Evaluation of karstic aquifers contribution to streams by the statistical analysis of recession curves

A Cem Koc

Pamukkale University, Civil Engineering Department, Kinikli Kampusu, 20017 Denizli, Turkey.

Karstic aquifers significantly contribute to streams in most of Turkey's river basins, so studies on karst water resources have great importance for Turkey. Karstic aquifer contributions are generally emerging at several locations near the river bed and are not readily measured by direct hydrometric methods. In this study, the extent of karstic aquifer contributions to a stream will be investigated by the statistical analysis of recession coefficients of recession curves. Six stream gauging stations on different streams in the western Mediterranean region of Turkey are selected. Recession periods of the streams are simulated by exponential and quadratic recession curve models. Recession coefficient series of the stream gauging stations are statistically investigated. The comparison of various statistical parameters shows that the recession coefficient series are fairly related to the karstic aquifer contributions. Especially, the measure of spread parameters, standard deviation and interquartile range of recession coefficient series are related to the extent of the karstic aquifer contributions to streams.

1. Introduction

Surface and subsurface karst terrains, which cover about one-third of Turkey, belong to the Mediterranean hole of the Alpine orogenic belt. Most of the carbonate rocks of the southern part of Turkey are highly karstified (Elhatip 1997). Karstic aquifers significantly contribute to streams in some of Turkey's river basins. Ten out of 26 Turkish surface hydrological basins contain karstic aquifers. Approximately 1/3 of the gross potential of these basins is raised from karstic aquifers with a contribution ratio from 6% to 60% of the total water potential of the basins (Baran *et al* 1995).

Most of the karstic aquifer contributions are emerging at several locations near the river bed and are not readily measured by direct hydrometric methods. Various indirect evaluations such as comparison of specific discharges of basins to those of upstream or neighbouring basins, description of karst spring flow through parameters of single or reversible linear bivariate regression between observed data of two stream gauging stations and water budget balance, have been applied to assess the karstic aquifer contributions to a stream.

The separation of components of a stream discharge gathering from various storages is extremely complex (Griffiths and Clausen 1997). Complexity of the karstification phenomena in the underlying carbonates in most karst regions makes it very difficult to determine the boundaries of underground catchment areas of large karst springs, aquifers and rivers (Elhatip 1997).

Natural climatic variations, anthropogenic influences and land use changes affect the recession coefficient of a recession curve from one year to another. Karstic aquifers are consisting highly permeable fractures, faults and karst channels in carbonate rocks (Kiraly 2003). This formation allows the storage of plenty of water in the karstic voids or transportation of water between the neighbouring basins. So the fluctuation effect of the surface events on the recession coefficient is reduced by karstic aquifer contributions. The variability of recession coefficients of a stream in a karstic area

Keywords. Recession curve; karstic aquifer; western Mediterranean Basin–Turkey; data analysis; hydrology; modelling.

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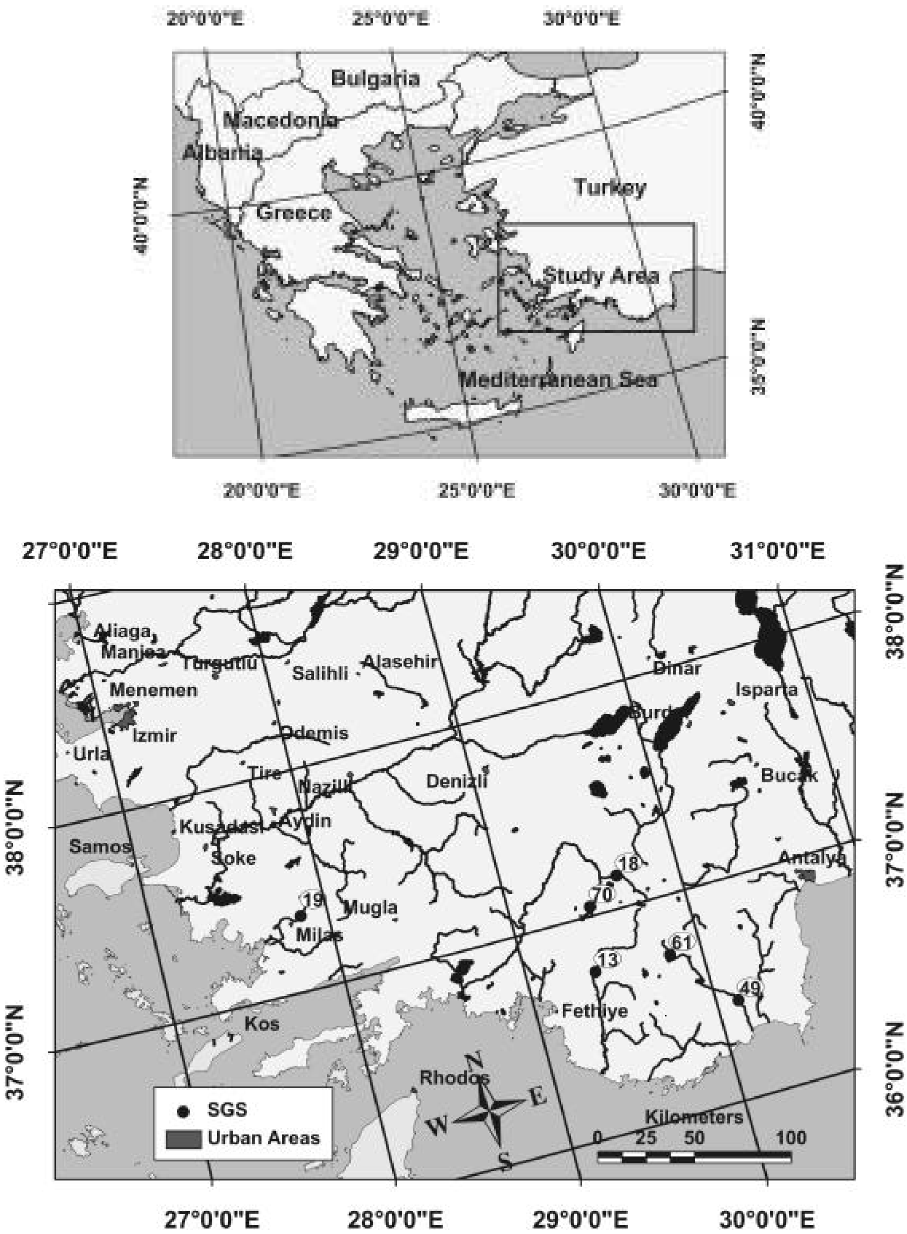

Figure 1. Locations of SGSs.

can give an idea about the volume of a karstic aquifer.

In the present study, the recession coefficients of recession curve series are analyzed statistically and the extent of karstic aquifer contributions are determined. The hypothesis of the more karstic aquifer contribution to a stream, the more regular or alike recession curve parameters one year to another, is investigated.

To show the validity of the hypothesis, recession hydrographs of six stream gauging stations in the western Mediterranean region of Turkey are investigated statistically. Recession hydrographs are modelled with two simple recession curve models and recession coefficients are obtained. Descriptive statistical parameters of the recession coefficients such as mean, standard deviation, coefficient of skewness are calculated and box plots of the recession coefficients are drawn and the probability plot correlation coefficients of recession coefficients are also calculated. The relationship between the statistical parameters and karstic aquifer contributions are discussed.

2. Description of the study area and data

This study was carried out in the western Mediterranean region in southwest Turkey (figure 1).

Table 1. *SGSs used in the study.*

SGS number	13	18	19	49	61	70
SGS name (Stream)	Orenkoy (Esen)	Ballik Pass (Ballik)	Kocakavak (Saricay)	Gokbuk (Basgoz)	Mumur (Mumur)	Yaprakli (Horzum)
Latitude (N)	36° 45′ 00″	37° 13′ 04″	37° 20′ 00″	36° 27′ 00″	36° 44′ 00″	37° 02′ 23″
Longitude (E)	29° 23′ 00″	29° 40′ 01″	27° 50′ 00″	30° 07′ 00″	29° 48′ 00″	29° 27′ 30″
Drainage area (km^2)	807.0	126.2	145.0	222.2	260.2	372.8
Altitude (m)	190	1091	66	208	1030	1018
Precipitation (mm/year)	615	475	775	554	522	577
Baseflow (mm/year)	492	175	74	142	0	347
Observation period (No. of considered years)	1961–1984 (23)	1967–2001 (33)	1968–1986 (18)	1965–1999 (31)	1970–2000 (27)	1973–1990 (17)

This basin is called as the Independent Western Mediterranean Waters. Karstic aquifer contributions are considerable; 33% of the total water potential comes from karstic aquifers in the basin (Baran *et al* 1995). The southern cost fringes enjoy the Mediterranean climate featuring hot, dry summers and mild, rainy winters. The study area gets less than one day snow in a year and the snow cover stays less than one day so the effect of the snow melt will be neglected in this study.

Six stream gauging stations (SGSs) of the Turkish State Hydraulic Works (DSI) are selected for the study. The locations of the SGSs are shown in figure 1. Names of the SGSs and the streams, coordinates, drainage areas, altitudes of the SGSs, mean annual total precipitations at the SGSs' locations and baseflows of the basins obtained from the previous studies are given in table 1.

Measurement period of each SGS and record lengths are also given in table 1, measurements of some years are not taken into consideration because of the improper data such as dam influence, insufficient recession curve, etc. Any year mentioned herein imply the hydrologic year which starts on 1 October of the previous calendar year and ends on 30 September. Daily mean discharge measurements are used in the study (DSI 1961 to 2001).

According to the daily stream measurements upstream of the SGSs 13, 18, 49 and 70 are of perennial character and upstream of the SGSs 19 and 61 are of intermittent character. Although the Horzum Creek (SGS 70) dried out for five days in September 1977, it is not an intermittent stream.

Previous studies showed that upstream of SGSs 13, 18, 19, 49 and 70 are contributed by karstic aquifers. A previous study (Baran *et al* 1995) exposed that mean karstic spring contributions are $12.6\,m^3/s$, $0.7\,m^3/s$, $1.0\,m^3/s$ and $4.1\,m^3/s$ for SGSs 13, 18, 49 and 70 respectively. That study was based on the comparison of specific discharges of basins with those upstream or neighbouring basins. Another previous study (Barut and Gürpınar 2005) based on water budget which was performed in Saricay Basin (SGS 19) showed that mean baseflow is $0.34\,m^3/s$. This stream is contributed by small volume karstic aquifers and baseflow becomes zero in some dry years. There is no karstic spring contribution reported by the previous studies conducted for the upstream of the SGS 61.

3. Recession curves

The recession studied here is not only baseflow recession, but the recession of total flow, so the 'recession curve' will denote the complete decreasing part of the hydrograph. Recession segments are selected from the daily mean discharge hydrographs as shown in figure 2. Figure 2 shows the hydrographs and the recession segments of the SGSs for the years 1979–1984. Recession period of the studied streams usually starts after the winter rains (end of March) and goes on until the start of the summer (end of May). In this study, a recession period started at a peak discharge value and lasted until stream flow began to increase or recession curve flattened. Start and finish days of recession periods of all SGSs are given in table 2.

3.1 *Modelling the recession period*

Stream recession flow of a single linear reservoir is commonly characterized by the exponential equation or in the alternative power form equation. However, in reality the groundwater dynamics of even the simplest aquifers may behave in a nonlinear fashion (Mishra *et al* 2004). Among the plenty of very successful linear, nonlinear and multi-linear storage–discharge relationship models (Chapman 1999, 2003; Wittenberg 1999, 2003), or probabilistic approach to modelling of recession curves (Aksoy *et al* 2001), two simple models are selected to represent the recession curves in this study.

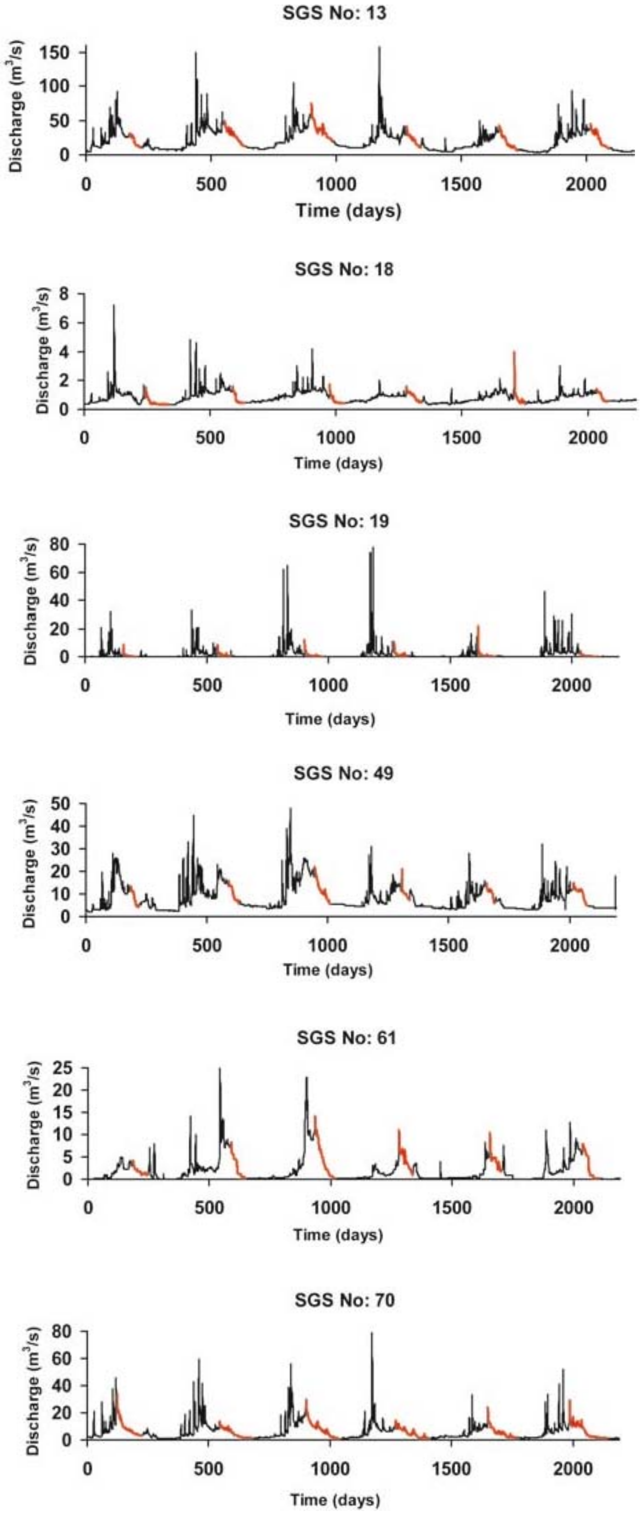

Figure 2. Daily mean discharges and selected recession periods (red lines) from 1979 to 1984.

The first model is the well-known Maillet formula given in

$$Q_t = Q_0 \exp(-\alpha_e t), \tag{1}$$

where Q_t is the discharge t days after the recession period started, Q_0 is the initial discharge, α_e is the recession coefficient of the exponential model and t is time. This approximate analytical solution is proposed by Boussinesq. Maillet approximated the aquifer recession curve using an analogue model of a water-filled single reservoir emptying through a porous plug (Dewandel *et al* 2003). This model will be called as the exponential model from now on.

The second model, a quadratic equation, based on the solution of the general differential equation of the non-artesian flow in one dimensional homogenous aquifer with horizontal bottom is given by

$$Q_t = \frac{Q_0}{(1+\alpha_q\, t)^2}, \tag{2}$$

where Q_t is the discharge t days after the recession period started, Q_0 is the initial discharge, α_q is the recession coefficient of the quadratic model and t is the time. This will be called as the quadratic model from now on (Werner and Sundquist 1951).

3.2 *Calibration of nonlinear recession curve models*

Nonlinear optimization is to minimize a function. Numerical methods for nonlinear optimization problems are iterative. Consider a system of nonlinear equations as shown in

$$\min_{x\in\Re^n} f_i(x), \tag{3}$$

where $f_i(x) = 0 \quad (i = 1, \ldots, m)$ are continuous differentiable functions in $\Re^n$. We try to compute a least square solution, which means we need to solve the nonlinear least squares problem of

$$\min_{x\in\Re^n} \|F(x)\|_2^2, \tag{4}$$

where $F(x) = (f_1(x), \ldots, f_m(x))^T$ and $\|\cdot\|_2$ is the Euclidian norm. The Gauss–Newton (GN) method for the problem which is shown in equation (4) is iterative and at the current iterate x_k, the GN step is given as

$$d_k = -(A(x_k)^T)^{-1} F(x_k), \tag{5}$$

where $A(x) = \nabla F(x)^T$ is the Jacobi matrix. It is easy to see that the GN step is the minimum norm solution of the subproblem as given in

$$\min_{d\in\Re^n} \|F(x_k) + A(x_k)^T d\|_2^2, \tag{6}$$

which is an approximation to the original problem given in equation (4) near the current iterate

Table 2. *Start and finish days of recession segments.*

	Stream gauging station no.											
	13		18		19		49		61		70	
Year	Start	Finish	Start	Finish	Start	Finish	Start	Finish	Start	Finish	Start	Finish
1961	195	253										
1962	170	254										
1963	182	267										
1964	154	214										
1965	199	253					181	212				
1966	188	254										
1967	234	292	233	304								
1968	203	274	203	253	165	230						
1969	202	254	225	305	201	257	168	213				
1970	196	254	201	287	172	260	172	212	195	261		
1971	191	265	228	271	182	271	144	166	211	298		
1972	160	240	194	273	159	236	159	188	254	277		
1973	167	235	208	283	150	226	149	174	201	253	151	243
1974	190	263	195	287	167	246	165	188	189	241	190	305
1975	187	249	232	293	162	195	144	189	186	265	144	300
1976	198	231	198	259	121	181	206	254	198	262	197	328
1977	205	261	205	255	153	258	205	248	204	238	204	312
1978												
1979	177	219	244	332	158	216	186	216	185	246	124	223
1980	190	265	225	271	179	234	225	268	225	282	180	314
1981	171	253	244	303	171	253	216	277	204	287	171	305
1982	185	241	184	244	174	227	211	243	185	243	175	314
1983	191	263	248	291	154	229	196	230	195	242	189	310
1984	191	264	210	251	210	281	191	245	214	281	162	316
1985			195	273	137	222	195	237	193	247	171	307
1986			189	275	146	230	147	190	185	248	147	306
1987			215	267			213	261	220	263	185	297
1988			215	246			199	235	213	261	198	304
1989			186	262			177	204	177	211	177	309
1990			189	256			151	177	166	186	152	270
1991			200	288			190	220				
1992			203	268			203	240	195	249		
1993							222	258	225	257		
1994			223	317			181	213	205	238		
1995			219	276			183	214				
1996			200	277			131	156	199	238		
1997			201	252			182	200				
1998			207	265			225	264	209	263		
1999			208	254			147	178	201	286		
2000			218	301					196	245		
2001			196	264								
Mean	188	253	210	276	165	236	183	218	201	254	172	298

x_k. One difficulty of using the GN step is that the Jacobi matrix $A(x_k)$ may be ill-conditioned, which normally leads to a very big step d_k causing the algorithm to break or fail in line searches. The Levenberg–Marquardt (LM) method chooses the step as shown in

$$d_k = -(A(x_k)A(x_k)^T + \lambda_k I)^{-1} A(x_k) F(x_k), \quad (7)$$

where $\lambda_k \geq 0$ is a parameter which is updated from iteration to iteration. The original idea at LM method is to introduce the parameter λ_k to overcome the ill-condition of $A(x_k)$ or to prevent $\|d_k\|_2$ being too large. Equation (7) is a solution of the subproblem given in

$$\min_{d \in \Re^n} \|F(x_k) + A(x_k)^T d\|_2^2 + \lambda_k \|d\|_2^2, \quad (8)$$

which is a modification of equation (6). The additional term $\lambda_k \|d\|_2^2$ can be viewed as a penalty term which prevents $\|d_k\|$ from being too large. Define a positive scalar Δ_k as given in

$$\Delta_k = \|(A(x_k)A(x_k)^T + \lambda_k I)^{-1} A(x_k)F(x_k)\|_2. \quad (9)$$

Then for any $\|d\|_2 \leq \Delta_k$, d_k is a solution of equation (8) and also a solution of the problem given in

$$\min_{d \in \Re^n} \|F(x_k) + A(x_k)^T d\|_2^2, \quad (10)$$

which is a trust region (TR) subproblem. A TR algorithm for nonlinear least squares is similar to the LM method, except that the bound Δ_k is updated from iteration to iteration instead of the parameter λ_k (Yuan 1994).

In the present study, the parameters of both models are calibrated by the TR method by means of the Curve Fitting Toolbox (CFT) of MATLAB®. In the CFT, TR, LM and GN algorithms are available for nonlinear least squares curve fitting calculations.

While all three algorithms are based on Newton's method, the TR method has some advantages on the others (the MathWorks 2005). The GN method is not always reliable particularly in the presence of insufficient data, topological or parameter errors. The TR formulation is more robust than the GN method (Pajic and Clements 2005).

Adjusted determination coefficient (AR^2) is used as a goodness of fit measure. AR^2 is the proportion of variance of the dependent variable that is explained by the independent variables as given in

$$AR^2 = 1 - \frac{SSE(n-1)}{SSy(n-p)}, \quad (11)$$

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2, \quad (12)$$

$$SSy = \sum_{i=1}^{n} (y_i - \bar{y})^2, \quad (13)$$

where SSE is the sum of squares due to error, SSy is the sum of squares about the mean, n is the number of data points, p is the number of model parameters, y_i and $\hat{y}_i$ are the observed and fitted data values, respectively and $\bar{y}$ is the mean of the observed data values.

According to the aforesaid explanations the model coefficients (Q_0 and α_e or α_q) of both models are computed for each SGS. As an example, 1981 year measurements of the SGS 61 will be examined in detail. The 1981 water year is from day 732 to 1096 (figure 2). The recession period is also shown in figure 2. Discharges were divided by the peak discharge value to present the recession hydrograph values as the ratio of the starting value as shown in figure 3.

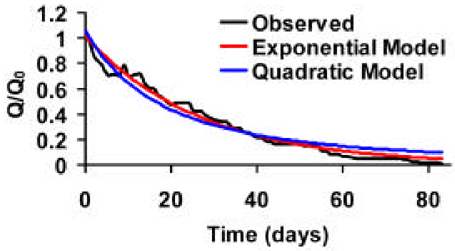

Figure 3. Observed and model recession hydrographs of SGS 61 for the year of 1981.

Model parameters are calculated by using the TR algorithm. The parameters of exponential and quadratic models are found as

$$Q_t = 1.013 \exp(-0.037t), \quad (14)$$

$$Q_t = \frac{1.057}{(1 + 0.028\, t)^2}. \quad (15)$$

AR^2 values for the exponential and quadratic models are 0.98 and 0.92 respectively. Recession hydrographs of the models are shown in figure 3 from which it is seen that both models adequately fit.

Model parameters are calculated in the same way for other SGSs and given in table 3. Then the recession coefficients (α_e and α_q) of both models are obtained. Initial discharges (Q_0) are obtained from models but not used in this study. Mean Q_0 values are given in table 3.

4. Statistical analysis of recession coefficients

Recession coefficients of the SGSs are arranged as series and analyzed statistically. Simple summarization methods are applied to α_e and α_q series. Mean ($\bar{\alpha}$) is used as the measure of location, standard deviation (σ_α) is used as the measure of spread and the coefficient of skewness $C_{s,\alpha}$ is used as the measure of skewness. Calculated values of the mean, standard deviation and skewness of α_e and α_q series are given in table 3.

In addition determining the normality of α_e and α_q series, probability plot correlation coefficient (PPCC) values (r) are calculated using

$$r = \frac{\sum_{i=1}^{n} (\alpha_i - \bar{\alpha})(w_i - \bar{w})}{\left[\sum_{i=1}^{n} (\alpha_i - \bar{\alpha})^2 \sum_{i=1}^{n} (w_i - \bar{w})^2\right]^{1/2}}, \quad (16)$$

Table 3. *Recession coefficients, descriptive statistics, PPCC (r) and mean Q_0 values.*

	Stream gauging station no.											
	13		18		19		49		61		70	
Year	α_e	α_q	α_e	α_q	α_e	α_q	α_e	α_q	α_e	α_q	α_e	α_q
1961	0.016	0.010										
1962	0.008	0.005										
1963	0.007	0.004										
1964	0.006	0.003										
1965	0.015	0.009					0.005	0.003				
1966	0.014	0.010										
1967	0.012	0.008	0.016	0.011								
1968	0.013	0.008	0.027	0.019	0.061	0.111						
1969	0.015	0.009	0.005	0.003	0.156	0.191	0.015	0.009				
1970	0.011	0.007	0.010	0.006	0.039	0.048	0.006	0.003	0.043	0.039		
1971	0.012	0.007	0.019	0.011	0.046	0.063	0.025	0.014	0.050	0.042		
1972	0.012	0.008	0.011	0.006	0.028	0.029	0.010	0.006	0.100	0.091		
1973	0.017	0.011	0.014	0.009	0.289	0.021	0.013	0.007	0.044	0.033	0.015	0.010
1974	0.010	0.017	0.013	0.009	0.040	0.037	0.050	0.035	0.045	0.031	0.014	0.010
1975	0.014	0.009	0.018	0.012	0.139	0.139	0.011	0.006	0.034	0.027	0.010	0.006
1976	0.028	0.026	0.013	0.007	0.034	0.042	0.017	0.011	0.038	0.028	0.015	0.014
1977	0.022	0.021	0.035	0.026	0.031	0.048	0.019	0.011	0.049	0.041	0.016	0.011
1978												
1979	0.028	0.018	0.011	0.009	0.055	0.052	0.038	0.024	0.021	0.016	0.016	0.016
1980	0.014	0.009	0.038	0.028	0.042	0.043	0.024	0.015	0.049	0.039	0.017	0.015
1981	0.011	0.007	0.023	0.017	0.042	0.085	0.019	0.013	0.037	0.028	0.017	0.014
1982	0.020	0.013	0.018	0.011	0.025	0.039	0.014	0.008	0.026	0.018	0.017	0.015
1983	0.025	0.018	0.027	0.019	0.038	0.047	0.017	0.009	0.021	0.013	0.018	0.016
1984	0.020	0.014	0.026	0.016	0.033	0.032	0.011	0.006	0.078	0.087	0.019	0.022
1985			0.014	0.010	0.019	0.015	0.032	0.022	0.049	0.047	0.020	0.021
1986			0.007	0.004	0.039	0.041	0.020	0.012	0.043	0.034	0.014	0.012
1987			0.033	0.022			0.011	0.007	0.059	0.040	0.019	0.013
1988			0.054	0.035			0.019	0.011	0.081	0.087	0.032	0.029
1989			0.008	0.005			0.037	0.024	0.085	0.063	0.009	0.006
1990			0.010	0.006			0.023	0.014	0.249	0.188	0.010	0.006
1991			0.006	0.003			0.007	0.003				
1992			0.009	0.005			0.006	0.003	0.034	0.022		
1993							0.038	0.027	0.078	0.055		
1994			0.008	0.005			0.044	0.029	0.074	0.056		
1995			0.002	0.012			0.005	0.003				
1996			0.009	0.006			0.042	0.031	0.061	0.046		
1997			0.018	0.011			0.016	0.008				
1998			0.019	0.012			0.040	0.033	0.060	0.043		
1999			0.022	0.015			0.009	0.005	0.078	0.121		
2000			0.008	0.005					0.045	0.043		
2001			0.010	0.006								
$\bar{\alpha}$	0.015	0.011	0.017	0.012	0.064	0.060	0.021	0.013	0.060	0.051	0.016	0.014
σ_α	0.006	0.006	0.011	0.008	0.067	0.045	0.013	0.010	0.043	0.037	0.005	0.006
$C_{s,\alpha}$	0.810	1.106	1.421	1.365	2.674	1.907	0.753	0.955	3.450	2.276	1.391	0.960
r	0.966	0.949	0.938	0.934	0.762	0.871	0.954	0.938	0.784	0.866	0.917	0.960
Q_0	0.777	0.825	0.755	0.793	0.225	0.288	0.664	0.683	0.873	0.976	0.576	0.682

where r is the linear correlation coefficient between the ordered observations (α_i) and the corresponding fitted quantiles (w_i) of α_e or α_q series. Values of r approaching 1.0 suggest that the observations could have been drawn from the fitted distribution. In this study, quantiles are obtained from the cumulative normal distribution function. $\bar{\alpha}$ denotes the average value of the observations and $\bar{w}$ denotes the average value of the fitted quantiles in equation (16).

More robust and resistant to the extreme values, data summarizing techniques may be used besides the classical measures. A very useful and concise graphical display for summarizing the distribution of a data set is the boxplot. Centreline of the box indicates the median which is the measure

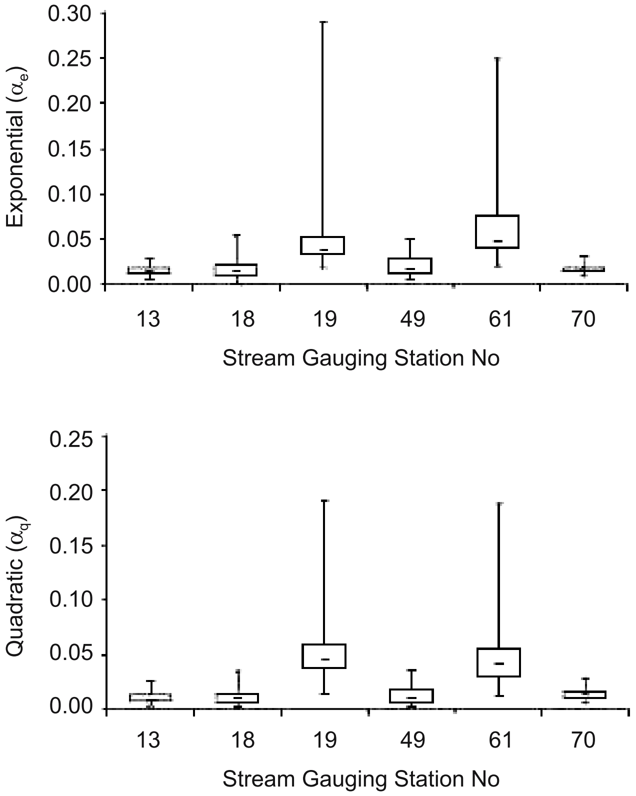

Figure 4. Boxplots of recession coefficients for the exponential and quadratic models.

of location. The box height denotes the interquartile range (IQR) which is the measure of spread. The relative size of box handles shows the *quartile skew* which is the measure of skewness (Helsel and Hirsch 2002). Boxplots of recession coefficients of α_e and α_q series are given in figure 4. Simple boxplots are used in this study displaying the minimum, lover quartile, median, upper quartile and the maximum, respectively from bottom to the top of the box.

Boxplots for both models have the same character as shown in figure 4. SGSs can be grouped into three groups for similarities of boxplots. The first group is SGSs 13 and 70, they have small IQR values and the length of box handles are small, the second group is SGSs 18 and 49, their IQR values and the length of box handles are increased. Finally, the third group is SGSs 19 and 61, their IQR values and especially the length of box handles are much more than the others.

5. Results

As mentioned previously, karstic aquifers contribute to the upstreams of the SGSs 13, 70, 18, 49, 19 and 61 in the order of decreasing quantity. SGS numbers are listed in descending order due to the karstic aquifer contribution amounts in table 4. Studied streams can be grouped into three classes according to their karstic aquifer contribution amounts as high, medium and low levels; SGSs 13 and 70 can be accepted as high level, SGSs 18 and 49 medium level, SGSs 19 and 61 low level or non-karstic aquifer contributed streams.

The extent of the karstic aquifers contribution to streams will be discussed by comparing various criteria. The first comparison is performed for the measure of location values (mean and median) of α_e and α_q series. SGS numbers are listed from low to high mean and median values of α_e and α_q series in table 4. This arrangement shows that the more karstic aquifer contribution the less $\bar{\alpha}$ or median value of recession coefficients. But recession coefficient of a basin is a characteristic and distinguishing parameter, it depends on various features of basin. Standalone mean or median of the recession coefficients does not seem to be enough to determine the volume of karstic aquifer that contribute to the stream.

The second comparison is performed for the measure of spread values (σ_α and IQR) of α_e and α_q series. SGS numbers are listed from low to high σ_α and IQR values in table 4. This arrangement shows that the more karstic aquifer contribution to the streams, the less recession coefficient variation one year to another. Order of IQR values for the quadratic model is exactly the same with the enumeration of karstic aquifer contribution rate values.

The third comparison is performed for the measure of skewness values ($C_{s,\alpha}$) of α_e and α_q series.

Table 4. *Listing the SGS numbers due to various parameters (karstic aquifer contribution amount and r are in decreasing order; $\bar{\alpha}$, median, σ_α, IQR and $C_{s,\alpha}$ are in increasing order).*

Karstic aquifer contribution amount	$\bar{\alpha}$		Median		σ_α		IQR		$C_{s,\alpha}$		r	
	α_e	α_q	α_e	α_q	α_e	α_q	α_e	α_q	α_e	α_q	α_e	α_q
13	13	13	13	13	70	13	70	13	49	49	13	70
70	70	18	18	18	13	70	13	70	13	70	49	13
18	18	49	70	49	18	18	18	18	70	13	18	49
49	49	70	49	70	49	49	49	49	18	18	70	18
19	61	61	19	61	61	61	19	19	19	19	61	19
61	19	19	61	19	19	19	61	61	61	61	19	61

SGS numbers are listed in ascending order for $C_{s,\alpha}$ values in table 4. The SGSs list of $C_{s,\alpha}$ values do not match with the SGSs list of karstic aquifer contribution rate values. Skewness value of the recession coefficients does not seem to be enough to determine the volume of karstic aquifer that contribute to the stream.

The last comparison is performed for the normality (r) values of α_e and α_q series. SGSs are listed from high to low r values in table 4. The more karstic aquifer contributed streams the higher r values of α_e and α_q series, but r values like $C_{s,\alpha}$ values are not successful determining the volume of karstic aquifer that contribute to the stream.

6. Conclusion

Whether descriptive statistical parameters of recession coefficients of a stream in the karstic area help to estimate the volume of the aquifer contributing the stream is investigated in this paper. Results of the study show that there is a considerable relationship between some statistical descriptors of the recession coefficients and karstic aquifer volumes. Especially measure of spread statistics seems to be an adequate indicator for the karstic aquifer contributions. Physical explanation of this result can be the regulation effect of water accumulated in the karstic voids or arriving from neighbouring basins via karstic channels. Karstic aquifer contributed streams act as if they were being regulated by a reservoir and less affected by surface effects than other types of aquifer contributed streams. However, this relationship gives a rough estimation about the volume of the aquifer and not a certain value. For a general statement, more similar studies should be performed.

References

Aksoy H, Bayazıt M and Wittenberg H 2001 Probabilistic approach to modelling of recession curves; *Hydrol. Sci. J.* **46** 269–285.

Baran T, Harmancioglu N and Ozis U 1995 Average base flow rates of karst spring effluents in Turkey; *International Symposium and Field Seminar on Karst Waters & Environmental Impacts*, September 10–20 Antalya Turkey.

Barut I F and Gürpınar O 2005 An approach to the hydrogeological circulation model of the salty karstic springs in the Milas (Mugla) basin; *Univ. Istanbul J. Earth Sci.* **1** 1–22 (in Turkish).

Chapman T 1999 A comparison of algorithms for stream flow recession and baseflow separation; *Hydrol. Process.* **13** 701–714.

Chapman T G 2003 Modelling stream recession flows; *Environ. Modell. Softw.* **18** 683–692.

Dewandel B, Lachassagne P, Bakalowicz M, Weng Ph and Al-Malki A 2003 Evaluation of aquifer thickness by analyzing recession hydrographs. Application to the Oman ophiolite hard-rock aquifer; *J. Hydrol.* **274** 248–269.

Elhatip H 1997 The influence of karst features on environmental studies in Turkey; *Environ. Geol.* **31** 27–33.

Griffiths G A and Clausen B 1997 Streamflow recession in basins with multiple water storages; *J. Hydrol.* **190** 60–74.

Helsel D R and Hirsch R M 2002 Statistical Methods in Water Resources; *U. S. Geological Survey Open-File Rep.* 1–50.

Kiraly L 2003 Karstification and Groundwater Flow; *Speleogenesis and Evolution of Karst Aquifers* 1 (3) Available at: http://www.speleogenesis.net.

Mishra A, Hata T and Abdelhadi A W 2004 Models for recession flows in the upper Blue Nile River; *Hydrol. Process.* **18** 2773–2786.

Pajic S and Clements K A 2005 Power system state estimation via globally convergent methods; *IEEE Trans. on Power Syst.* **4** 1683–1689.

The MathWorks 2005 Curve fitting toolbox for use with MATLAB® User's Guide.

Turkish State Hydraulic Works (DSI) 1961–2001 Stream Gauging Annuals.

Werner P W and Sundquist K J 1951 On the Groundwater Recession Curve for Large Water-sheds; *IAHS General Assembly* (Brussels: IAHS Publ.) **33** 202–212.

Wittenberg H 1999 Baseflow recession and recharge as nonlinear storage processes; *Hydrol. Process.* **13** 715–726.

Wittenberg H 2003 Effects of season and man-made changes on baseflow and flow recession: case studies; *Hydrol. Process.* **17** 2113–2123.

Yuan Y X 1994 Nonlinear Programming: Trust Region Algorithms; (eds) Xiao S T and Wu F, *Proceedings of Chinese SIAM Annual Meeting Hsinghua University Beijing*, 1–20.

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