EFFECT OF MONITORING TIME INTERVAL ON THE RESULTS OF STOCHASTIC ANALYSIS OF KARST WATER RESOURCES[*]

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Abstract – Data monitoring is important in the study and analysis of hydrological behaviors of karstic systems. Monitoring shows the various regimes of groundwater flow (laminar or turbulent), depletion, filling, filtration and karstification degree of karst aquifers. In recent years, analyses of these data had considerable advances using stochastic time series analyses. An important problem related to these analyses is the constraint of financial and technical human support. If we can increase the time intervals, the costs are lowered and development of new monitoring networks will be possible. In this research, the effect of monitoring time intervals on the results of time series analysis and calculated hydrologic delay times are studied, using bivariate analyses in spectral domain. The first (shorter) and the second (longer) delay times are related to the flow of groundwater through the larger and smaller fractures of the karstic system, respectively. Daily groundwater level data of three piezometers and the discharge of a spring in the Maharlu karst basin in Iran ($52°12'$ to $53°28'E$ and $29°1'$ to $30°6'N$) were acquired and then six different time series having different time intervals (1, 3, 7, 10, 14 and 30 days) were extracted and analyzed. The results show that the variation of the computed stochastic parameters with increasing time intervals is unpredictable, but the variation of time (period) corresponding to the frequency at the peak of amplitude function (curve) shows a linear and predictable relationship, which is unique for every kind of karstic aquifer having different degrees of karstification.

Keywords – Karst, time series, squared coherency, phase, amplitude, delay time

1. INTRODUCTION

Karstic aquifers have their own unique hydrodynamic characteristics, which differ from porous media, i.e. porosity, isotropy, homogeneity, groundwater flow regime and etc. [1-3]. Therefore, they behave hydrologically different in comparison with alluvium aquifers and need special planning and management. On the other hand, the flow in a karst system is more of a dynamic process, therefore, in a study of such a system, the stochastic approach is more useful [4]. Due to the existence of caverns and underground conduits, the amount and intensity of rainfall are effective parameters on the response of the groundwater level or the discharge of karstic springs, and also the delay times of these responses with respect to the starting time of the rainfall. On the other hand, the behavior of karstic systems depends on various factors such as geological conditions and the type and degree of their karstification, which in turn affect their flow characteristics and water level fluctuations.

Continuous measurements and monitoring of karst water resources is very important for better evaluation and study of the behavior of the karst systems. In this regard, the main task is to decide for

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the optimum time interval of their monitoring from the economic point of view and also to understand the effect(s) of the change from a short time interval (i.e. daily) to a longer time interval (i.e. monthly) on their data analysis. If these effects are enormous, then how long should the monitoring time interval be for karstic aquifers having different extent of karstification, so that the result of the analysis remains acceptable. According to Milanovic [4], measuring the groundwater level and discharge is important in the karst water investigations and suggests that, where the water level has rapid fluctuations, the monitoring time intervals should be short, and continuous measurement is the best treatment. In his opinion, intervals longer than a day in wet seasons cause errors in the analysis of the data and misinterpretation occurs. However, this time interval may increase to 2 days or longer in dry seasons. ASTM [5] addresses some valuable issues in karst and hard rock water resource monitoring, but has not given solid advise on optimum monitoring time intervals and their criteria. Bonacci [6], Larocque et al [7], Mangin [8, 9], and Zhang et al [10] have further studies on stochastic analysis in karst systems.

In this research, stochastic analysis is applied to water level hydrographs of 3 piezometers and the discharge hydrograph of a karstic spring in the Maharlu basin, Fars province, Iran. In the first step, the main objective is to find the effects of different monitoring time intervals of these hydrographs on the results of stochastic analysis, and in the next step, possibly suggesting a procedure to choose the monitoring time interval for different karstic aquifers with different karstification extents.

2. GEOLOGY AND HYDROGEOLOGY OF THE STUDY AREA

Maharlu basin, in the south of Iran ($52°12'$ to $53°28'E$ and $29°1'$ to $30°6'N$), has a surface area of 4200 km^2 with a semi-arid climate, annual rainfall of 326 mm [in Shiraz Airport Station with an elevation of 1491 meters (a.m.s.l) in the center of the area], mean annual temperature of 17.3 $°C$ and 43 average rainy days.

Geologically, this basin lies in the simply folded zone of the Zagros Range with several connected anticlines and synclines. Its most important karstic units are carbonatic Asmari-Jahroum formation (Fig. 1). Due to suitable lithology, climate and tectonic conditions, karstic features and solutional channels are developed, and several karstic aquifers in the basin created. The Karstic area covers 37 percent of the basin, which provides more than 50 percent of the potable water for the city of Shiraz, having a population of about 1.5 million [11].

In this study, three piezometers located in three different karstic aquifers (i.e. Qara, Kaftarak and Sabzpooshan) and a spring located in the Qasreqhomsheh karstic aquifer (Fig. 1) was instrumented with a water level recorder for a period of time. The water level of the piezometers and the discharge of the spring were recorded continuously on separate charts. Table 1 shows the general information of the anticlines (karst zones) selected for this study. The Sabzpooshan aquifer has the maximum, and approximately uniform porosity (about 45%) with few underground solution conduits, while the Kaftarak aquifer has an overall porosity of 26% and has large underground solution channels, most probably in its recharge passages. The porosity of the Qara aquifer is evaluated to be 24%, while the Qasreqhomsheh aquifer has not been recorded. The recovered drilling cores from Babahadji piezometer (Qara) were relatively consolidated and uniform, which were completely different from those of Pirbanu and Kaftarak pizometers (in Sabzpooshan and Kaftarak anticlines). There are not many mature karst features such as sinkholes in the whole area (i.e. Maharlu basin).

Average transmissivities on the basis of pumping tests vary as low as 2150 m²/day for Qara to 11516 m²/day for Sabzpooshan, and are measured to be 5603 and 6079 m²/day for Kaftarak and Qasreqhomsheh anticlines, respectively. The measure of pumping rate per unit of draw down of the water level in the discharge well in a steady state condition is a suitable measure to evaluate the karstification extent and hydraulic connection between the well and its surroundings in a karstic aquifer. These values are as high as 151.5 l/s/m for Sabzpooshan to 0.89 l/s/m for Qara aquifers and are evaluated to be 12.70 and 5.90 l/s/m for Kaftarak and Qasreqhomsheh aquifers, respectively. Table 1 shows information and different parameters of the karstic aquifers and piezometers studied. Based on the field information collected and post calculations and evaluations done, the karstic zones and the vicinity of the piezometers chosen for this study are qualitatively divided into "high" extent of karstification (Sabzpooshan and Kaftarak), "medium" karstification (Qasreqhomsheh), and "low" extent of karstification (Qara,) which correspond to the classification of Rahnemaei [12], for the Maharlu basin carbonatic aquifers.

3. METHODOLOGY

Daily water level and discharge recorded on water level recorder charts are used to extract time series of one day, 3 days, weekly, 10 days, bi-weekly and monthly interval data. The daily rainfall data at the Shiraz airport station in the East and Ghalat station in the West of the area (Fig. 1) for the same period is then employed and the sum of the rainfall computed for the time intervals mentioned above. In this manner we have five time series of water levels (3), discharge (1) and rainfall (1) for the analysis.

The trend and the seasonal components of the series were removed and then transformed to stationary series by a differencing method [12-15]. Thereafter, cross-amplitude, phase and squared coherency were calculated and plotted using methods presented in [13, 15-16]. The methods and calculations are given extensively in [12].

4. RESULTS AND DISCUSSIONS

The results of cross-amplitude, phase and squared coherency functions are shown by the graphs in Fig. 2 for daily time series (these graphs are prepared for other time intervals, but not presented). The results show that frequency at the maximum peak point of the squared coherency functions differ for different monitoring time intervals of water level or discharge [Fig. 3 (c) and (b)], also their variations are not similar for different karst aquifers. This is the same for the phase value at these frequencies too [Fig. 3 (c) and (d)]. It seems that the variation of these two parameters tends to be more complex with the increasing degree of karstification and are practically unpredictable. As a result, we can conclude that the relationships of rainfall / water level and rainfall / discharge have more variations with the advancement of karstification, especially when the heterogeneity increases in the depth of the aquifer and in the surrounding of the piezometers.

The inverse of the frequency value at the peak point of the cross-amplitude function represent the time or the period at which the correlation between input and output is at its maximum [16]. Table 2 shows these periods for different monitoring time intervals series and the mentioned karst systems, which are plotted in Fig. 4. According to this Figure, the period of maximum correlation linearly increases with the monitoring time interval. In other words, this relation is linear for all kinds of karst aquifers, where only the slope of the best-fitted line differs for various karst aquifers. The slope of the line for the Kaftarak piezometer is about 1.25 times its value for Babahadji [ratio of slope of equation

of Fig. 4b to the one of Fig. 4a], i.e. the time representing the maximum correlation between input and output is higher in the Kaftarak piezometer in comparison to Babahadji. Extending this argument to Pirbanu and Qasreqhomsheh, the ratio of these slopes is about 1.45, which brings up to the conclusion that the sensitivity of stochastical analysis increases as the karstification degree intensifies. Therefore, we should not select very long monitoring times in the case of "well-developed karstification". It is necessary to note that, sometimes due to absence of peak points at cross amplitude functions, we cannot evaluate the time representing the maximum correlation between input and output.

Table 2. Frequency and period in days corresponding to the peak point of the cross-amplitude
function in the studied karst water resources and various monitoring time intervals

Monitoring time interval	Babahadji		Kaftarak		Pirbanu		Qasreqhomsheh Spring	
	Frequency	Period	Frequency	Period	Frequency	Period	Frequency	Period
Daily	0.41	2.4	0.38	2.6	0.38	2.6	0.33	3.0
3 Days	0.50	6.0	0.50	6.0	0.50	6.0	0.50	6.0
Weekly	0.44	15.9	0.42	16.6	0.46	15.2	0.50	14.0
10 Days	*	*	*	*	0.42	23.8	0.34	29.4
Bi-weekly	0.42	33.4	0.42	33.3	0.36	38.8	0.50	28
Monthly	0.50	60.0	0.39	76.9	0.28	107.1	0.38	78.9

*Unaccepted or undefined values

The Ratio of the value of the phase function to the frequency of the peak value of the squared coherency function determines the lag times. On the basis of the dual porosity condition in karstic aquifers and the dual recharge system idea in the karst aquifers [17], at least two-peak points at squared coherency functions are depicted, from which the two lag times (t_1, t_2) can be evaluated. For example, for a Kafatark piezometer, there is a maximum squared coherency (equal to 0.19697) at a frequency of 0.16206 day^{-1} (Fig. 2e). So the phase value at this frequency is equal to 0.91898 (Fig. 2f), and one can evaluate the first lag time t_1, equal to 0.9 days (i.e. $\dfrac{0.91898}{2\pi \times 0.16206}$ according to Wei [16]).
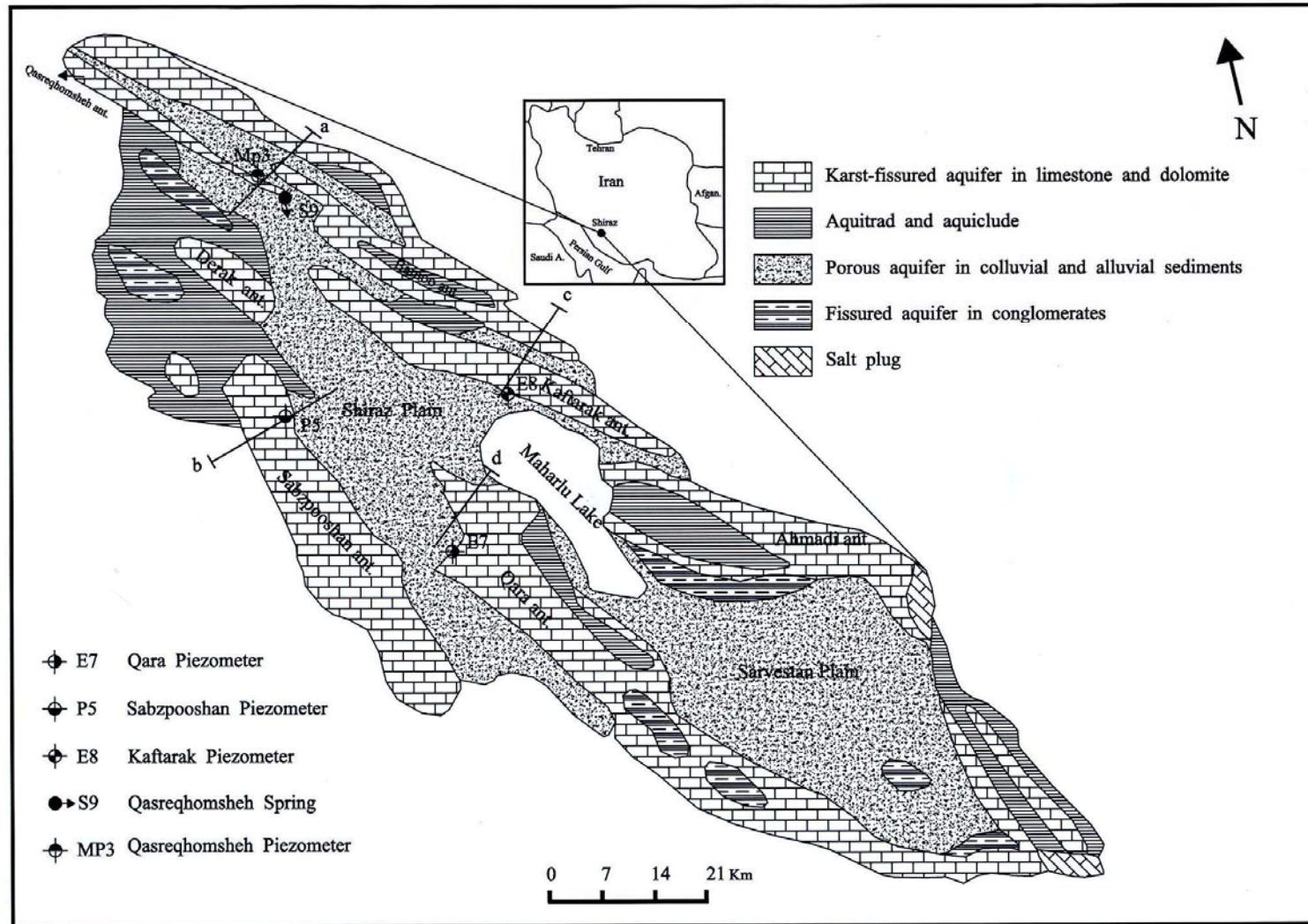
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Fig. 1. Hydrogeological map of Maharlu basin in Fars Province, location of the studied piezometers and karst spring

Table 1. General characteristics and data of the studied karst water resources in the Maharlu basin

Karstic zone	Source of data	Elevation (a.m.s.l) (m)	Minimum water level (a.m.s.l) (m)	Maximum water level (a.m.s.l) (m)	Average depth of water level (m)	Depth of drilling (m)	T^a	q^b	P^c	Period of available data	Karstification Degree[d]
Qara	Babahadji Piezometer	1491.2	1481.1	1486.2	1483.1	156.5	2150	0.018	24	Jan 92 to Jun 95 (28 months)	Weak with marl interbed
Sabzpoo-shan	Pirbanu Piezometer	1515.0	1503.8	1504.4	1504.1	45.0	11516	0.360	45	Apr 93 to Oct 95 (29 months)	Well developed, High porosity
Kaftarak	Kaftarak Piezometer	1509.2	1479.6	1482.4	1481.1	178.0	5603	0.002	26	Mar 93 to Sep 94 (18 months)	Well developed, with collapsed caverns & conduits
Qasreqhom-sheh	Qasre-qhomsheh spring	1717.3[e]	489.4[f]	697.3[f]	634.9[f]	217.0[e]	6079	0.026	---	Mar 93 to Sep 94 (18 months)	Medium

[a]Transmissivity (m^2/day)

[f]Units in l/s .In this karst spring, the ratio of Max./Min. discharge is equal to 1.42

[c] Porosity (%)

[e]In a piezometer 50 m North-east of the spring (elevation=1750.96 a.m.s.l)

[d]Based on field studies and drilling data presented in the report of Maharlu karst basin [11]

[b] Specific discharge: discharge per unit drawdown (l/*s/m*)
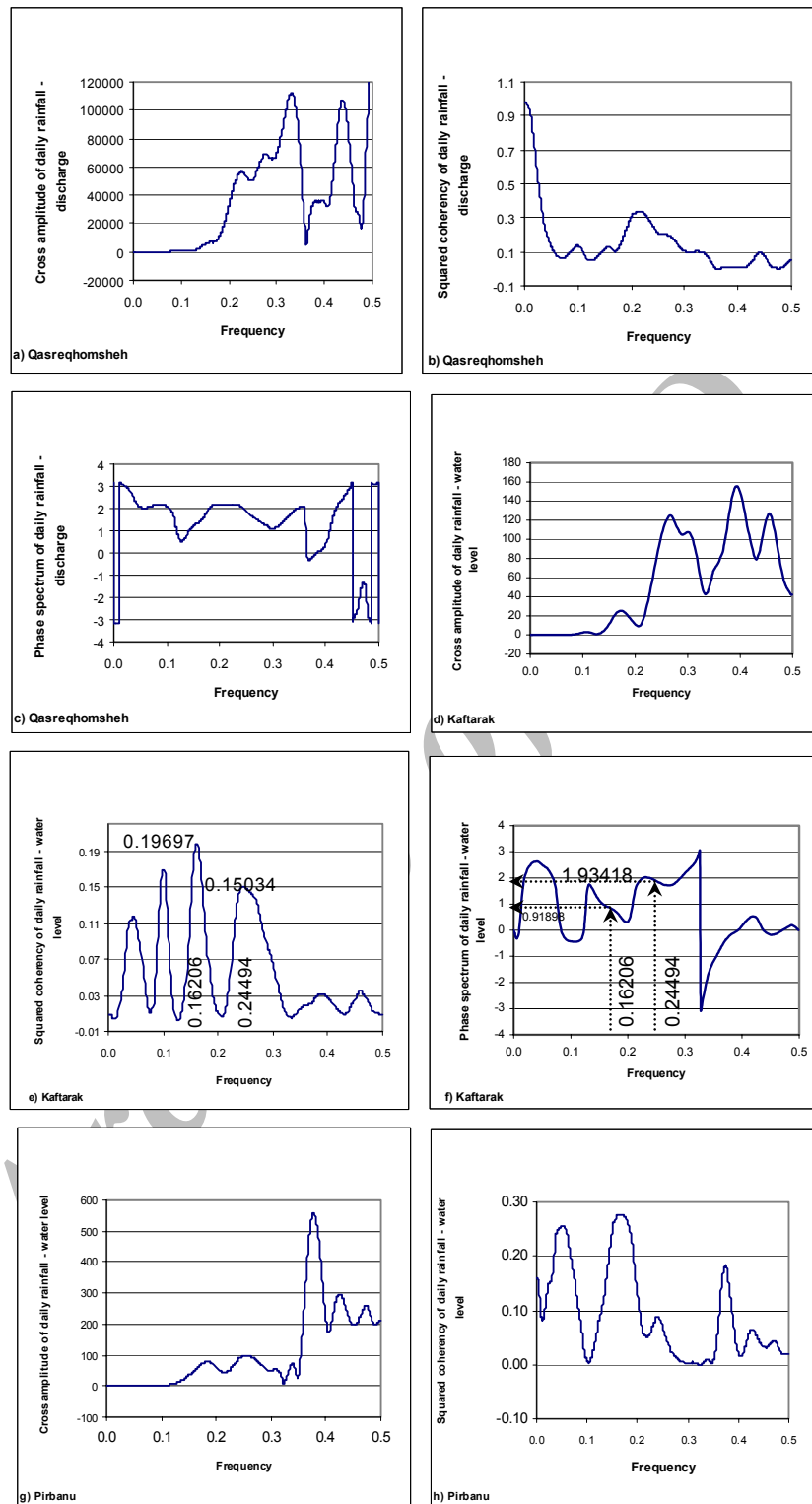
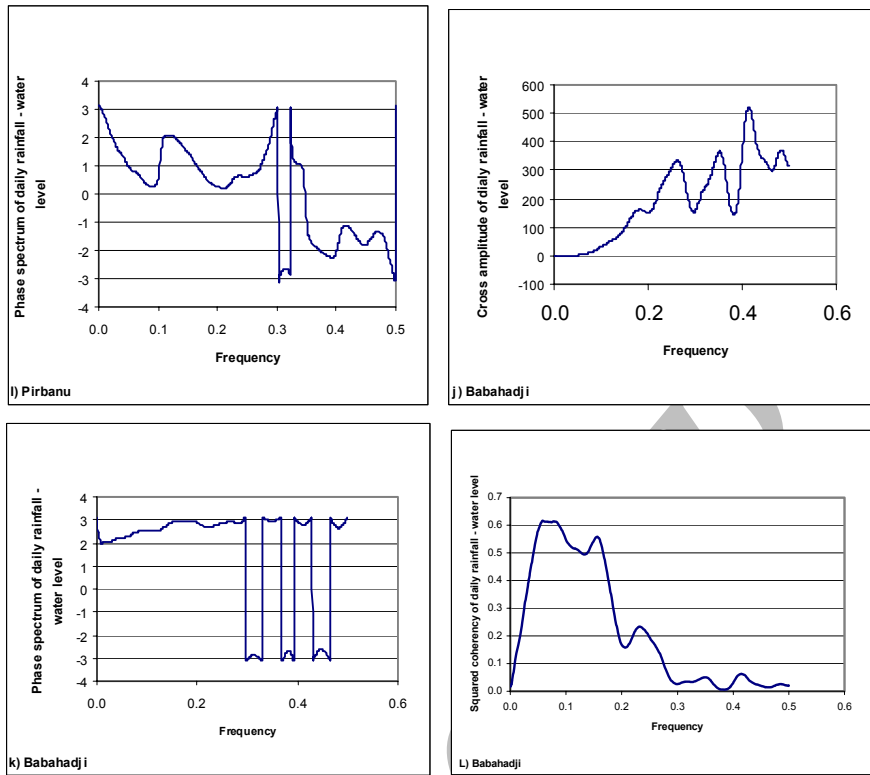Fig. 2. Phase, amplitude and squared coherency graphs for the studied time series
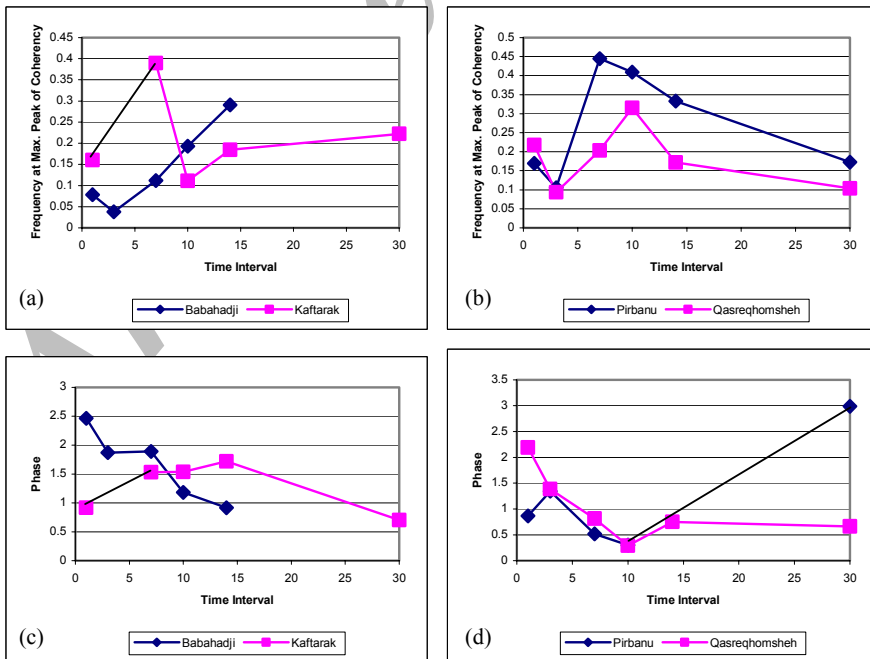
Fig. 2. (Continued)

Fig. 3. Diagrams of phase and frequency variations at the squared coherency
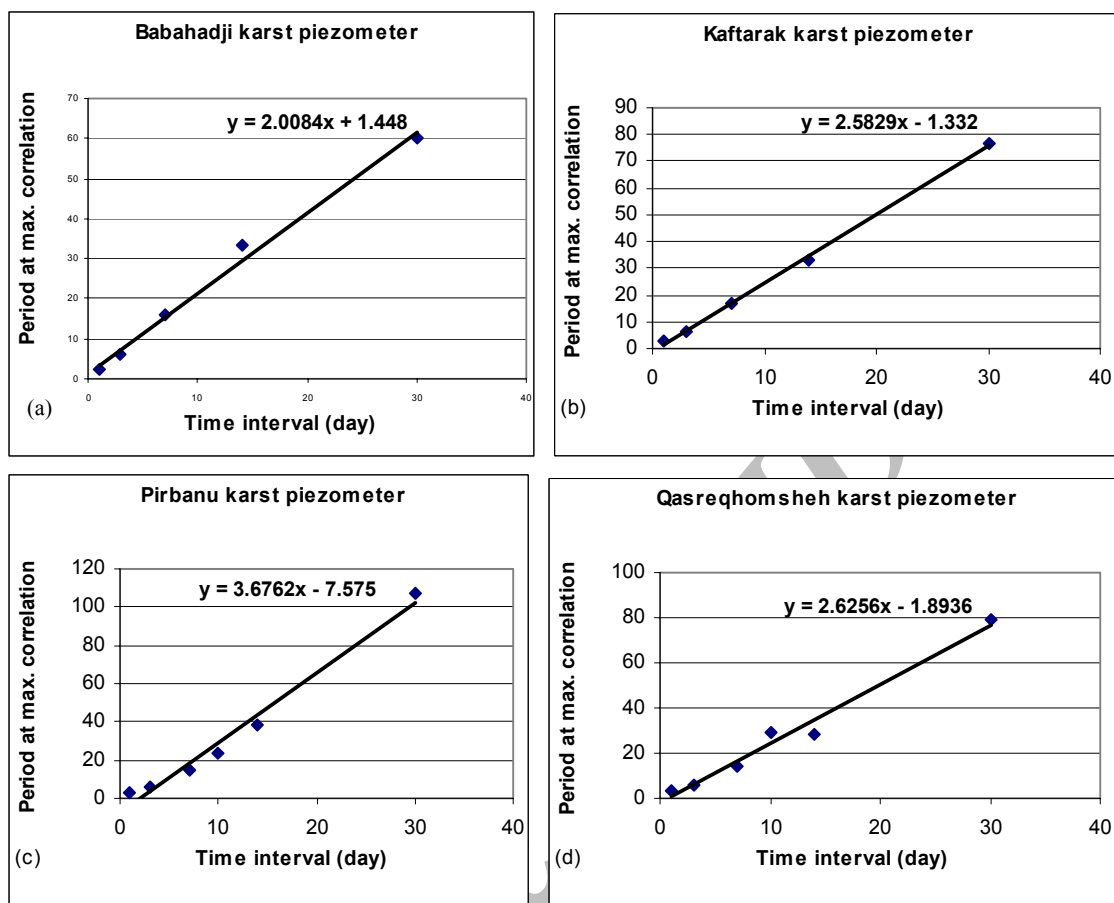peaks with monitoring time intervals in the studied karst aquifers

Fig. 4. Variation of periods of maximum correlation between rainfall and water level/discharge (using frequency of peak point of cross amplitude functions) with monitoring time intervals in the studied karst aquifers

The second lag time, t_2, is equal to 1.25 days, which is also calculated from the second peak at the squared coherency graph. It is common to interpret the first and second lag times relating to the flow of water in larger and smaller fractures respectively. However, it should be mentioned that the cross correlation approach is more correct and more complete than that of the comparison of the lag times. This is because the response of the system is driven by what occurs in the saturated as well as infiltration zones. In the infiltration zone, slow and fast infiltrations are generally related to two–phase and one-phase flows respectively, partly depending on the development of the epikarst near the ground surface. In the saturated zone, the flow occurs at the same time in the conduits, fissures and cracks, all being hydraulically connected.

Table 3 shows the evaluated first and second lag times for different monitoring time intervals as well as the studied karst aquifers. As this Table shows, except for daily time interval, some of the computed values for t_2, are not valid physically or can not be calculated, because the squared coherency graphs do not show any identified second peak point. Therefore, the second lag times could not be evaluated correctly; perhaps as it is mentioned above, this is due to the dominant effect of main fractures in the flow of water, and as a result, the increase in internal correlation. It seems that, in some regions in which matrix and finer fractures are more effective in passing the water

(flow), the second lag time can be evaluated more correctly and more reasonably. It is necessary to say that in all cases, lag times evaluated from daily data are closer to the real values.

Table 3. The first and second lag times evaluated from squared coherency
functions at various time intervals in the studied karst water resources

Time Interval	Lag times for the studied karst aquifers (in days)							
	Babahadji		Kaftarak		Pirbanu		Qasreqhomsheh Spring	
	t_1	t_2	t_1	t_2	t_1	t_2	t_1	t_2
Daily	5.0	6.18	0.9	1.3	0.8	2.7	1.6	3.2
3 Days	23.8	*	*	33.7	6.1	*	7.1	*
Weekly	18.8	*	4.4	38.3	1.3	6.0	4.5	*
10 Days	9.8	*	21.9	*	1.2	17.9	1.5	*
Bi-weekly	7.0	*	20.8	*	*	*	9.7	15.2
Monthly	*	*	15.1	*	82.7	*	30.6	46.3

*Unaccepted or undefined values (due to no peak in squared coherency graphs or negative phase)

The plot of the first lag time for various monitoring time intervals is given in Fig. 5. As it is shown, for the Babahadji piezometer (Qara), the first lag time increases from 5 days to 23.8 days for a 3 day interval, but after that, with the selection of weekly and bi-weekly data, it decreases to 7 days and gets close to the lag time of daily data. This is probably due to the lower physical development of karst in the system, and also the short time of the monitoring period (about 2.5 years). The first lag time can not be evaluated from the monthly interval data, since the number of observations of one every 30 days during an 18 to 30 month period gives a too short time series. Therefore, it is suggested that for evaluation of the lag time, the total monitoring time be more than 3 years, and from an economical point of view, 4 years of data could be enough. On the basis of the evaluated first lag time, in weak developed karsts like Babahadji, bi-weekly interval measurements can be considered as an optimum interval.
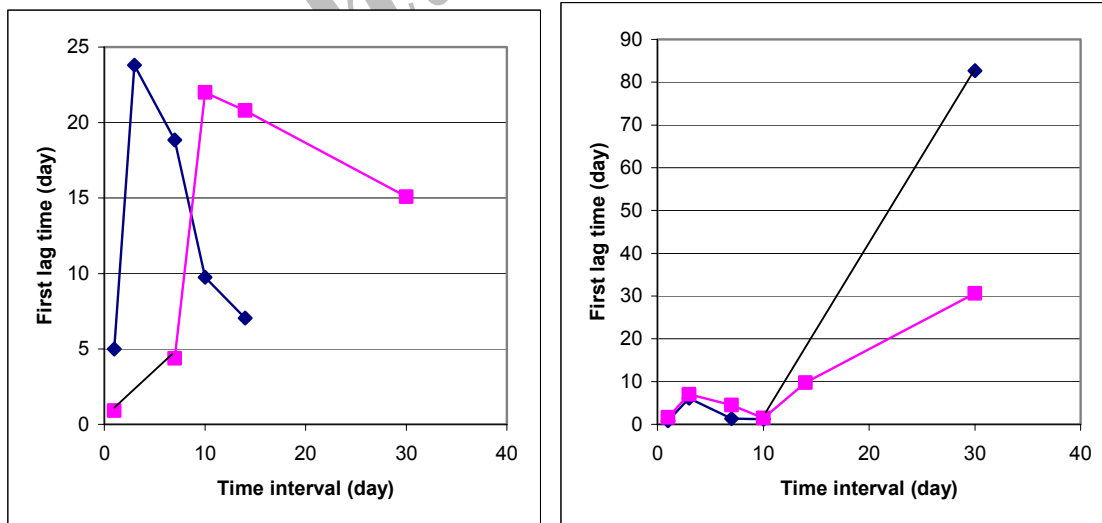

Fig. 5. Variation of the evaluated first lag time from squared coherency
graphs with monitoring time intervals in the studied karst aquifers

Figure 5 also shows variation of the first lag time for the Kaftarak piezometer. The first lag time increases with the monitoring time interval and then decreases. Compared with daily interval data, all other intervals show a longer first lag time, which diverts from the physical reality of the "well-developed karst". Therefore, daily monitoring is recommended for this type of karst and the minimum duration of data is suggested to be 3 years.

Considering the lag times calculated for the Pirbanu piezometer also with a well developed karstification condition, Fig. 5 shows that the first lag time is low for daily interval data and increases to about 6 days for 3 day interval data, and then decreases to about the value of daily interval for weekly and 10 day intervals data. This value for monthly interval data is very high, and physically not correct. From an economic point of view, a weekly monitoring interval can be recommended for a well-developed karst like the Pirbanu (Sabzpooshan) condition.

In the case of the Qasreqhomsheh spring with a "medium" extent of the karstification condition, the first lag time is 1.6 days, increasing to about 7 days for the 3 day interval data, and then decreasing to about the daily interval data for 10 day interval data and then increasing again for bi-weekly and 30 day intervals (Fig. 5). Based on these observations, a 10 day interval is also recommended for conditions like Qasreqhomsheh with "medium" karstification. Table 4 summarizes the recommendations for monitoring time intervals (L_d) in days, and the total period of data (L_t) needed in years for the stochastic analysis of the data in karst aquifers having different degrees and extents of karstification.

5. CONCLUSIONS

In all karstic aquifers, the phase and its corresponding frequency in squared coherency functions differ unpredictably with the variation of monitoring time intervals which do not follow a unique rule.

Regardless of the extent of karstification, periods evaluated for describing the maximum correlation between input and output, linearly corresponds with monitoring time intervals. But only the slope of this line differs for various karstification degrees, i.e. the slope increases as the karstification develops, which shows that the evaluation of this time in amplitude functions have high sensitivity in "well developed karsts".

With the advancement of karstification, variation of the first lag time (t_1) becomes more complex, which emphasis the importance of an appropriate decision of monitoring time intervals. This monitoring time interval is more important in the analysis of "medium to well-developed" karstifications.

Regarding the decrease in the number of peak points at squared coherency graphs in relation to increasing the monitoring time interval, the possibility of evaluation of the first and second lag times also decreases. This shows that the dual porosity phenomena in karst systems cannot be studied with only monthly data (Table 3). Therefore, monitoring of well extended karstified aquifers is recommended to be maximum from one day to one week (depending on the extention of the karst), for medium karstification (10 days), and for weak karstification (2 weeks). Squared coherency graphs of monthly water levels in Kaftarak and Pirbanu piezometers have only one peak and do not show any peaks in the Babahadji piezometer. It seems that with the increase of total monitoring period to more than 3 years at these piezometers, it is possible that squared coherency graphs of monthly data will show more peaks. It may be concluded that for producing at least two peak points in squared coherency graphs of monthly data, a period of more than 3 years data in "weak karst" and more than 2 years in "medium" to "well-developed karst" is needed.

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Table 4. Number of peak points (n) in squared coherency graphs, the first evaluated lag time (in days), recommended minimum monitoring period in years (L_t) and optimum monitoring time interval in days (L_d)

Type of the karst (example)	No. of peak points in squared coherency graphs and period of first lag time (t_1) in days												L	L
	Daily		3 days		Weekly		10 days		Bi-weekly		Monthly			
	t_1	n	t_1	n	t_1	n	t_1	n	t_1	n	t_1	n		
Low extent of karstification (Babahadji)	5.0	4	23.8	2	18.8	2	9.8	2	7.0	2	---	-	14	4
Well extent of karstification (Kaftarak)	0.9	4	--	3	4.9	2	21.9	2	20.8	2	15.1	1	<1	3
Well extent of karstification with collapsed caverns and conduits (Pirbanu)	0.8	3	6.1	3	1.3	2	1.2	2	--	2	82.7	1	7	3
Medium extent of karstification (Qasreqhomsheh)	1.6	4	7.1	3	4.5	1	1.5	1	9.7	2	30.6	2	10	3

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