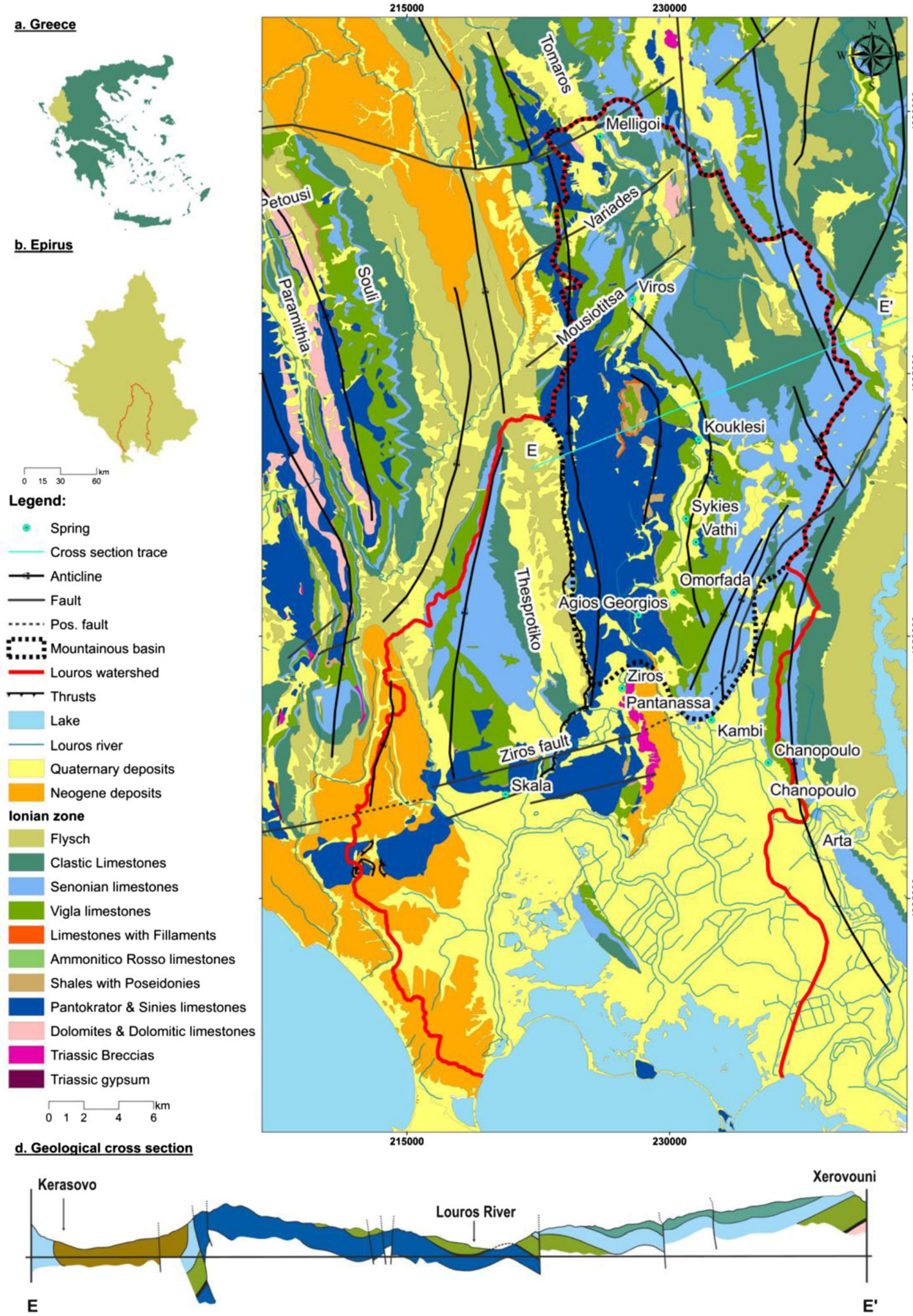

Fig. 1 The geological map of the study area

synclines and anticlines with a general direction of NNW to SSE due to the overthrust of the isopic zones from east to the west. Such synclines filled with flysch limit the area from the east and west and control the movement of water. Strike-slip fault systems display same directions, while younger ones normal to the previous create a tiered structure and contribute to the formation of individual karst units. Finally, diapirism resulted to slip surfaces of gypsum which facilitated the overthrusting, contributing to the complex tectonic structure, and affected groundwater quality.

A vast number of exokarstic and endokarstic forms, such as small dolines, caves etc., indicates a relatively developed karst. The most important aquifers of the area have been mainly developed in the Pantokrator and the Upper Senonian limestones. These formations show high permeability due to their intense karstification and fracture porosity. Individual karst units, more or less interconnected, form a karst system which is drained by the Louros River. These units are discharged by 11 karst springs, distributed at three distinct levels, where three aquifers are developed. In the upper part at an elevation of 280–350 m, Meliggoi (0.15 m^3/s) and Viros (0.80 m^3/s) springs (Table 1) discharge from the Senonian limestones. The quality of the groundwater is of Ca-HCO_3 type, clearly differentiating this part of the area. The majority of the springs are located in the middle part at altitudes ranging between 50 and 150 m (Table 1). These springs are Kouklesi (0.10 m^3/s), Sykies (0.15 m^3/s), Vathi (1.80 m^3/s), Omorfada (0.70 m^3/s), Ziros (0.08 m^3/s) and Agios Georgios (2.90 m^3/s) rising from the Pantokrator formation. Their outlets arranged along the river bed, contribute to the formation of the most important aquifer of the area. It is developed in the granular sediments and the surrounding carbonate rocks of the middle part. The groundwater affected by the presence of evaporatic layers shows a Ca-HCO_3-SO_4 water type. Relations between surface and groundwater are common and obvious in this part of the area, where depending on the season, the adjacent aquifer recharges or it is recharged by the river. In the lower part, at an elevation of few meters, Kambi (0.65 m^3/s) and Chanopoulo (4.50 m^3/s) springs rise from the Senonian limestones, while Skala (3.20 m^3/s) from Pantokrator formation. The rise of these springs of overflow type is due to the difference of permeability between the carbonate and the granular formations. In the same area, the Arta low-enthalpy geothermal field is developed in the alluvial sediments. It covers an area of 10 km^2 with a calculated geothermal grade between 5 and 11 °C/100 m (Hatziyannis 2011). The alluvial deposits are underlain by carbonate rocks of the Ionian zone constituting the thermal water reservoir. Tectonics plays an important role in the infiltration of meteoric water at greater depths, as well as in the thermal water circulation and uprise (Vriniotis and Papadopoulou 2004). Chanopoulo spring having a Na-Ca-HCO_3-SO_4 water type indicates a deep circulation.

The Louros mountainous basin has an extent of 400 km^2 (Katsanou 2012). It is well defined by the flysch outcrops at the western and the Ziros-Zalongo fault zone at the southern margin (Fig. 1). The southern, the eastern and the northern limits were determined by stable isotope analyses and hydraulic load distribution maps (Leontiadis and Smyrniotis 1986; Katsanou 2012). A detailed study of the hydrogeological balance (2008–2010) carried out by Katsanou (2012) led to the estimation of the real evapotranspiration (33 %) and the karst formations' properties, such as the storage capacity which exceeds 1 % and it is considered as elevated. All springs discharge more or less hydrogeologically individual units that contribute to the formation of a complex system.

4 Results

Figure 2 comprises of four characteristic hydrographs that correspond to the upper (Fig. 2a), the middle (Fig. 2b, c) and the lower parts (Fig. 2d) of the study area.

Table 1 The recession coefficients of the springs hosted in Louros basin

Spring	Formation	Absolute elevation (m)	$\overline{Q}(m^3/s)$	Recession period	Recession coefficient (d^{-1})	Recession period	Recession coefficient (d^{-1})
1. Meliggoi		350	0.15	9/3–23/10/1984	$-(1.05–1.67)\times10^{-2}$		
				23/1–14/10/1985	$-(1.91–2.44)\times10^{-2}$	13/5–2/9/1985	-8×10^{-3}
				2/3–24/10/1986	$-(1.25–6.69)\times10^{-2}$	1/8–5/9/1986	-8×10^{-3}
2. Viros		280	0.80	14/4–20/09/1984	$-(3.8–9.4)\times10^{-3}$		
				23/5–28/08/1985	-8.7×10^{-3}		
3. Sykies		140		23/03–22/10/1985	$-(3.66–5.87)\times10^{-3}$		
			0.15	13/03–25/10/1986	$-(3.26–8.44)\times10^{-3}$		
				21/02–19/06/1987	$-(4.32–6.28)\times10^{-3}$		
4. Vathi		138	1.80	23/04–23/10/1985	$-(3.13–4.71)\times10^{-3}$		
				27/02–16/12/1986	$-(2.2–4.58)\times10^{-3}$		
				04/04–07/10/1987	$-(3.17–3.71)\times10^{-3}$		
5. Omorfada		120	0.70	20/03–18/11/1984	$-(1.66–1.80)\times10^{-3}$		
				23/03–04/11/1985	-1.63×10^{-3}		
				25/02–14/12/1986	$-(1.39–1.83)\times10^{-3}$		
6. Agios Georgios		100	2.90	22/03–21/10/1985	$-(2.34–3.47)\times10^{-3}$		
				24/02–14/12/1986	$-(2.12-3.32)\times10^{-3}$		
7. Kouklesi		138	0.10	23/02–11/02/1982	$-(4.43–9.36)\times10^{-3}$		
				17/03–18/06/1982	$-(5.18–7.65)\times10^{-3}$		
				26/02–07/06/1983	$-(5.84–7.76)\times10^{-3}$		
				16/03–30/03/1984	-5.28×10^{-3}		
8. Ziros		50	0.08	27/03–10/09/1982	$-(3.50–6.85)\times10^{-3}$		
				02/04–18/09/1983	$-(5.26–9.92)\times10^{-3}$		
				27/02–18/09/1984	$-(2.53–4.55)\times10^{-3}$		
9. Skala		12	3.20	09/03–16/05/1984	$-(1.20–2.17)\times10^{-2}$	17/05–21/10/1984	-7.38×10^{-3}
				20/02–14/05/1985	$-(1.61–2.89)\times10^{-2}$	15/05–30/08/1985	-8.36×10^{-3}

Table 1 (continued)

Spring	Formation	Absolute elevation (m)	$\overline{Q}$(m^3/s)	Recession period	Recession coefficient (d^{-1})	Recession period	Recession coefficient (d^{-1})
				17/03–07/07/1986	$-(1.59–3.20)\times10^{-2}$	08/07–04/09/1986	$-(6.84–9.00)\times10^{-3}$
10. Kambi		10	0.65	24/02–21/06/1984	$-(1.03–1.75)\times10^{-2}$	22/06–19/09/1984	-2.45×10^{-4}
				24/03–26/06/1985	$-(1.14–1.76)\times10^{-2}$	23/06–24/10/1985	$-(3.84–4.00)\times10^{-4}$
				28/02–20/09/1986	$-(1.33–2.19)\times10^{-2}$		
				05/04–19/07/1987	$-(1.18–3.20)\times10^{-2}$	18/07–29/09/1987	-4.2×10^{-4}
11. Chano-		5	4.5	05/01–30/07/1983	$-(3.67–8.70)\times10^{-3}$	30/07–18/09/1983	$-(6.41–6.56)\times10^{-4}$
poulo				26/02–28/07/1984	$-(5.16–7.99)\times10^{-3}$	10/08–20/09/1984	$-(7.05–7.63)\times10^{-4}$
				17/02–04/06/1985	$-(5.31–6.90)\times10^{-3}$	06/06–23/10/1985	$-(8.83–9.25)\times10^{-4}$

In humid climates as in the case of the Louros basin, the constant and repeated precipitation interrupts the recession of the hydrograph. This implies that every time series having individual discharge is plotted on a semi-logarithmic diagram as a number of linear segments of diverse duration. The main problem in these cases is the variety of recessions that accompany those different segments corresponding to different stages in the aquifer discharge. Thus, either the construction of an overall representative recession curve or the calculation of the mean slope from each individual segment is required. This problem was overcome by the construction of the master recession, which is essentially an average recession curve (Johnson and Dils 1956; Toebes et al. 1969). Nowadays, there are several computer codes which can calculate the master recession curve (Nathan and McMahon 1990; Posavec et al. 2006 and others). The recession coefficient in Louros basin was calculated for each of these segments (Table 1). From the analysis of the spring's recession coefficients one or two groups with similar recession coefficient values were obtained for each spring (Table 1) indicating homogeneous karst aquifers (Riggs 1964; Petras 1986).

The recession coefficients show two principal groups displaying values between $(1–2)\times 10^{-3}$ and 8×10^{-3} d^{-1} (Meliggoi spring, Table 1) for the upper part. This, in agreement with Mangin (1975) and Amit et al. (2002), indicates the presence of two types of flow (fast and slow) verified by the two main slopes of the recession curve. Viros spring, belonging to the same area, presents only one type of flow with values in between 3.8×10^{-3} and 8×10^{-3} d^{-1}.

Coefficients values of similar order of magnitude are observed in the middle part of the area and range between 1.4×10^{-3} and 9×10^{-3} d^{-1}. For each spring, the calculated recession coefficients are very similar for all years. Within this group; Sykies, Vathi, Omorfada, Agios Georgios, Ziros and Kouklesi springs present only one type of flow. All these springs are discharged at similar elevations along Louros bank forming a common aquifer that regulates the spring water flow shading the fast and slow flow discrimination.

In the lower part of the area; Skala, Kambi and Chanopoulo springs (Table 1) present two principal coefficients corresponding to two types of fast and slow flow. Skala and Kambi springs strongly differentiate from the Chanopoulo spring in the coefficient of fast flow, which for the first two lies in between $(1.2 \text{ and } 3)\times10^{-2}$ d^{-1} and for Chanopoulo spring between 3.5 and 8×10^{-3} d^{-1}. The difference of the one order of magnitude between these springs implies a higher hydraulic conductivity and consequently a more developed karst (Soulios 2008).

The lag time of the autocorrelation function is associated with the memory of the karst systems. According to Mangin (1984); the memory of a karst unit may be related to the storage of the volume of water, during a precipitation event, which is discharged much later from the system. It is therefore concluded that the greater the lag time, the larger the memory and thus the poorly developed is the draining network of the karst system.

Figure 3 presents the autocorrelation diagrams for the karst springs' discharge. There is a sharp drop in the autocorrelation function for the initial days, though the bimodal characters of the karst units were obviously not deduced. They display a variability in lag time values for $r(k)=0.2$ which range between 70 and 120 days forming three groups of springs.

The first group classifies Viros and Meliggoi springs, which rise at altitudes of about 300 m a.s.l. Their lag time values range between 100 and 125 days. The second group constitutes of Sykies, Vathi, Agios Georgios, Ziros and Kouklesi springs, at altitudes of 50–150 m, reaching $r(k)=0.2$ after about 88 days.

The lag time values are identical for all the aforementioned springs, with the exception of Omorfada spring displaying a lag time value of 111 days. Skala, Kambi and Chanopoulo springs constitute the third group and display lag time values between 70 and 79 days.

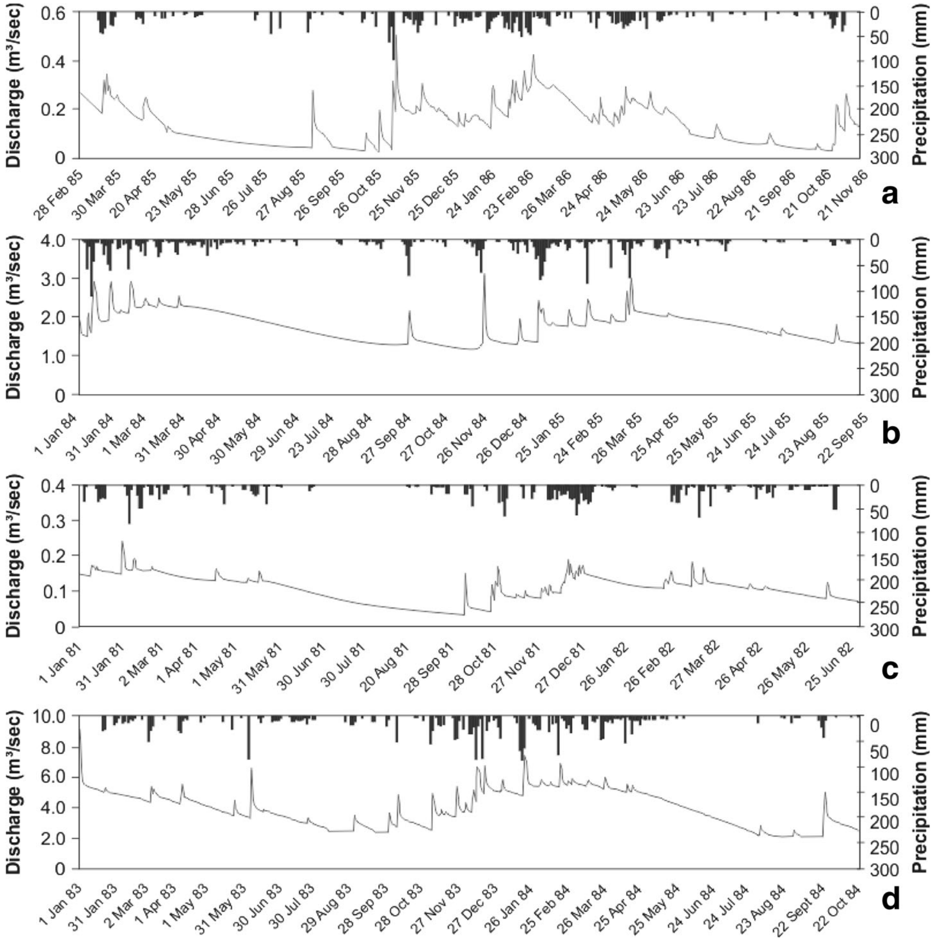

Fig. 2 Hydrograph of the springs' discharge for **a**. Meliggoi, **b**. Vathi, **c**. Kouklesi and **d**. Chanopoulo springs plotted together with precipitation values (*black histograms*)

The comparison of the three groups pointed out different grade of karstification among them. The units of the first group are characterized as less developed and even lesser than the second one. The karst units with the most developed network belong to the third group and exhibit shorter lag time (70–79 days).

Figure 4 shows the plots of the cross-correlation functions of the 11 karst springs. For all the springs there is a direct response to rainfall with correlation coefficients ranging between 0.35 and 0.45. For values $r_{x,y}(k)=0.1-0.2$, the lag time is not higher than 1–3 days while the function resets after 25–40 days. This suggests that these units have a relatively well-developed network of fast and slow flow conduits.

According to Padilla and Pulido-Bosch (1995) model, the characteristic evolution of Louros karst system, classifies it into the category of the intermediate ones.

The complexity of the karst units is studied with the aid of the duration curves. A simple karst unit exhibits a normal distribution on a probabilistic graph while its duration curve is

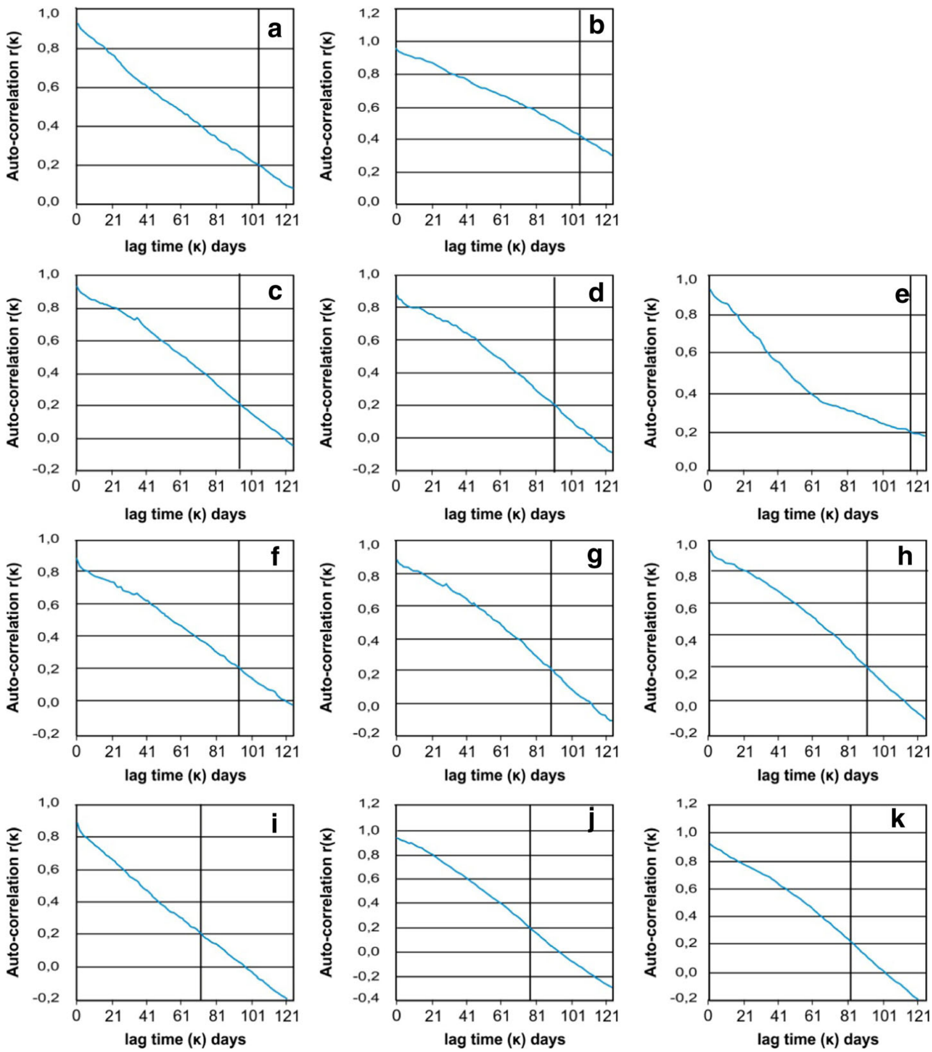

Fig. 3 Auto-correlation diagrams for Louros basin karst springs: **a**. Meliggoi, **b**. Viros, **c**. Sykies, **d**. Vathi, **e**. Omorfada, **f**. Agios Georgios, **g**. Ziros, **h**. Kouklesi, **i**. Skala, **j**. Kambi and **k**. Chanopoulo

presented by a straight line with a certain slope (Soulios 1985; 1991). In complex karst units; overflow or discharge loses towards an adjacent unit, or a supplementary recharge results in the differentiation of the duration curve, i.e., the change of its inclination (Soulios 1985; 1991).

The duration curves of Louros basin can be categorized into three groups. The first group classifies the duration curves of Viros and Meliggoi springs. Figure 5 presents similarities to the discharge distribution of these two karst units possibly attributed to their similar function mechanism (Mangin 1971; Florea and Vacher 2006). According to the aforementioned, the arrangement of the points on a relatively straight line characterizes them as simple.

The duration curves of the middle part have a sigmoid shape showing three segments of different slopes (Fig. 6). The first, having a gentle slope, corresponds to low flow rates and hence to a similar low recharge. It is followed by a second one with a steeper slope corresponding to higher flow rates and recharge. This segment indicates the existence of additional water losses, beyond the spring's outlet, i.e., the functioning of e.g., conduits transmitting water to adjacent units due to overflow. The third segment corresponds to the highest flow rates and has even gentler slope. Its presence is attributed to the function of supplementary conduits that recharge the unit and are put into operation after high intensity rainfall (Mangin 1971). The above description implies that the units of the second group are complex possibly interacting through conduits that are put into operation under certain recharge conditions.

Skala and Chanopoulo springs belong to the third group. According to Fig. 7, their duration curves show two different slopes. Change in slope, getting significantly lower values, takes place at very high flow rates (Q>9 m^3/sec) and it is interpreted as a supplementary recharge through conduits operating under conditions of very high recharge. As explained above, this group of units only receives supplementary recharge while their discharge is achieved through a single outlet.

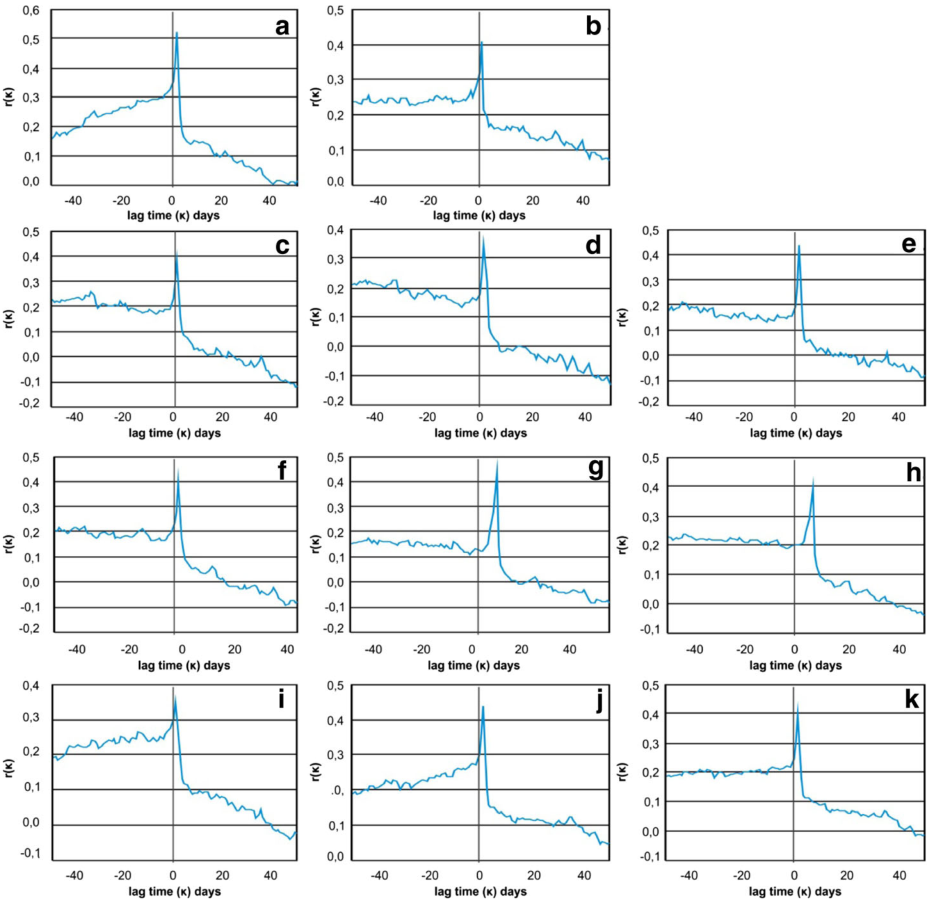

Fig. 4 Cross-correlation diagrams for Louros basin karst springs: **a**. Meliggoi, **b**. Viros, **e**. Sykies, **d**. Vathi, **e**. Omorfada, **f**. Agios Georgios, **g**. Ziros, **h**. Kouklesi, **i**. Skala, **j**. Kambi and **k**. Chanopoulo

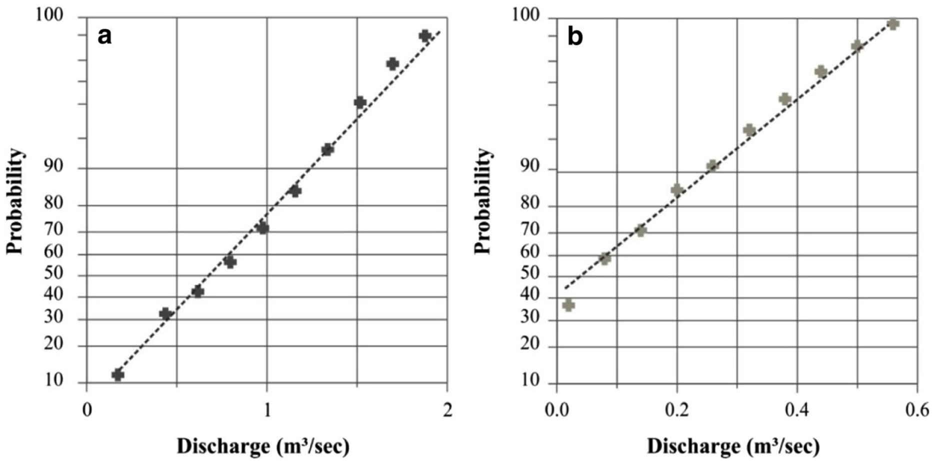

Fig. 5 Duration curves of **a** Viros and **b** Melligoi springs

5 Discussion and Conclusions

Nowadays the knowledge of the characteristics and the properties of the karst aquifers are essential for the groundwater management, given that 25 % of the global population is supplied by drinking water from such formations (Ford and Williams 2007). The duality of the karst aquifers, concerning fast and slow groundwater flow, was very early recognized and described (Ford and Williams 2007). Which flow is the dominant one depends on the karst evolution and the properties of the hosted aquifers. The Louros karst system is described using a methodological approach as a novel strategy. It is based on discharge data and consists of a combination of carefully selected methods. It is concluded that this approach is very useful, practical and effective and comprises the evaluation of a) the spring's hydrographs recession curves, b) the statistical functions and c) the duration curves.

The hydrograph analysis and especially those of the recession curve easily highlights the duality of the individual karst units. The calculated recession coefficients having two different values [~1–2×10^{-2} d^{-1} and~7–8×10^{-3} d^{-1} (or in some cases~4–8×10^{-4} d^{-1})] clearly demonstrate the fast and slow flow component. A unique recession coefficient was calculated for most of the springs of the middle part. The single slope of a recession curve reveals the uniformity of the individual karst units in terms of hydraulic conductivity and storativity (Riggs 1964; Petras 1986). Given of the precedent conclusion on the duality of the karst, this uniformity of the middle part is perhaps not true. This might be explained by the fact that these springs rise at similar elevations along the Louros bank forming a common aquifer that regulates the springs' flow.

The classification of the individual karst units into three groups was achieved by the autocorrelation analysis as the decorrelation time clearly differentiates for each of them. This function also demonstrates the large memory of the units, corresponding to the storage capacity of the aquifers. The values of the lag time for the aforementioned groups are comparable, but slightly higher than those corresponding to karst systems of intermediate to fully developed conduits (Mangin 1984). According to Panagopoulos and Lambrakis (2006), the lag time for the holokarst system of Almyros Crete reaches 55 days. This is in line with Padilla and Pulido-Bosch (1995) who obtained similar results for such systems (holokarstic or

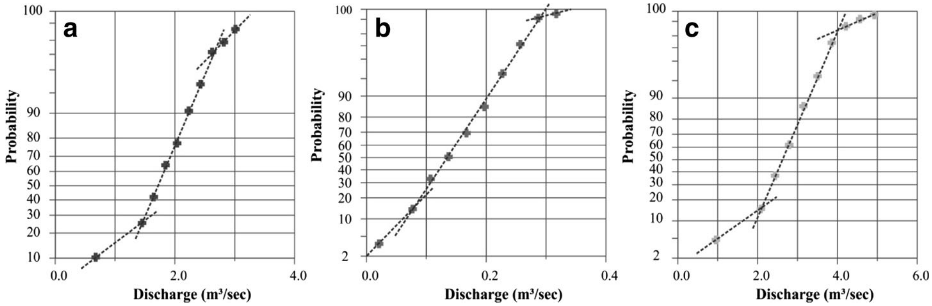

Fig. 6 Duration curves of **a**. Vathi, **b**. Sykies and **c**. Agios Georgios springs

telogenic). The lag time values for aquifers exhibiting large memory range between 32 and 117 days (Angelini and Dragoni 1997; Larocque et al. 1998; Amraoui et al. 2003; Panagopoulos and Lambrakis 2006; Kovacic 2010), while for aquifers of shorter memory lower values were reported. According to Kovacic (2010), in certain cases, the limited discharge capacity of a karst aquifer results in deviations from the expected values. This explains the elevated lag time of Omorfada spring which also belongs to the second group. The cross-correlogram exhibits a steep slope for most of the springs with a lag time of about 3 days reflecting a rapid response to rainfall. According to Padila and Pulido-Bosch (1995); this lag time corresponds to fully developed karst systems with conduits of fast and slow flow.

The complexity degree of the karst units is demonstrated by the duration curves. The similarity of the duration curves per springs' group suggests a proportionality of units' function and a different evolution in the conduits development (Florea and Vacher 2006). Thus, there is transition, and perhaps transfer of water quantities from upstream to downstream. This transition occurs from simple individual units upstream, at the level of 280–350 m, to complex units receiving and transmitting water to the adjacent ones in the middle part at the level of 50–150 m, and finally to the units at the level of 0–10 m that only receive water from the upper part. The individual karst units can be considered as one, forming a larger karst system which is very important for the hydroeconomy of Western Epirus having a large storage capacity and

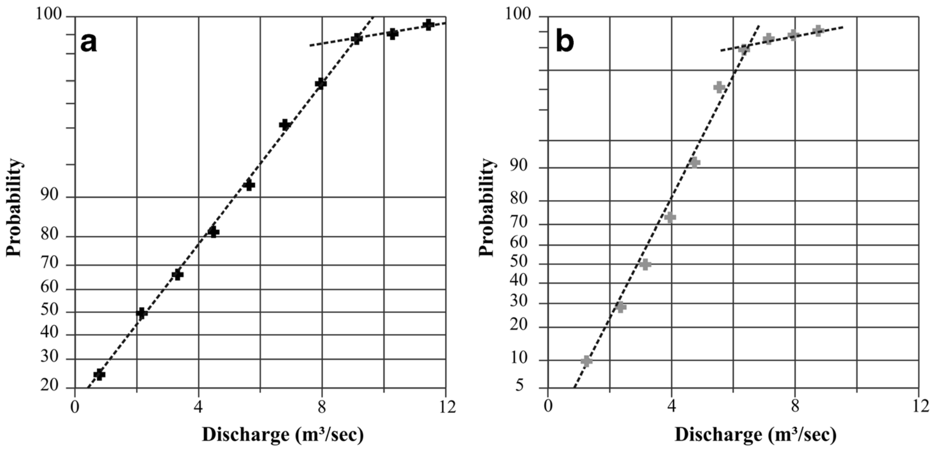

Fig. 7 Duration curves of **a**. Skala and **b**. Chanopoulo springs

allowing transfer of large amounts of groundwater. The results of the present research are in agreement with an extensive hydrogeological investigation that took place in the same area (Katsanou 2012) and highlight the efficiency of the proposed methodology. Although the application of the above methodology to a significant number of springs discharging different lithological karst units does not give details on the nature of these units, it provides quickly and easily a clear picture on the organization and the evolution of the karst.

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References

Alexakis D, Tsakiris G (2010) Drought impacts on karstic spring annual water potential. Application on Almyros (Crete) brackish spring. Desalin Water Treat 16:229–237

Amraoui F, Razack M, Bouchaou L (2003) Turbidity dynamics in karstic systems. Example of Ribaa and Bittit springs in the Middle Atlas (Morocco). Hydrol Sci J 48(6):971–984

Amit H, Lyakhovsky V, Katz A, Starinsky A, Burg A (2002) Interpretation of spring recession curves. Ground Water 40(5):543–551

Angelini P, Dragoni W (1997) Problem of modeling limestone springs: the case of Bagnara (North Apennines, Italy). Ground Water 35(5):612–618

Bonacci O (1993) Karst springs hydrographs as indicators of karst aquifers. Hydrol Sci J 38(1–2):51–62

Box GEP, Jenkins GM, Reinsel GC (1994) Time series analysis: Forecasting and control, 3rd edn. Prentice Hall Inc, Englewood Cliffs

Bouchaou L, Mangin A, Chauve P (2002) Turbidity mechanism of water from a karstic spring: example of the Ain Asserdoune spring (Beni Mellal Atlas, Marocco). J Hydrol 265:34–42

Coutagne A (1968) Les variations de débit en période non influence par les précipitations. La Houille Blanche 3: 416–436 (in French)

Eisenlohr L, Kiraly L, Bouzelboudjen M, Rossier Y (1997) Numerical simulation as a tool for checking the interpretation of karst spring hydrographs. J Hydrol 193:306–315

Florea JL, Vacher LH (2006) Springflow hydrographs: eogenetic vs. telogenetic karst. Ground Water 44(3):352–361

Ford DC, Williams PW (2007) Karst hydrogeology and geomorphology. Wiley, Chichester

Franchini M, O'Connell PE (1996) An analysis of the dynamic component of the geomorphologic instantaneous unit hydrograph. J Hydrol 175:407–428

Galabov M (1972) Sur l'expression mathématique des hydrogrammes des sources et le prognostic du débit. Bull Bureau de Recherches Géol et Minières 2:51–57 (in French)

Groves C, Meiman J, Howard AD (1999) Bridging the gap between real and mathematically simulated karst aquifers. In: Palmer AN, Palmer MV, Sasowsky ID (eds) Karst modeling, 5th edn. Karst Waters Institute Special Publication, Charles Town, pp 197–202

Graf KE, Elbert T (1990) Dimensional analysis of the waking EEG. In: Basar E (ed) Chaos in brain function. Brain, Dynamics, pp 135–152

Hatziyannis G (2011) The geothermal energy of Epirus: fields and perspectives of exploitation. The geological research as a lever of development of Epirus, EGE Workshop, July, 2011, Ioannina (In Greek)

Johnson EA and Dils RE (1956) Outline for compiling precipitation, runoff, and ground water data from small watersheds. USDA Forest Service, Southeastern Forest Experiment Station, 68

Jothityangkoon C, Sivapalan M, Farmer DL (2001) Process controls of water balance variability in a large semi-arid catchment: downward approach to hydrological model development. J Hydrol 254(1–4):174–198

Karakitsios V, Pomoni-Papaioannou F (1998) Sedimentological study of the triassic solution-collapse breccias of the ionian zone (NW Greece). Carbonate Evaporite 13(2):207–218

Katsanou K, Maramathas A, Lambrakis N (2014) Simulation of karst springs discharge in case of incomplete time series. Water Resour Manag. doi:10.1007/s11269-014-0898-2

Katsanou K (2012) Environmental hydrogeological study of louros watershed, Epirus, Greece. PhD Dissertation, University of Patras (in Greek)

Katsanou K, Maramathas A, Lambrakis N (2011) The use of hydrographs in the study of the water regime of the Louros watershed karst formations. In: Lambrakis N, Stournaras G, Katsanou K (ed) Advances in the research of aquatic environment. Environmental Earth Sciences, 1, pp 493–502

Katsikatsos G (1992) The geology of Greece. University of Patras, Patras (in Greek)

Kovacic G (2010) Hydrogeological study of the malenscica karst spring (SW Slovenia) by means of a time series analysis. Acta Carsol 39(2):201–215

Labat D, Ababou R, Mangin A (2000) Rainfall-runoff relations for karstic springs. Part II: continuous wavelet and discrete orthogonal multiresolution analyses. J Hydrol 238(3–4):149–178

Lambrakis N, Andreou AS, Polydoropoulos P, Georgopoulos E, Bountis T (2000) Nonlinear analysis and forecasting of a brackish karstic spring. Water Resour Res 36(4):875–884

Larocque M, Mangin A, Razack M, Banton O (1998) Contribution of correlation and spectral analyses to the regional study of a large karst aquifer (Charente, France). J Hydrol 295:217–231

Leontiadis I, Smyrniotis Ch (1986) Isotope hydrology study of the Louros River plain area. In: Morris A and Paraskevopoulou P (ed) Proceedings of 5th International Symposium on Underground Water Tracing. Institute of Geology and Mineral Exploration, Athens, pp 75–90

Machkova M, Pulido-Bosch A, Dimitrov D (1994) Study of discharge variability of some mountain karst springs in Bulgaria by time series analysis. In: Molnár L', Miklánek P, Mészároš I (ed) Development in Hydrology of Mountainous Areas, Stará Lesná, pp 141–144

Mangin A (1970) Contribution a l'etuded'aquiferes karstiques a partir de Panalyse de courbes de decrues et de tarissement. Ann Speleol 25:581–609

Mangin A (1971) Etude des débits classes d'exutoires karstiques portent sur un cycle hydrologique. Ann Speleol 28:21–40

Mangin A (1975) Contribution a l'étude hydrodynamique des aquifères karstiques. PhD Dissertation, Université de Dijon (in French)

Mangin A (1981) Utilisation des analyses correlatoire et spectrale dans l'approche des systemes hydrologiques. Comptes Rendus d'Acad Sci 293:401–404

Mangin A and Pulido-Bosch A (1983) Aplicacion de los analisis de correlatorie spectral en el estudio de los acuiferos karsticos. Tecniterrae 51–53

Mangin A (1984) Pour une meilleure connaissance des systemes hydrologiques a partir des analyses correlatoires et spectrales. J Hydrol 67:25–43

Mimikou M and Baltas E (2012) Engineering hydrology, 5th Edition. Papasotiriou (in Greek)

Nathan RJ, Mcmahon TA (1990) Evaluation of automated techniques for baseflow and recession analysis. Water Resour Res 26(7):1465–1473

Nikolaou E and Lagaris V (1990) Technical report on the results of the drilling research (May 1987-November 1988) Epirus, Greece. IGME, Preveza, Greece (in Greek)

Nikolaou E, Pavlidou S, Katsanou K (2011) Aquifer systems of Epirus, Greece: An overview. In: Lambrakis N, Stournaras G, Katsanou K (ed) Advances in the Research of Aquatic Environment. Environmental Earth Sciences, 1, pp 425–434

Ozis U, Alkan A, Tatlioglu UE (1993) Effect of karst springs on flow duration curves of rivers. In: Gunay G, Johnson AI, BackW (ed) Hydrogeological processes in karst terranes. IAHS Publications 207, pp 209–222

Padilla A, Pulido-Bosch A, Mangin A (1994) Relative importance of baseflow and quickflow from hydrographs of karst spring. Ground Water 32(4):267–277

Padilla A, Pulido-Bosch PA (1995) Study of hydrographs of karstic aquifers by means of correlation and cross-spectral analysis. J Hydrol 168:73–89

Panagopoulos G, Lambrakis N (2006) The contribution of time series analysis to the study of the hydrodynamic characteristics of the karst systems: application on two typical karst aquifers of Greece (Trifilia, Almyros Crete). J Hydrol 329:368–376

Petras I (1986) An approach to the mathematical expression of recession curves. Water SA 12(3):145–150

Posavec K, Bacani A, Nakić Z (2006) A visual basic spreadsheet macro for recession curve analysis. Ground Water 44(5):764–767

Pulido-Bosch A, Padilla A, Dimitrov D, Machkova M (1995) The discharge variability of some karst springs in Bulgaria studied by time series analysis. Hydrol Sci J 40(4):517–532

Riggs HC (1964) The base-flow recession curve as an indicator of groundwater. Int Assoc Sci Hydrol Publ 63: 352–363

Schoeller H (1965) Hydrodynamique dans le karst (écoulement d'emmagasinement). Hydrogéol Roches Fissurées IAHS Coll Hydrol Roches Fissurées 1:3–20

Searcy JK (1959) Flow-duration curves, Manual of hydrology-Part 2. Low-flow techniques: U.S. Geological Survey Water-Supply Paper 1542-A, 33 pp

Skourtsis-Coroneou V, Solakius N (1999) Calpionellid zonation at the jurassic/cretaceous boundary within the vigla limestone formation (Ionian Zone, western Greece) and carbon isotope analysis. Cretaceous Res 20: 583–595
Smyrniotis C (1991) Preliminary report of Louros karst system hydrogeological study. Technical report. Institute of Geological and Mineral Research, Athens (in Greek)
Soulios G (2008) General hydrogeology, 2nd edn. University Studio Press, Greek)
Soulios G (1991) Contribution a l'etude des courbes de récession des sources karstiques: exemples du pays helléniques. J Hydrol 124:29–42
Soulios G (1985) Recherches sur l'unite des systèmes aquifers karstiques d' âpres des exemples du karst hellénique. J Hydrol 81:333–354
Toebes C, Morrissey WB, Shorter R and Hendy M (1969) Base-flow-recession curves. In: Handbook of hydrological procedures, Proc 8, Ministry of Works, Wellington, New Zealand. http://docs.niwa.co.nz/library/public/HHPP8.pdf
Tsakiris G and Alexakis D (2013) Karstic spring water quality: the effect of groundwater abstraction from the recharge area. Desalin Water Treat 1–8
White WB (2003) Conceptual models for karstic aquifers. Speleolog Evol Karst Aquifers 1(1):1–8
Vriniotis D, Papadopoulou K (2004) The role of Louros and Arachtos rivers in the development of sediments of the Arta's plain with the contribution of geochemical parameters. Bull Geol Soc Greece XXXVI:150–157, in Greek)
Yu YPT, Liu CA (2002) Regional model of low flow for Southern Taiwan. Hydrol Process 16(10):2017–2034