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CONDUIT AND FRACTURE FLOW CHARACTERISTICS OF PINARBAŞI SPRING, CENTRAL TAURUS REGION, SEYDİŞEHİR, TURKEY

ZNAČILNOSTI KANALA IN RAZPOKLINSKEGA TOKA IZVIRA PINARBAŞI, REGIJA CENTRALNI TAURUS, SEYDİŞEHİR, TURČIJA

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Abstract UDC 556.36(235.12)

Mehmet Çelik & Süleyman Selim Çallı: Conduit and fracture flow characteristics of Pınarbaşı spring, Central Taurus Region, Seydişehir, Turkey

This study was conducted to investigate the flow and storage mechanisms of a karst aquifer located at the central Taurus Mountains, Turkey. As the biggest discharge point of the aquifer system, the flow characteristics are investigated at Pınarbaşı spring by using recession and time-series analyses. Continuous water level measurements are taken from the spring and are converted to flow rate by using a rating curve. The spring flows for 7 months (December 2014 – July 2015) and dries up for the rest of the year. Six individual recession periods are investigated and analyzed in the discharge time series. The recession coefficients (between 0.029 day^{-1} and 0.695 day^{-1}) show that the flow within the aquifer system is mainly controlled by large open conduit and partly fracture porosity. The peak discharge is measured as 7.08 m^3/s, and the maximum storage within the aquifer is calculated as 3.15 million m^3. The continuous discharge data of the spring were evaluated combined with daily rainfall, temperature, electrical conductivity, and amount of suspended sediment in the water. Also a dye-tracing test was also applied to obtain the recharge-discharge relationship and porosity type of the aquifer system. Statistical tests on discharge hydrograph and tracer test showed that the memory of the karst aquifer was found to be about 3 days in the DJF period and about 15 days in the MAM period. The average elevation of the recharge area of the spring was determined to be 1,490 m by using stable isotope data of snow samples and was validated by dye tracer test made via the swallow hole in the recharge area. The total discharge for the year 2015 is estimated at 16.2 million m^3 that approximately 25% of the total discharge is caused by snowmelt.

Key words: Pınarbaşı spring, recession analysis, time series analysis, snowmelt, karst aquifer, Seydişehir, Turkey.

Izvleček UDK 556.36(235.12)

Mehmet Çelik in Süleyman Selim Çalli: Značilnosti kanalskega in razpoklinskega toka izvira Pinarbaşi, Centralni Taurus, Seydişehir, Turčija

Raziskovali smo dinamiko toka in skladiščenja v kraškem vodonosnika v Centralnem Taurusu v Turčiji. Z recesijsko analizo in analizo časovnih vrst pretoka smo raziskovali značilnosti največjega izvira vodonosnika, izvira Pınarbaşı. Časovno vrsto pretoka smo izračunali iz podatkov zveznih meritev nivoja in pretočne krivulje. Izvir je bil aktiven med decembrom 2014 in julijem 2015, preostali del leta je bil suh. Analizirali šest recesijskih obdobij. Koeficienti recesije, ki so med 0.029 dan^{-1} in 0,695 dan^{-1}, kažejo na kanalsko in razpoklinsko poroznost. Največji izmerjeni pretok je bil 7,08 m^3/s, največji izračunani volumen uskladiščene vode pa 3,15 milijona m^3. Z analizo časovnih vrst smo raziskovali korelacijo med pretokom ter padavinami, temperaturo, električno prevodnostjo in motnostjo. Polnjenje in praznjenje ter strukturo vodonosnika smo določali tudi z sledilnim poskusom. Statistična analiza in rezultati sledenja so pokazali, da je spominski čas vodonosnika 3 dni v obdobju od decembra do februarja in 15 dni v obdobju od marca do maja. Z analizo stabilnih izotopov v vzorcih snega smo ugotovili, da je povprečna nadmorska višina prispevnega območja 1490 m. To potrjuje tudi sledilni poskus z vnosom sledila v enega od ponorov, ki jih najdemo na tej nadmorski višini. Celoten odtok izvira v letu 2015 ocenjujemo na 16,2 milijona m^3, pri čemer je približno 25 % prispevalo taljenje snega.

Ključne besede: izvir Pınarbaşı, recesijska analiza, analiza časovnih vrst, taljenje snega, Seydişehir, Turčija.

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INTRODUCTION

Karst aquifers are important water resources for humanity. Most of the Mediterranean countries such as France, Spain, Slovenia, and Turkey have large karstic outcrops. Approximately a quarter of the human population obtain drinking water from karst aquifers (Ford & Williams 2007). Chen *et al.* (2017) pointed out the importance of karst aquifers for regional and global perspectives to obtain an international strategy for exploration, protection, and sustainable management of the karst water sources. The Mediterranean region has shown large climate shifts in the past (Luterbacher *et al.* 2006) and it has been identified as one of the most vulnerable zones in future climate change projections (Giorgi 2006). Climate projections anticipate an increase in the air temperatures together with the irregularities in the amount and intensity of precipitations in the following decades, especially around the Mediterranean region (Alpert *et al.* 2008; Christensen *et al.* 2007; Ribes *et al.* 2019). Although, some exceptions in East-Mediterranean zone showed an increasing amount of precipitation (in central and south Israel), most stations from Greece, Turkey, Syria, Lebanon and Israel for the period 1951–1990, all showing decreasing trends (Xoplaki *et al.* 2000; Kadıoğlu *et al.* 1999; Paz *et al.* 2003). Hartmann *et al.* (2014) pointed out the impact of climate change as recording that some karst springs in the Eastern Mediterranean dried as a result of excessive pumping. Turkey is located in a very sensitive position where most of the karst exposures are located in low latitudes (36-39 N). According to the study of Giorgi and Lionello (2008), the decrease of the winter precipitations inside the southern part of the Anatolian peninsula (where we focused on this study) will reach up to 30 % till the years 2071-2100. For that reason, the karst aquifers in the East Mediterranean will face increasing stress due to the decrease of precipitations and increasing water demand shortly (Hartmann *et al.* 2014). A better understanding of the flow and storage mechanisms of karst aquifers is crucial to develop hydrogeological models to predict the possible changes in the amount and quality of the karst water in the future, and develop efficient management strategies against climate change. The most common methods to obtain the flow and storage characteristics of a karst aquifer are the recession and time series analysis of the spring hydrograph. On the other hand, recharge variability of a karst catchment can play an important role in the modeling process. Defining a more accurate recharge process can significantly decrease model prediction uncertainties.

Snowmelt recharge is an important process in karst aquifer recharge especially in high altitude catchments (Chen *et al.* 2017; Doummar *et al.* 2018). Viviroli *et al.* (2007) defined the Alps as water towers of Europe due to the long-existing snow cover at the top. Doummar *et al.* (2018) showed the importance of snowmelt recharge in a karst catchment in semi-arid climatic conditions. The Taurus Mountains are defined as the roof of southern Turkey and there are wide karstic outcrops that are covered by snowpack more than half of a year. The snowmelt process inevitably contributes to the recharge of the adjacent karst systems due to the high altitude karstic outcrop without vegetation on top. Snowmelt recharge and its impacts on mountainous hydrological systems have been investigated during the last decade (Kraller *et al.* 2012; Chen *et al.* 2018; Doummar *et al.* 2018). Taurus Mountains karst recharge zone contributes both the northern and southern side of the karst massif. The previous studies (Karanjac & Altuğ 1980; Günay 1986; Hatipoğlu *et al.* 2009; Bayarı *et al.* 2011; Eris & Wittenberg 2015) focused on the southern side of the Taurus Mountains where highly populated cities (Antalya, Adana, Alanya, and Muğla) are located. In this study, we focused on the karst springs flowing towards Suğla Polje, northern side of the Central Taurus Mountains. Suğla Polje is located on the northern border of the Central Taurus karst massif where Seydişehir and Beyşehir districts (population over 150,000) placed in. The land area of the polje is mainly used for agriculture and water demand is getting higher. The surface and partially groundwater collected in the Suğla Lake area which recharging by Şehirçay stream channel from Lake Beyşehir have transmitted to the Konya plain through transmission channels for agricultural irrigation.

The increase in the demand for domestic use and drinking water scarcity will be inevitable in the future because the region is under the impact of a semi-arid climate and shows a gradual increase in population. The karst aquifer will be used for drinking and domestic usage purposes such as agricultural irrigation. Besides, there is also a need for animal livestock water during dry periods in which the springs do not flow in the surroundings of Seydişehir. This study will help the decision-makers to find solutions to the water scarcity problem of the residents during dry periods.

This study aims to reveal (1) the discharge and storage characteristics of the karst aquifer by using hydrograph recession curve and time series analysis; (2) to what extent the snowmelt affects the spring discharge variations; (3) the delineation of the karst aquifer recharge and–discharge mechanism based on the spring water hydro-chemical and isotopic signatures, tracer tests, and suspended content analyses.

STUDY AREA

One-third of Europe's land surface is constituted of karst outcrops and some of the European countries (e.g., Austria, and Slovenia) receive up to 50 % of drinking water from karst systems (COST 1995; Andreo *et al.* 2006). Most karst exposures of Europe are found in the Mediterranean region (Hartmann *et al.* 2012). Approximately a quarter of Spain, around 35% of France and Turkey, and nearly half of Slovenia and Croatia are covered by karstic rocks (Lewin & Woodward 2009). Turkey and many other Eastern Mediterranean countries are located in the semi-arid climate zone, which makes their karst water resources more vulnerable to climate change scenarios. According to COST (1995), only 5 % of the drinking water of Turkey is supplied directly from karst springs. Indeed, the 5 % rate is not representing the real values (in reality it should be more than 10-15 %) because the biggest surface water dams (e.g., Keban and Atatürk Dams on the Euphrates River, Manavgat Dam on the Manavgat River, Ermenek Dam on the Göksu River) which also used for drinking water supply have a significant amount of karst water contribution. According to the long term (1929-2019), meteorological records of State Meteorological Affairs General Directorate of Turkey (MGM) (accessed from Mevbis in 2018), Central Anatolia region is the poorest region utilizing the precipitation (approximately 328 mm/year) among all geographic regions of Turkey. The karst water in Central Anatolia is mainly used for agricultural irrigation, especially by pumping from the submerged karst aquifers. Several studies concerning the karstification mechanism and sinkhole occurrence in Central Anatolia region due to over-pumping (Canik & Çörekçioğlu 1985; Bayarı *et al.* 2009; Özdemir 2015; Bayari *et al.* 2017; Calo *et al.* 2017; Öztürk *et al.* 2018). On the other hand, the stress on the karst groundwater in the Central Anatolia region is supposed to increase with the emergence of more drinking water need in the future.

The Taurus Mountains are divided into three subregions as Western Taurus, Central Taurus, and Eastern Taurus (Özgül 1976). Central Taurus karst groundwater flows through both the north (through Beyşehir, Suğla Polje, and Central Anatolia) and to the south (Manavgat and Antalya) which makes the region an important water resource. The potential groundwater divides of the Central Taurus karst terrain are drawn regarding Beyşehir, Derebucak, and the Geyik Mountains peaks (Fig. 1).

The karst morphology and hydrology in the Tau-

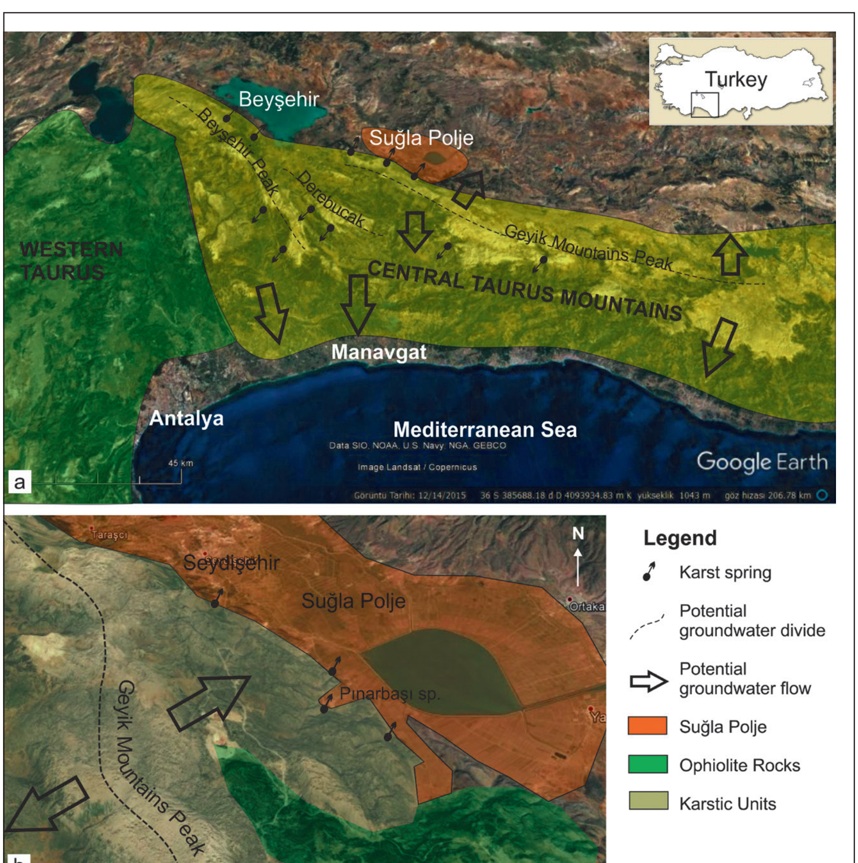
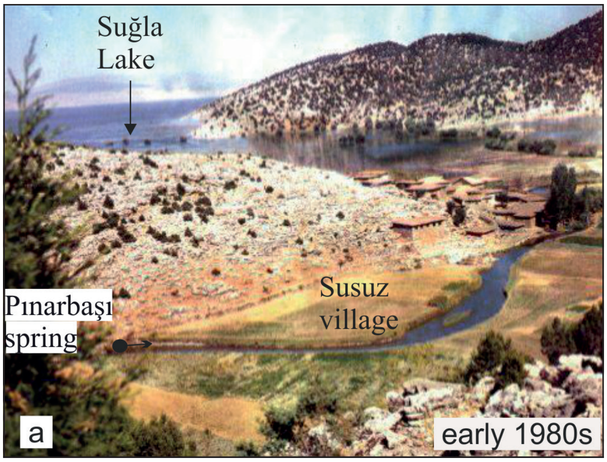


Fig. 1: (a) General view of Central Taurus Mountains, (b) more detailed view of the surroundings of Suğla Polje based on Google Earth SIO, NOAA, U.S. Navy, NGA, GEBCO [14th December 2015].



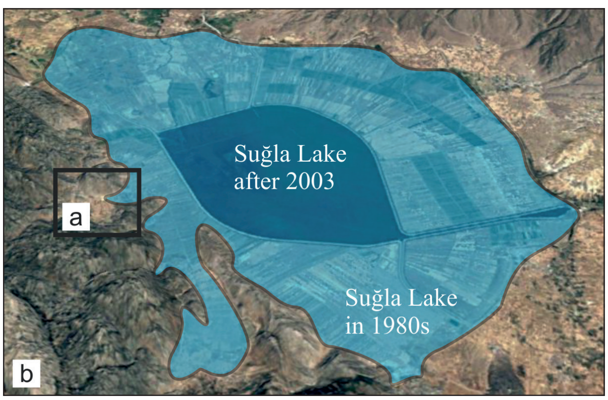


Fig. 2: (a) The view of the Suğla Lake in the early 1980s from Susuz village (before the flood-prevention wall was installed), (b) the google-earth view of the lake in 1984 (light blue), and 2003 (dark blue). The picture in (a) was taken at the squared area in figure (b) based on Google Earth Landsat Copernicus [31st December 1984].

rus region have caught the attention of many researchers (Blumenthal 1947a, b; Aygen 1967; Bakalowicz 1968; Monod 1977; Güldalı *et al.* 1980; UNDP 1983; Güldalı & Nazik 1984; Doğan & Koçyiğit 2018). Several studies regarding the conceptualization (Günay *et al.* 2015) and flow mechanism (Karanjac & Altuğ 1980; Günay 1986; Hatipoğlu *et al.* 2009; Bayarı *et al.* 2011; Eriş & Wittenberg 2015) of Taurus karst aquifers focused on the southern side of the Taurus karst massif.

Suğla Polje is located on the northern side of the Central Taurus Mountains (Fig. 1). There are lots of permanent and temporary karst springs flowing from the Geyik Mountains towards Suğla Polje. Pınarbaşı spring is located in Susuz Village and it has the highest discharge among the springs flowing to Suğla Polje (Çelik *et al.* 2018). Pınarbaşı spring is seasonally active that dries approximately for 5 months and flows out the rest of a year (Çelik *et al.* 2015). Susuz village's drinking water is supplied from the karst aquifer via a pumping well located downstream of the Susuz springs.

The paleo water level mark on the limestone walls is seen between 1,090-1,099 m a.s.l. topographic elevation which strengthens the hypothesis that Suğla Lake water used to reach to Pınarbaşı spring before the flood prevention wall was installed by the State Hydrological Works of Turkey (DSİ) in 2003. The photos of Susuz village in the 1980s (Fig. 2a) make it clear that Suğla Lake's waters in flooding periods had raised to 1,099 m a.s.l. and it used to sink into Pınarbaşı spring which used to make it an Estavelle (Çelik *et al.* 2015). No flood event has been recorded since the prevention wall was installed (Fig. 2b).

A continuous measurement device inside the restored drainage canal at 330 m downstream of Pınarbaşı spring to obtain a discharge time series (Çelik 2017). The device measured hydraulic head with 30 min interval between December 2014 and December 2015. The head values are converted to discharge by using a rating curve.

The studies regarding define precipitation-discharge relation (Romano *et al.* 2013, Fiorillo 2014; Russo *et al.* 2015; Adji & Bahtiar 2016), karstification degree (Malik 2007; Malik & Vojtkova 2012), and flow characteristics (Fiorillo *et al.* 2015; Adji *et al.* 2016) helped us to build our methodology.

GEOLOGY AND HYDROGEOLOGY

The Central Taurus belt is generally covered with units consisting of karstic carbonate rocks. Because of the weak soil cover, karstic features can generally be seen on the surface. It is possible to see many swallow holes, uvalas, and permanent or temporary karst springs in the region (Güldalı & Nazik 1984). Some of the well-known macro karstic features are Tınaztepe Cave, Tınaztepe Doline, Susuzyayla swallow holes, Güvercindeliği Cave, Susuz village springs (Fig. 3). The springs of Susuz village have occurred alongside the Susuz Normal Fault taking place between Polat Formation's Jurassic limestone and Quaternary alluvium (Fig. 3). Discharge elevation of the Pınarbaşı spring is the lowest among them (Pınarbaşı 1,099 m, Yağini 1,109, and Böğet springs 1,107 m a.s.l.).

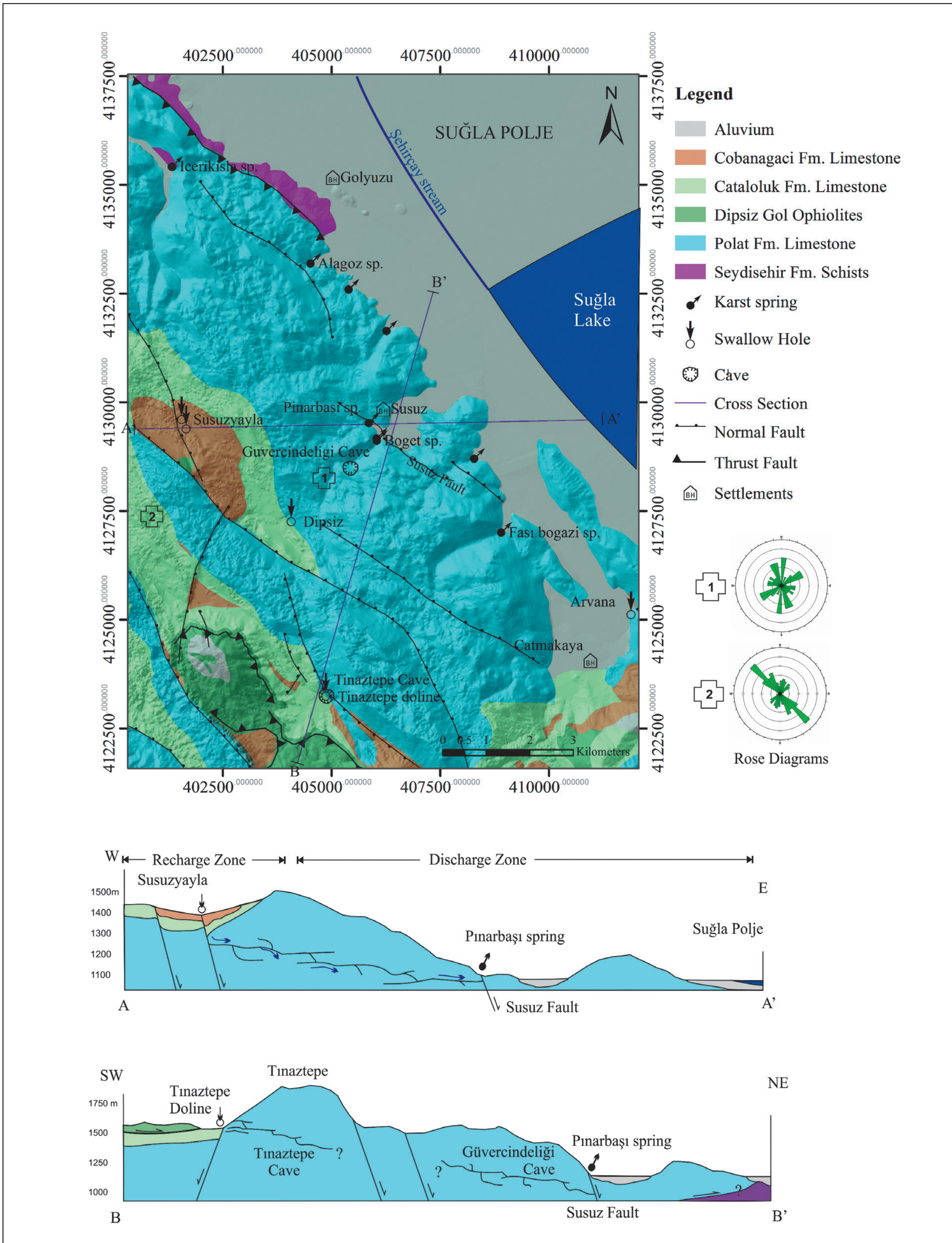


Fig. 3: Hydrogeological map of the study area and cross-sections from the karst massif to Suğla Polje (The map is modified from MTA (General Directorate of Mineral Research and Exploration), 1993).

Alagöz spring, Fası Boğazı spring, and the İçerikışla spring are the other springs flows from the same karst aquifer (Fig. 3). According to Çallı (2017) and Çelik (2017), all springs in the regions are seasonally active. They have measured physicochemical parameters and discharge on these springs in different seasons. The karst aquifer in the study area composed of Jurassic Polat Formation limestone and very little dolomite (Fig. 3). The formation covers approximately 1,000 km^2 on the Central Taurus belt. The formation has lots of fractures and faults. The fractures near the Susuz Fault generally have N-S and NE-SW directions (Fig. 3). Seydişehir Formation's schist (Blumenthal 1947b; Özgül 1976, Monod 1977) which is thought the impermeable basement unit of the Polat carbonate aquifer lies along the thrust fault line to the direction of east-west (Fig. 3).

Campanian-Maastrichtian aged Çataloluk formation limestones overly the Polat formation limestone aquifer with an unconformity. The formation presents highly karstic morphology. The formation has one dominant fracture system in the direction of NW-SE. Çataloluk formation is covered by Upper Paleocene-Lower Eocene aged Çobanağacı formation limestones and clastic sediments (Fig. 3). Dipsiz Göl Ophiolite Mélange (Özgül 1997) which is generally impervious, overlies the limestone formations in the south of the study area (Fig. 3). The eastern side of Susuz village and southern side of Seydişehir are covered with the Quaternary alluvium of Suğla Polje. The alluvium consists of pebble, sand, and clay form the eastern border of Susuz springs.

Güldalı and Nazik (1984) pointed out a hydraulic connection between Tınaztepe Cave and Pınarbaşı spring, but the hypothesis is not verified by a tracer experiment. The hydraulic connection between Susuzyayla region and Pınarbaşı spring is verified by a tracer test by Çelik *et al.* (2018).

MATERIALS AND METHODS

DATA COLLECTION

Daily precipitation and daily mean air temperature data were obtained from the Seydişehir Meteorological Station located on Suğla Polje (1,116 m a.s.l.), 16 km north side of the Pınarbaşı spring and is assumed to be enough representative of the climate of the region (MGM, 2018). The daily discharge time series of the spring is obtained by Aquabar BS pressure device which was installed approximately 330 m downstream of the spring outlet. The device measures the water level with the intervals of 30 minutes and with the precision of ± 0.1 % cm between the dates 3rd of December 2014 and 3rd of December 2015. A Baro Diver device fixed outside of the canal (265 cm above the pressure sensor) to measure the open-air pressure at that point (with the precision of 0.25 cm H_2O). The devices are compensated by using the Schlumberger Diver Office software. Teledyne RD Instruments Stream Pro ADCP (Acoustic Doppler Current Profiler) device was used in different periods and in different water levels at the point in which the instant measurement device was placed and the flow rate of Susuz creek was calculated. The water level values in the spring have been transformed into flow rate via the attained stage-discharge curve (Çelik 2017).

To get a better understanding of (1) whether a piston flow mechanism occurs, and (2) to what extent the snowmelt recharge affects TSS and Q, Total Suspended Solid (TSS) analysis was conducted during a 60-day period (15th of February 2015 – 15th of April 2015) when rising and falling limbs occurred inside. TSS data was collected by filtering the water samples manually taken from the spring outlet with 20-liter bottles. The amount of TSS was determined by gravimetric methods in the Hydrogeology Laboratory of Ankara University. To delineate potential recharge area of the karst aquifer, stable isotope (Oxygen-18 and Deuterium) contents of snow and spring water samples were investigated.

RECESSION ANALYSIS

Hydrograph or discharge analysis is a simple method to obtain the aquifer parameters. The recession curve is defined as the part of the hydrograph that extends from a discharge peak to the base of the next rise (Amit *et al.* 2002). Tallaksen (1995) and Fiorillo (2014) published very useful papers about recession analysis techniques. Dewandel *et al.* (2003) made a comparison of most common recession analysis methods regarding each of their approximations and limitations. Maillet (1905) model is a robust model defined as a simple exponential equation (Fu *et al.* 2016). Maillet (1905) exponential equation can be used for the baseflow recession curve but there is an ongoing debate on the use of the equation in the influenced stage because of the non-exponential behavior of early recession periods (Tallaksen 1995; Dewandel *et al.* 2003). Birk and Hergarten (2010) conducted a study of the linear behavior of the early recession and the exponential behavior of the late recession. Even though the overall shapes of any recession curve are similar, differences are observed from one to another (Dewandel *et al.* 2003). The shape of the curve can change with the aquifer properties (Schoeller 1948; Forkasiewicz & Paloc 1967; Drogue 1967), and geometry of the aquifer system (Horton 1945; Eisenlohr *et al.* 1997).

If a recession hydrograph is plotted on a semi-log paper, one or more linear trends can be seen regarding the flow regimes inside the aquifer (Bonacci 1993). If the semi-log plotted recession curve shows one linear trend, it can be mathematically explained using one exponential equation. If more than one linear trend, each trend should be explained using separate exponential equations, and the sum of these equations gives the total flow equation, which is called "Modified Maillet Formula" (Barnes 1939; Schoeller 1948; Forkasiewicz & Paloc 1967; Fu *et al*. 2016). In this study, we determined the recession coefficients using Maillet exponential equation, and we defined recession equations by using a modified Maillet formula.

The recession coefficients give much information about the flow behavior of karst aquifers. Recession coefficient value changes directly proportional to the change in discharge, while inversely proportional to change in time. Highly karstified systems have generally large conduits where flow rate can change in shorter times, so higher recession coefficients are expected in a well-karstified aquifer system. Malik & Vojtkova (2012) determined the karstification degree of an aquifer system by using the recession analysis. According to Smart & Hobbs (1986), sudden rising limbs and high recession coefficients are indicators of concentrated recharge, low storage, and the concentrated flow inside the aquifer, which all these are the signatures of the highly-karstified aquifer system.

We used Maillet (1905) Eq. 1 for each flow component in the recession period:

$$Q = Q_0 e^{-\alpha t} \qquad [1]$$

Where Q is the discharge, Q_0 is the discharge at t = 0, and α is the recession coefficient. Modified Maillet model (Eq. 2) is the sum of the exponential equations for different types of flow:

$$Q = \sum_{i=1}^{n} Q_{0i} \times e^{\alpha_i t} \qquad [2]$$

Where "i" represents the component "i" in the aquifer, Q_{0i} represents the discharge of media i at t = 0 and n represent the total number of flow components (Fu *et al.* 2016). So, the modified Maillet equation can be written as Eq. 3:

$$Q = Q_c \times e^{\alpha_c t} + Q_f \times e^{\alpha_f t} + Q_m \times e^{\alpha_m t} \qquad [3]$$

Where Q_c, Q_f, Q_m are discharges and α_c, α_f, α_m are the recession coefficients of the conduit, fracture, and matrix reservoirs, respectively. The discharge equation of the spring was obtained using Eq. 3. We calculated the water volume of each flow type of the karst aquifer using the Eq. 4 that was used by many researchers (Mangin 1975; Pfaff 1987; Marsaud 1996; Çallı 2017; Çallı & Çelik 2018).

$$V = \sum_{i=1}^{n} \frac{Q_i}{\alpha_i} \times 86400 \qquad [4]$$

TIME SERIES ANALYSIS

Box and Jenkins (1976) defined a time series as a set of observations generated sequentially in time. The phenomenon of 'persistence' is highly relevant to the hydrologic time series, which means that the successive members of a time series are linked in some dependent manner (Shahin *et al.* 1993). For continuous variables, persistence typically is characterized in terms of serial correlation, or temporal autocorrelation (Wilks 2006). The prefix "auto" in correlation denotes the correlation of a variable with itself so that the temporal autocorrelation indicates the correlation of a variable with its future and past values (Wilks 2006). In other words, 'persistence' denotes the tendency for the magnitude of an event to be dependent on the magnitude of previous event (s), i.e., a memory effect (Machiwal & Kumar 2012). For example, the tendency for low streamflows to follow low streamflows and that for high streamflows to follow high streamflows (Machiwal & Kumar 2012). Thus, 'persistence' can be considered synonymous with autocorrelation (O'Connel 1977). The plot of the autocorrelation coefficient as a function of lag k, is called the autocorrelation function (ACF) of the process (Box & Jenkins 1976). The ACF methodology in the discharge time series is widely used in karst hydrology (Moussu *et al.* 2011; Panagopoulos & Lambrakis, 2006; Valdes *et al.* 2006). The autocorrelation of discharge starts as 1 with no lag, and it falls below 0.2 (insignificance threshold) with increasing lag. For the lag-1 autocorrelation in a time series with "n" elements, there are (n-1) pairs. Denoting the sample mean (μ) of the first (n-1) values with the subscript "-" and that of the last (n-1) values with the subscript "+" the autocorrelation is given by Eq. 5.

$$r_1 = \frac{\sum_{i=1}^{n-1}[(x_i-\mu_{x-})(x_{i+1}-\mu_{x+})]}{[\sum_{i=1}^{n-1}(x_i-\mu_{x-})^2 \sum_{i=2}^{n}(x_i-\mu_{x+})^2]^{0.5}} \qquad [5]$$

The cross-correlation function (CCF) is a measure of linear correlation between two variables. The cross-correlation based methodology is widely used to analyze the linear relation between input and output signals in hydrogeology (Mangin 1984; Larocque *et al.* 1998; Fiorillo & Doglioni 2010). The cross-correlation of two variables x and y with lag "k" is given in Eq. 6.

$$r_k = \frac{\sum_{i=1}^{n-k} [(x_i - \mu_x)(y_{(i-k)} - \mu_y)]}{\left[\sum_{i=1}^{n-k} (x_i - \mu_x)^2\right] \left[\sum_{(i=1+k)}^{n} (y_{(i-k)} - \mu_y)^2\right]^{0.5}} \quad [6]$$

Cross-correlation of the rainfall and spring discharge shows how fast the water transfer inside the karst system happens. According to Guinot *et al.* (2015) the shorter the delay, the faster the transfer. Jukić and Denić-Jukić (2008) explained that short term and long term memories of a karst aquifer can be determined by using short term and long term ACF's of spring discharge time series. Several studies show that the conduit flow memory may be up to 10-15 days, intermediate flow up to 80-100 days, and the diffuse flow memory can reach many hundred days (Jukić & Denić-Jukić 2015; Hosseini *et al.* 2017). If the high discharge peaks occur only at intense precipitation, it also implies a short memory of the karst aquifer. If the aquifer has a long memory, the high discharge peaks may not necessarily be triggered by intense rainfall (Latron *et al.* 2008; Guinot *et al.* 2015).

Examples of the application of the cross-correlation between rainfall and daily spring discharge are available from the literature (Mangin 1984; Padilla *et al.* 1994; Larocque *et al.* 1998). Seasonal autocorrelations of spring discharge give seasonal memory of the karst aquifer which can be related to seasonal water level fluctuations and karstification differences of different conduit layers inside the aquifer. Seasonal memory and karstification of a karst aquifer system can be obtained using ACF of discharge time series and, CCF between discharge and rainfall, respectively. In this study, we divided a hydrological year into four seasons (DJF: December-January-February; MAM: March-April-May; JJA: June-July-August; and SON: September-October-November) and determined seasonal persistence by using ACF of spring discharge to better understand the dominant flow process in each season. Thus, we used cross-correlation tests between both precipitation and discharge and air temperature and discharge to obtain the dominant recharge mechanism in each season.

RESULTS

DISCHARGE DYNAMICS OF PINARBAŞI SPRING

Discharge measurements of the spring were taken hourly and they were converted to average daily discharge to synchronize with daily rainfall data. The spring flows for approximately 7 months and dries the rest of a year (Fig. 4). The time-series data is missed for 7 days between the 24th and 31st of March because of a battery problem on the measurement device, and it is completed using artificial data. The discharge hydrograph shows that the aquifer system gives sudden responses to precipitation events, especially in the DJF period. The hydrodynamics of discharge in the late days of the DJF period, and MAM period is affected by snowmelt, and it is explained in section SNOWMELT EFFECT ON DISCHARGE. The spring flow rate has reached up to 7.3 m^3/s during the study period (Tab. 1). When the groundwater level de-

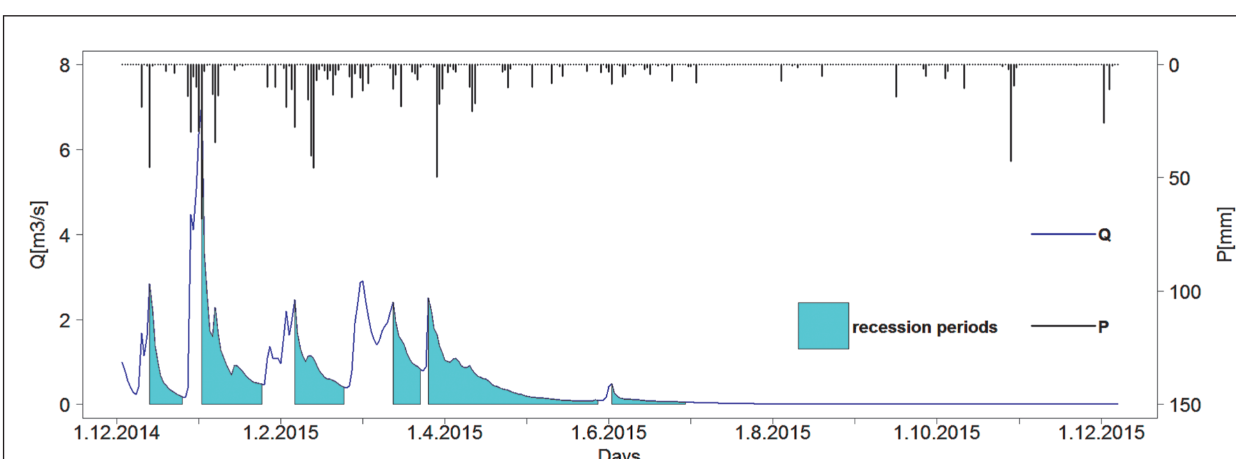


Fig. 4: Discharge hydrograph of the Pınarbaşı spring between December 2014 and December 2015.

creases below the spring elevation, the spring dries. For that reason, the precipitation in JJA, and the SON period hardly cause a flow.

According to the results of the ACF test, the persistence of the spring discharge is calculated as 3 days in the DJF period, and 15 days in the MAM period that mainly refers to a conduit, and conduit-fracture porosity, respectively (Fig. 5a-b). The linear correlation between the spring discharge and the rainfall in different seasons of the year is evaluated using CCF. The highest linear correlation between rainfall and discharge is seen with one-day lag in DJF, and it is explained with the high water level in the aquifer (Fig. 5c). In the DJF period, the conduit and fracture storage of the karst aquifer is nearly full, therefore the piston-flow mechanism occurs frequently. The effect of rainfall on the spring discharge becomes insignificant after three days (Fig. 5c). Due to the missing discharge data between 24th and 30th of April 2015, MAM period cross-correlations are calculated by completing the missing values with artificial discharge data. In SON period, the rainfall is insignificant on spring discharge, because the spring was dry.

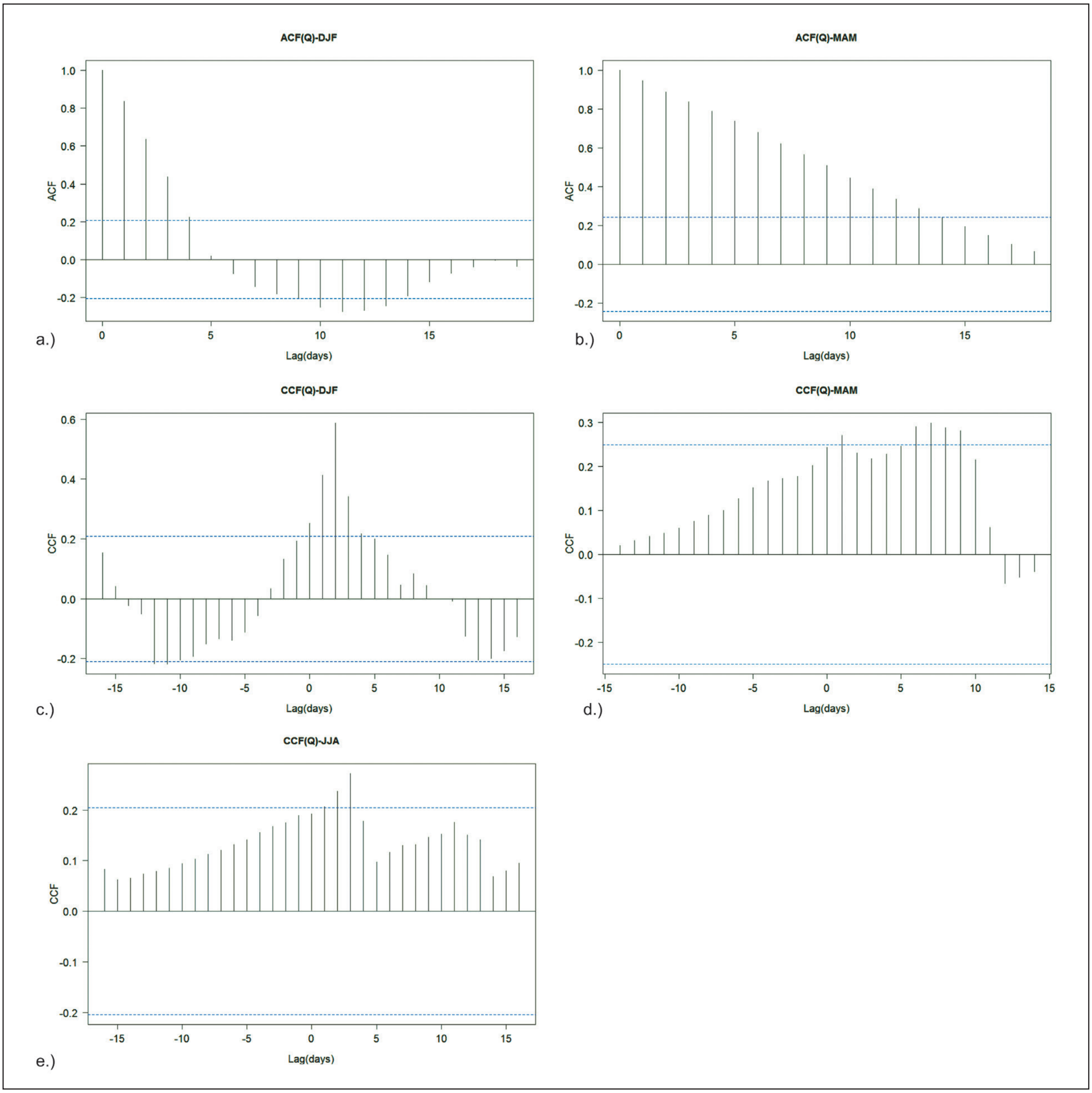


Fig. 5: ACF of discharge (a) in DJF, and (b) in MAM, CCF between Q and P in (c) DJF, (d) MAM, and (e) JJA (dashed lines show the significance level).

The discharge parameters of the Pınarbaşı spring were calculated in 6 separate individual recession periods within the year 2015 (Fig. 6a-f; Tab. 1). Six recession periods are shaded in Fig. 4, the length of the recessions and the recession coefficient results can be seen in Tab. 1. The recession graphs in Fig. 6a-f are shaded representing the flow environments. Fine fractures and matrix environments cannot be separated from each other and evaluated as a single environment in recession hydrographs (Fig. 6a-f). Tab. 1 shows that the karst aquifer system is mainly controlled by conduit and fracture porosity. The conduits and the coarse fracture environments are representing turbulent, fine fractures, and matrix is representing diffusive flow. In the DJF period, the spring flow is mainly controlled by conduit and coarse fracture environments and the diffuse flow proportion is changing between 24-37 %. In the 4th recession period on 12th-21st of March 2015, diffuse flow cannot be separated from coarse frac-

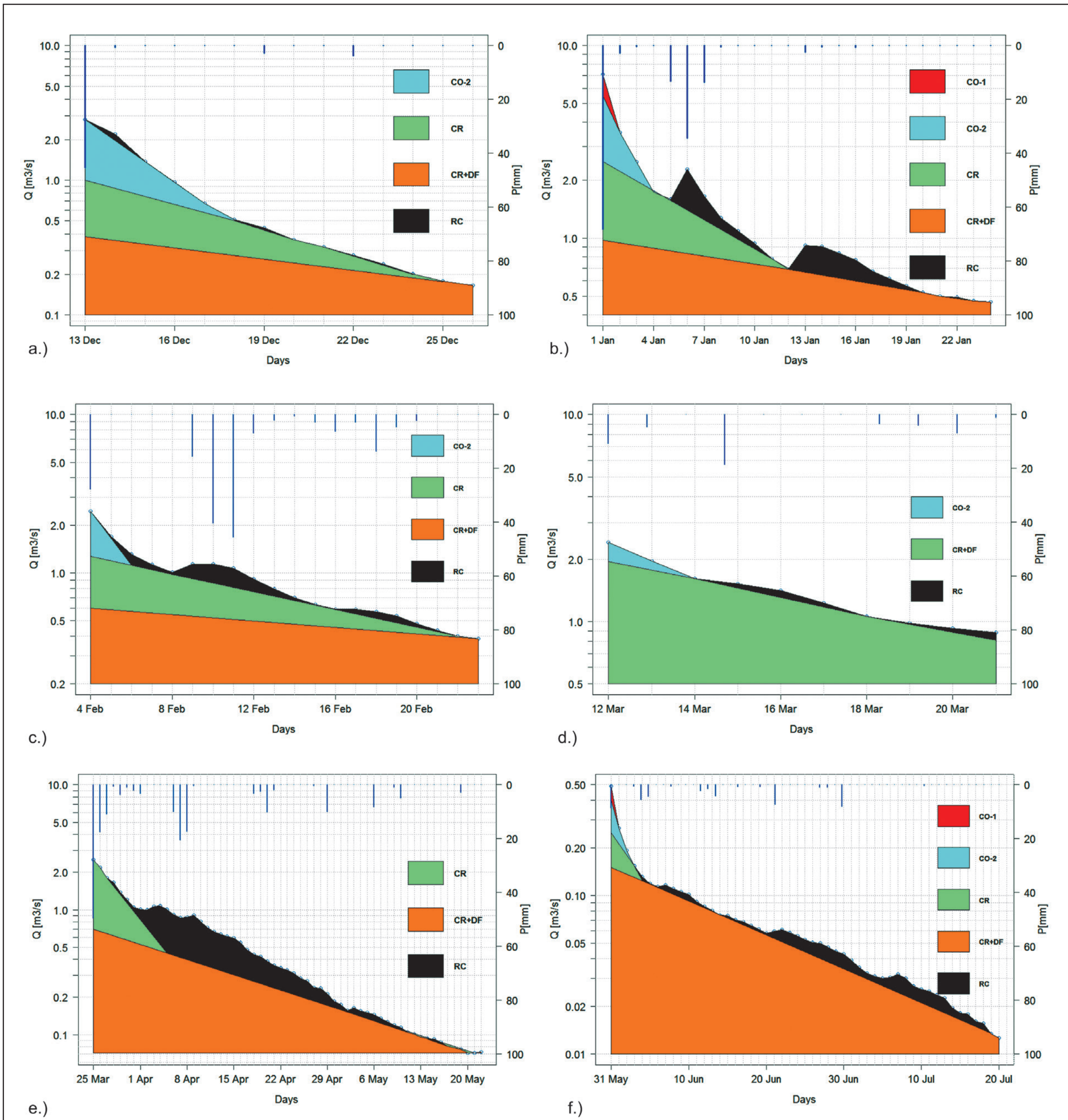


Fig. 6: Recession graphs of Pınarbaşı spring in different recession periods (CO-1: Conduit 1; CO-2: Conduit 2; CR: Coarse fracture; CR+DF: Fine fractures and diffuse; RC: Recharge).

Tab. 1: Discharge analysis results of Pınarbaşı spring (CO-1: conduit 1; CO-2: conduit 2; CR: coarse fracture; CR+DF: fine fracture+diffuse).

Recession period	Recession length (days)	Flow Rate (m^3/s)	Discharge coefficient (day^{-1})	Flow Environment	Discharge volume ($10^6 m^3$)	Cum. discharge ($10^6 m^3$)	CO-1, CO-2 (%)	CR (%)	CR+DF (%)	Discharge Equation
13 Dec.- 26 Dec. 2014	4 8 13	2.835-0.672 1.000-0.177 0.380-0.165	$\alpha_2 = 0.361$ $\alpha_3 = 0.168$ $\alpha_4 = 0.069$	Conduit-2 Fracture Fracture+Matrix	0.349 0.169 0.269	0.787	44	21	34	$Q = Q_{02}e^{-0.361t} + Q_{03}e^{-0.168t} + Q_{04}e^{-0.069t}$
1 Jan – 24 Jan 2015	1 2 8 23	7.083-3.549 5.200-1.742 2.500-0.692 0.600-0.467	$\alpha_1 = 0.695$ $\alpha_2 = 0.358$ $\alpha_3 = 0.116$ $\alpha_4 = 0.029$	Conduit-1 Conduit-2 Fracture Fracture+ Matrix	0.041 0.270 0.945 0.402	1.658	18	57	24	$Q = Q_{01}e^{-0.695t} + Q_{02}e^{-0.358t} + Q_{03}e^{-0.116t} + Q_{04}e^{-0.029t}$
4 Feb – 23 Feb 2015	2 18 19	2.461-1.010 1.275-0.399 0.600-0.399	$\alpha_2 = 0.315$ $\alpha_3 = 0.132$ $\alpha_4 = 0.059$	Conduit-2 Fracture Fracture+ Matrix	0.225 0.279 0.294	0.798	28	35	37	$Q = Q_{02}e^{-0.315t} + Q_{03}e^{-0.132t} + Q_{04}e^{-0.059t}$
12 Mar – 21 Mar 2015	2 9	2.406-1.613 1.900-0.983	$\alpha_2 = 0.201$ $\alpha_3 = 0.098$	Conduit-2 Fracture+ Matrix	0.090 1.336	1.416	6	94		$Q = Q_{02}e^{-0.201t} + Q_{03}e^{-0.098t}$
25 Mar – 21 May 2015	4 36	2.504-1.372 0.700-0.071	$\alpha_3 = 0.151$ $\alpha_4 = 0.045$	Fracture Fracture+ Matrix	1.940 1.210	3.150	-	62	38	$Q = Q_{03}e^{-0.151t} + Q_{02}e^{-0.045t}$
31 May – 20 Jul 2015	1 2 5 51	0.489-0.266 0.380-0.150 0.230-0.120 0.118-0.013	$\alpha_1 = 0.611$ $\alpha_2 = 0.329$ $\alpha_3 = 0.161$ $\alpha_4 = 0.048$	Conduit-1 Conduit-2 Fracture Fracture+ Matrix	0.002 0.018 0.063 0.186	0.268	8	23	69	$Q = Q_{01}e^{-0.611t} + Q_{02}e^{-0.329t} + Q_{03}e^{-0.161t} + Q_{04}e^{-0.048t}$

ture, so diffuse flow component is combined with coarse fracture flow. Diffuse flow is dominant only in the 6th recession period with 69 % when the water level inside the karst aquifer is significantly lower than the other periods. The spring went dry with the end of the 6th recession period.

Two different conduit levels (the 1st layer "CO-1" $\alpha_1 > 0.6$; the 2nd layer "CO-2" $0.6 > \alpha_2 > 0.2$ day^{-1}) and one coarse fracture level (CR, $0.2 > \alpha_3 > 0.075$ day^{-1}) were obtained from the recession analyses. During the low flow periods, matrix flow cannot differ from fracture flow, so we named the lowest period as fine fractures diffuse flow (CR+DF, $\alpha_4 < 0.075$ day^{-1}) representing fine fractures and matrix together. According to the field observations, the spring generally has diffuse flow under 1 m^3/s. The 1st conduit layer is observed in the 2nd and 6th recession periods and the recession coefficient (CO-1) is estimated as 0.695 day^{-1} and 0.611 day^{-1}, respectively. The 2nd conduit layer (CO-2) and the coarse fracture flow (CR) is observed in all recession periods, and the recession coefficients are calculated around 0.3 day^{-1}, and 0.1 day^{-1}, respectively. The recession coefficient of fine fracture and matrix (CR+DF) was calculated around 0.03 day^{-1} (Tab. 1).

The peak discharge of the spring occurred at the beginning of the second recession period with 7.083 m^3/s. The diffuse flow contribution cannot be separated from the fracture flow in the 4th recession period, and coarse fracture flow includes fine fracture and matrix contribution as well. Snowmelt recharge is significant on the recession periods (Fig. 6b-c) because increasing air temperature cause snowmelt on DJF and MAM periods. The first recharge in Fig. 6b is occurred due to the rainfall, but the second one is thought to occur as a result of snowmelt (dumped with rainfall). The recharge pulse is slightly increasing with such a high rate of rainfall, because the snowpack on that period withholds precipitation, and delays the recharge.

The maximum storage of the aquifer is calculated by using the 5th recession period is 3.15 million m^3. During high flow conditions (DJF period), diffuse flow contribution of the spring discharge is changing between 24-37 % of total discharge. But, in low flow conditions (MAM and JJA periods), fine fracture, and matrix contribution to the total discharge increasing up to 69 %. Another outcome of the recession analysis is that diffusive flow proportion is increasing from DJF to MAM period due to the constant diffusive recharge to the karst aquifer. The big proportion of the diffusive recharge is thought to be snowmelt recharge.

DSİ (General Directorate of State Hydraulic Works, Turkey) drilled wells surroundings of Susuz village for investigation purposes and the majority of the investigation wells failed to reach an adequate yield. An interview with the head of Karst Exploration Group of DSİ (Uğur Akdeniz, 2018) showed that a few of the drilling studies reached mud-filled conduits, but indeed they cannot obtain yield. Çallı (2017) investigated the thin sections of all of the limestone units in the study area and the results showed low primary porosity especially in Jurassic limestone units. The drilling studies and thin sections support Bakalowicz (2005) that Jurassic limestone taking place in the Mediterranean zone has low primary porosity and it is hard to observe matrix flow. The groundwater flow in the aquifer system is mainly controlled by inter-connected conduit and fracture networks. Well-developed conduit systems cause turbulent flow in the aquifer. According to the classification benchmarks of Malik and Vojtkova (2012), the karstification degree of the Polat formation karst aquifer is high, and it can be explained as the aquifer system is characterized as a well-karstified and well-interconnected large open conduits.

SNOWMELT EFFECT ON DISCHARGE

According to (Çelik *et.al.* 2019), the cave exploration and mapping studies showed that Güvercindeliği cave has large conduits and galleries (up to 10 m height, and width) that lies between Pınarbaşı spring and Susuzyayla region.

The precipitation data being used in this study merges rainfall and snow and does not differ one from the other. We determined the days with snow cover by using satellite images of NASA's Earth Observing System Data and Information System (EOSDIS) to better understand to what extent the snow affects the spring discharge. Long term satellite imagery survey showed that the catchment is covered by (mostly partial) snowpack from December to March and increasing air temperature and Lodos winds from the Mediterranean Sea (Libeccio winds from SW) cause snowmelt, then snow water can infiltrate into the karst aquifer system. Fig. 7 illustrates the correlation between air temperature and spring discharge in snow covered seasons. The positive correlation

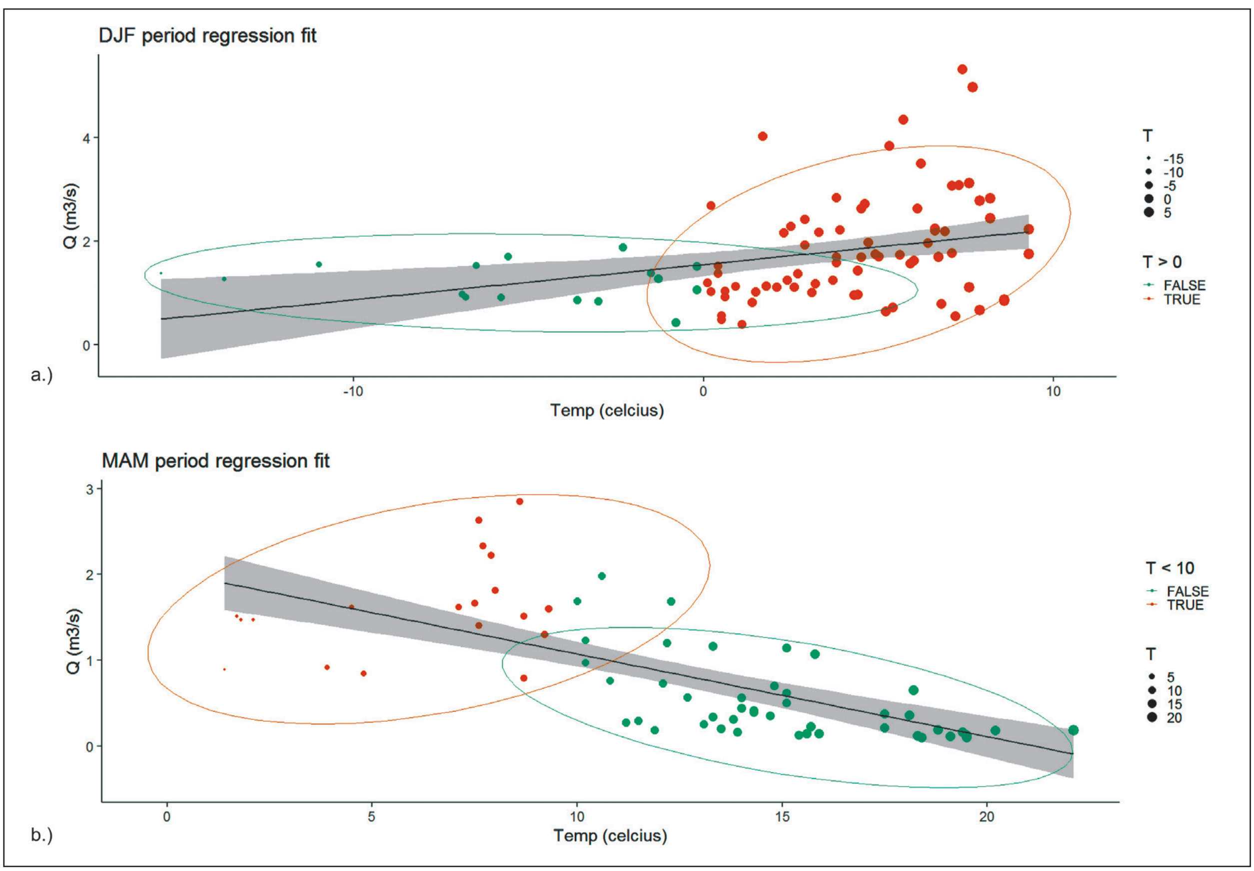


Fig. 7: Scatter diagrams of discharge vs air temperature in (a) DJF and (b) in the MAM period (dashed lines show 70 % confidence intervals).

between air temperature and spring discharge in the DJF period and R^2 is found 0.315 which can be partially related to the snowmelt effect of the aquifer recharge. The satellite images supported that the catchment is (partially/completely) covered by snow in the DJF period and, increasing air temperature melts snow, and increases the flow rate of the spring (Fig. 7a). It is also clear in Fig. 7a that, discharge rise steeply when the air temperature increase above 0 °C. In Fig. 7b, the red ellipse corresponds to the positive correlation between air temperature and discharge between 0 to 10 °C, then it turns to negative afterward (after 10 °C). The duality of the trend in the MAM period is explained that, the catchment is covered by snow in the early days (relatively colder days) of the period, and increasing air temperature (from 0 to 10 °C) causes snowmelt and increases discharge. In the late days of the MAM period (the temperature of the catchment gradually increased), snow cover becomes weaker (or depleted) and the increasing air temperature cannot cause recharge to karst aquifer. The interaction between increasing air temperature and decreasing discharge in MAM period can be explained as the depletion of snowmelt recharge, and the increase of actual evapotranspiration corresponding increasing air temperature.

Cross-correlation graphs in Fig. 8 show that in DJF, discharge is positively correlated with both precipitation and temperature. In contrast with DJF, the temperature rise is negatively correlated with discharge in MAM and JJA periods because the snowmelt contribution is getting weaker. This is thought that there must be a negative correlation between temperature and precipitation, and so, increasing air temperature causes both less precipitation and more evapotranspiration which affect discharge directly. In the SON period, the spring is dry and correlation cannot be calculated between discharge and neither precipitation nor air temperature.

Fig. 9 illustrates the interaction among air temperature, precipitation, and snowmelt recharge on the spring discharge. The grey shaded areas in Fig. 9 illustrate the snowmelt periods. The interaction between snowmelt and the spring discharge can be explained with four approximations: (1) If the air temperature is above the freezing threshold (generally 0 °C), and the recharge area is not covered by snowpack, precipitation is called liquid rainfall, and the rainfall can infiltrate into the aquifer; (2) if the air temperature is below 0 °C, and the land surface is covered by snowpack (or the ground surface is frozen without snowpack), precipitation generally freeze inside the snowpack (or freeze on the frozen ground) and it cannot completely infiltrate into the aquifer; (3) if the land surface of the recharge area is covered by snowpack, and the air temperature increases above 0 ˚C, snowmelt begins and the discharge increases, even there is not any significant rainfall (Fig. 9); and, (4) if the air temperature is above 0 °C, and the recharge area is covered by snowpack, liquid precipitation accelerates the melting process, and cause more intense recharge (Late February in Fig. 9).

The slope of the recharge limbs of the spring hydrograph can vary depending on precipitation type (rain or snow), intensity, and the air temperature. The slope of the rising limb in the spring hydrograph gives information about the recharge of the aquifer. It is expected that the precipitation causes a steep rise in hydrograph if the air temperature is greater than 0 °C. If precipitation occurs, and the air temperature is less than 0 °C, the rising limb will be seen with the delay because of the freezing effect on the ground surface. And finally, if there is no precipitation, and the air temperature is greater than 0 °C, snowpack starts melting, and rising limb of spring hydrograph gradually increase (Fig. 9). Our results in January, February, and March support the temperature and snowmelt effect on the spring hydrograph. The spring hydrograph does not rise during the precipitation events between the 12th and 27th of February 2015, because the precipitation is frozen on the snowpack (the air temperature is below 0 °C). The precipitation of those days cannot reach to groundwater so, the prior recession continues until the snowpack starts melting with the increase of air temperature above 0 °C on the 28th of February. Snowmelt recharge can be seen between the 12th of January, and 12th of February, 2015 when the air temperature increases above 0 °C. Rainfall events in the snowmelt period accelerate the melting process, and recharge to the karst aquifer becomes more intense (the 2nd, the 4th, and the 5th of February, 2015). Another rise in spring hydrograph caused by snowmelt occurred between the 7th and the 15th of March, when no significant precipitation was recorded (Fig. 9).

HYDROCHEMICAL AND ISOTOPIC STUDIES

All of the spring waters in the study area are in Ca-HCO_3 type and they are under-saturated to calcite, aragonite, and dolomite minerals. The recession analyses made it clear that the storage in the aquifer is low and the groundwater flow in the aquifer is conduit dominated. It also indicates fast groundwater circulation or short residence time. It can be expressed that the spring water doesn't have enough time in the aquifer to reach saturation. The EC of Pınarbaşı spring water is measured around 400 µS/cm (Çelik 2017). Electrical Conductivity values of spring water suddenly decrease to 250 µS/cm when recharge occurs and it takes about three days to reach the background value of 400 µS/cm (Fig. 10). The reason why the EC value in Fig. 10 does not reach to the exact value of 400 µS/cm is the following precipitation events. The

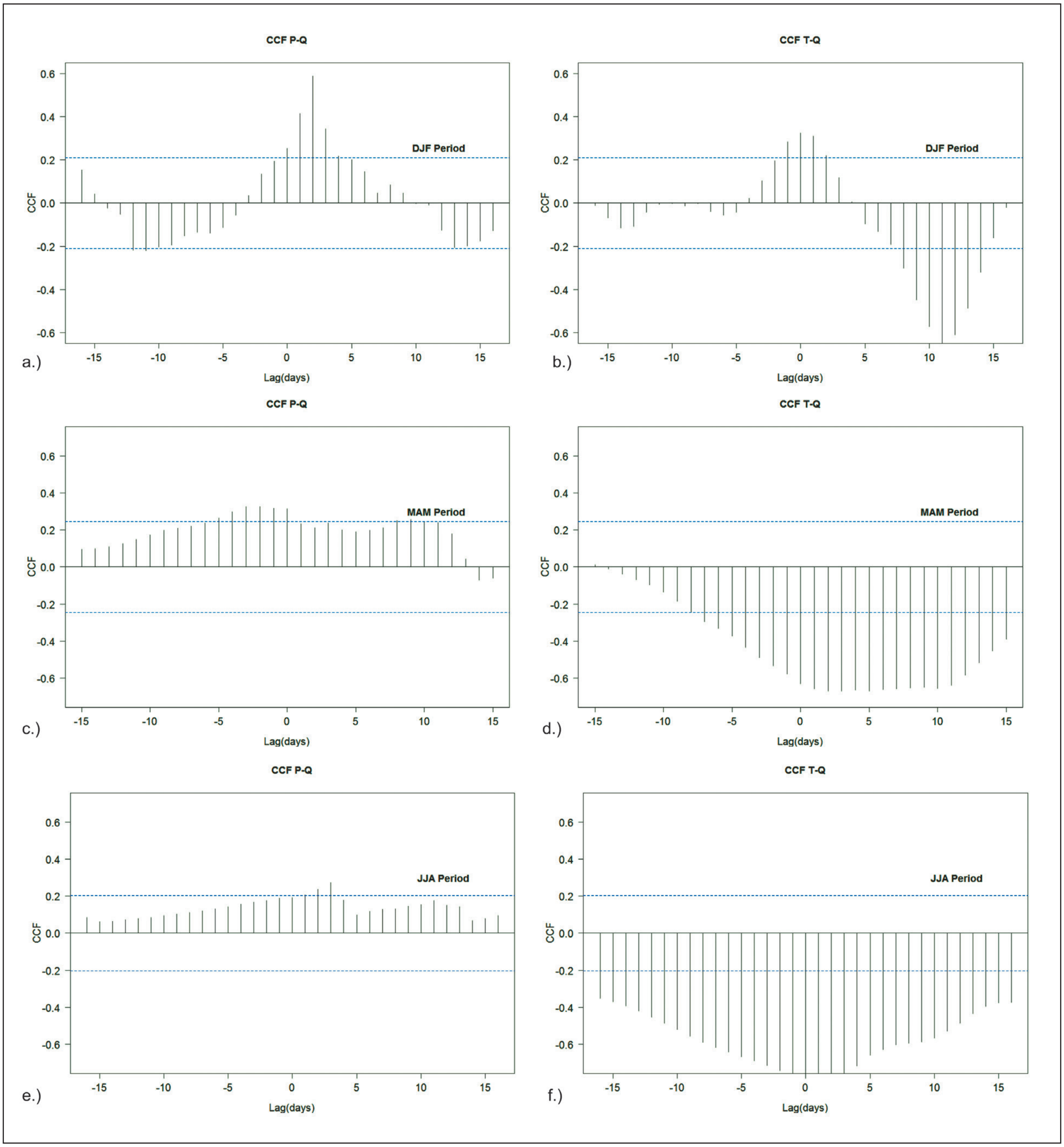


Fig. 8: Cross-correlation graphs in different seasons (CCF: cross correlation function, P: precipitation, Q: discharge, T: temperature, dashed lines show the significance levels).

decrease in the EC of the spring water from 400 µS/cm to 250 µS/cm in a short time indicates the concentrated and sudden recharging of the spring.

The EC graph in Fig. 10 shows that, the effect of precipitation is disappearing after 3 days that the karst aquifer has 3-day memory, following the CCF graphs in sub-section DISCHARGE DYNAMICS OF PINARBAŞI SPRING. In the DJF period and in the early days of MAM period EC changes with no lag, but in the late days of the MAM, and the SON periods there could be a time lag between rainfall and EC due to the changing flow velocity of groundwater. According to oxygen-18 isotope analyses conducted in limited number of the snow samples in the probable recharge area of the Pınarbaşı spring and the equation attained depending on the recharge elevation, it was determined that the oxygen-18 value was distilled

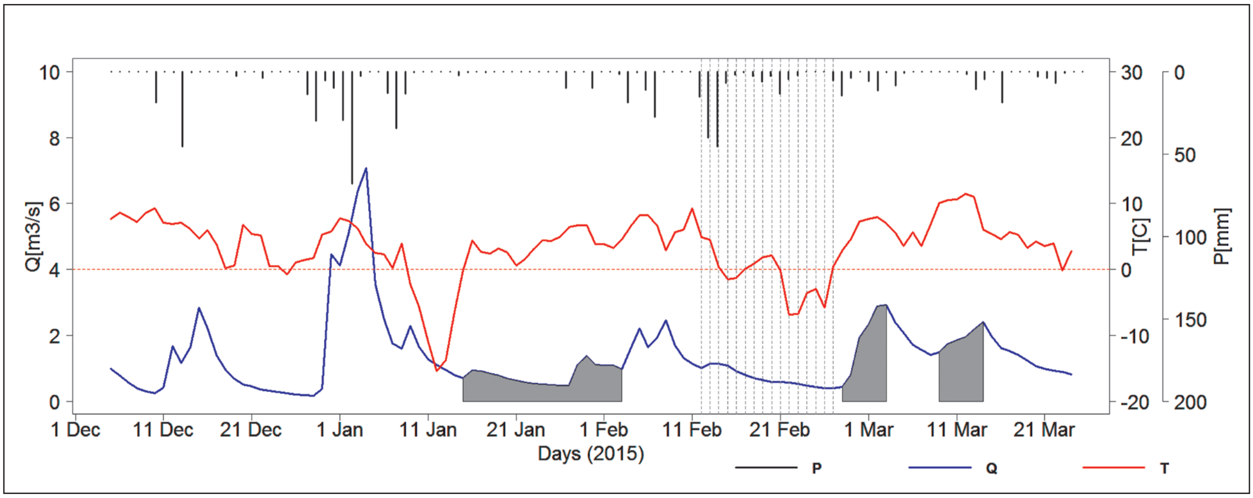


Fig. 9: Temperature and precipitation effect on the spring discharge (dashed lines show the days that precipitation is captured in snowpack while shaded areas show the snowpack melting periods).

by 3.45 ‰ with each increase of 100 m altitude (Çelik 2017). The oxygen-18 concentration of the Pınarbaşı spring water was determined as -9.2 ‰ and the recharge elevation was found around 1,490 m a.s.l. (Çelik 2017). The methodology and result of the recharge elevation of the karst spring in agreement with the previous studies that conducted on the karstic Kazanpınarı spring (Çelik & Ünsal 1999) and Dumanlı Spring (Karanjac & Günay 1980) in Antalya region.

The attained recharge elevation covers the Susuzyayla region, and Tınaztepe Doline and their surroundings which are estimated as the recharge area of the spring (Fig. 3). Çelik *et al.* (2018) performed a tracer test in April 2017 to determine the hydraulic connection between the Susuzyayla region and Susuz springs. The recovery curve was only obtained from Pınarbaşı spring, and approximately one-fifth of the tracer was recovered. The peak dye concentration was measured at the Pınarbaşı spring after 3 days and the mean flow velocity within the aquifer was estimated as 1,820 m/day which corresponds to the conduit dominated flow mechanism.

DISCHARGE-SUSPENDED CONTENT RELATION

Suspended content sampling was conducted daily for about 60 days between the 15th of February to 15th of April 2015 at the discharge point of the Pınarbaşı Spring to obtain a relationship between the discharge and TSS data. Water sampling could not be done for 10 days (between 7th and 17th of March). In every precipitation event in Fig. 11, the TSS amount is changing even the discharge rate does not change, and it is explained by the accumulated sediment load in the conduit system. This is

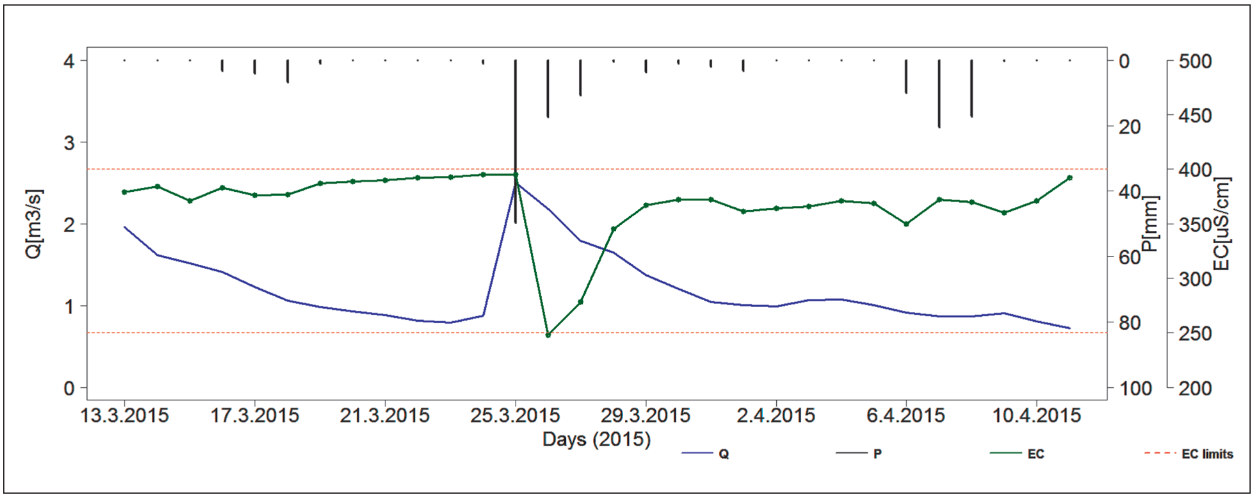


Fig. 10: EC change of Pınarbaşı spring water in MAM period (dashed lines show the limit values of EC).

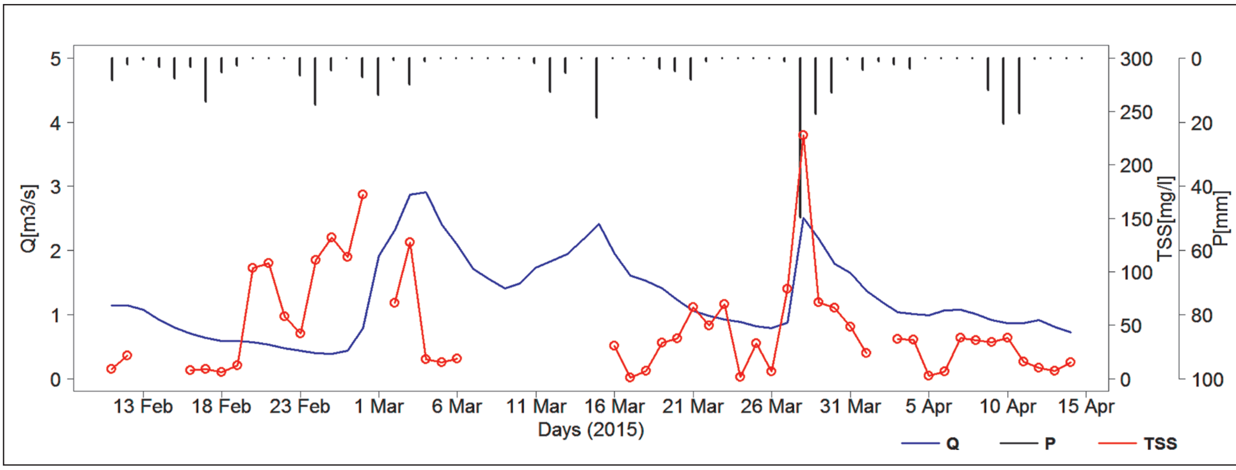


Fig. 11: TSS - P and Q relationship of Pınarbaşı spring in snowmelt periods.

thought that the precipitation in the rainy season causes a piston mechanism, and re-suspends the sediment load inside the conduits. The maximum TSS (230 mg/L) on the 28th of March 2015 occurred at the same time with the highest precipitation in the study period (Fig. 11). This is explained that the higher impulse of dense precipitation causes higher turbidity in the karst system. As we have mentioned in the section SNOWMELT EFFECT ON DISCHARGE, the snow accumulation and melt process is affecting the karst spring discharge. The precipitation in the snowy period (either air temperature is below 0 °C, or there is a snowpack at the recharge area) cannot cause turbidity. During the rainfall free periods (20th - 22nd February), snowmelt recharge pulse the system, and cause turbidity on the conduits, and increases TSS in spring water (Fig. 11). According to observations of Çallı (2017) and Çelik *et al.* (2018) suspended sediments mainly consist of ophiolite and carbonate sediments which are both autogenic and allogenic originated. There is a deficiency of information regarding the conduit/cave geometry and limited information has also been reached regarding the accumulation rate of sediments in conduit systems. The close relation between TSS and P is a signature of a well-developed conduit system which causes a rapid increase in TSS against recharge events.

CONCLUSION AND SUGGESTIONS

In this study, the flow and storage mechanism of the karst aquifer is determined by using recession and time-series analyses, water chemistry, isotope, tracer test, and TSS analyses. It was determined from the hydro-chemical studies that, the Pınarbaşı spring waters represent a carbonated environment with a Ca-HCO_3 water type. The water is under calcite and dolomite minerals saturation which implies short residence time within the carbonated karst aquifer. The textural, structural properties and karstification of the lithological units have an impact on their discharge coefficients which helped us to infer the discharge mechanism of the karst aquifer. These results strengthen the hypothesis that the conduit and cave porosity is dominant inside the karst aquifer. The recession analyses made it clear that recession coefficients of the aquifer system are characterized by two conduits; one coarse fracture, and one fine fracture-matrix subsystems. The interconnection of the 1st and 2nd conduit levels is explored inside the Güvercindeliği cave. The 2nd conduit reservoir starts in the cave and continues downstream towards Pınarbaşı spring. The 1st conduit level can also be seen in the cave, and it can be followed upstream towards the Susuzyayla region. The peak discharge of the spring was recorded as 7.083 m^3/s in the 2nd recession period (1st – 24th of Jan). The recession analyses in the DJF period and early MAM period showed that approximately 55-60 % of the total discharge composed of conduit-fracture, and 24-38 % of the total discharge composed of fine fractures-diffuse flow. In the late MAM period, karst aquifer conduit reserve is nearly depleted, and the proportion of fine fracture and diffuse flow increased by up to 69 % of total discharge. Snowmelt recharge can be seen in DJF and MAM periods, even in the early days of June. In these days, an intense precipitation event occurred, and a flush flow observed in spring. All conduit layers contributed to discharge in the 6th recession period. After the flush flow completed, the spring dried out in June.

In the 5th recession period (25th of Mar – 21st of May) the spring discharge volume was reached to 3.150 million m^3. The recession coefficients show that each conduit layer has a different karstification degree from one another. The karst aquifer is formed by large open conduits, and the flow within the aquifer is mostly turbulent. The phreatic zone is missing or its role is insignificant. According to the statistical analysis results, the aquifer has 3-days memory, which implies conduit dominated flow mechanism in the karst aquifer, following hydro-chemical signatures, and tracer tests. Suspended solid contents in spring water show a sudden increase depending on both rainfall and snowmelt recharge. Recharge elevation of the Pınarbaşı spring is determined as 1,490 m a.s.l. using Oxygen-18 isotopes, where lots of swallow holes can be seen. The recharge type of the aquifer system is generally concentrated and controlled by the swallow holes. It is observed that intense rainfall increases the slope of the rising limb of the spring hydrograph, in contrast with the snowmelt recharge. The total discharge volume of the spring is estimated at 16.2 million m^3 in the year 2015.

The karst system including Pınarbaşı and the other karst springs is planned to be monitored more detalied, and the tracer tests are planned to be carried out. Additionally, mineralogical studies on the rock, sediment and suspended samples should be carried out to better obtain recharge-discharge relation and better understand the transport mechanism within the karst aquifer system. Suggested studies will help us to determine the protection area and build a more accurate conceptual model of the karst aquifer system.

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