Quantitative and Qualitative Methods for the Characterization of Karst Springs (case study: Lorestan province, Zagros Mountain, Iran)

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Quantitative and qualitative methods for the characterization of karst springs (case study: Lorestan province, Zagros Mountain, Iran)

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Abstract

Karst groundwater resources in the Zagros Mountains are vital for supplying of different demands in the region which need to sustainable management and protection. Quantitative and qualitative characterization of karst aquifers in this region were understudied due to lack of site-specific logging-data and speleological investigations. In this study, a state-of-the-art of the statistical methods developed to characterize karst aquifer based on analyses of the spring recession hydrograph and spring water quality are presented. These methods including Manging's method for classification of karst aquifers, relationships of precipitation and discharge data, groundwater quality index (GQI), hydrochemical diagrams (Piper, Durov and Gibbs), and Saturation index (SI), Chloro-Alkaline indices (CAI). 42 major karst springs mainly located in folded part of Zagros region (western Iran) are selected for application of the reviewed methods. Results indicated that the saturated zone exerts almost main control over the discharge of 76% of the studied springs. The base-flow contributes as between 80.0% to 100% of total water storage in the study aquifers. 78.5% of the studied aquifers have a high karstification degree. An insignificant lag-time is observed between the precipitation on the karst basin and spring discharge. The hydrochemical diagrams show that the waters are dominated by HCO_3 and Ca and the majority of the waters are alkaline, with originate from silicate minerals weathering. Such repeatable methods adopted in this study can provide crucial information of the karst aquifers, especially those suffer scarcity of aquifer hydrodynamic data.

Keywords: Zagros Springs, Karst, Groundwater Hydrochemistry, Spring Hydrograph, Lorestan province.

1. Introduction

Karst aquifers as the second-ranked groundwater source supply ~10 % of the drinking water of world's population (Stevanović and Stevanović 2021). In 2019, it is estimated that 1.3 billion of the world's population live in karst areas (Goldscheider et al. 2020). The karst springs contribute as a crucial resource for water demands, ecosystems, agriculture, economic activities, tourism and recreation across the globe (Yuan et al. 2018; Stevanovic 2018).

Karst outcrops consist of ~13% of the Iran's area and most of the carbonate rocks are developed in the north (Mazandaran province) and northwest to southeast (e.g., Zagros Mountains) (Raeisi and Kowsar 1997). About 56% of the springs and most of the main rivers of Iran originate karst formations, especially Zagros zone (Ahmadipour 1999) which is vital for economic development, especially in regional ecological environments (Guo et al. 2019). The detailed study of the karst groundwater in the Zagros region which suffers lack of logging-data and speleological investigations is an essential to a sustainable development and protection of these water resource.

The chemical composition and physical properties of karst springs reflect the processes operating in the relevant geological environment (Appelo and Postma 2005). Investigation of karst spring hydrographs during recession period is frequently used to determine hydraulic characteristics and mechanisms that may define the dynamic of transfer mechanism of flow and storage in karst aquifer (Olarinoye et al. 2021). Moreover, karst hydrogeochemical processes that control spring water chemical helps in understanding of evolution properties in karst aquifer (Hwang et al. 2017), as well as could lead to effective management and suitable allocation of these water resources for different demands (Ndoye et al. 2018).

A summary of the quantitative and qualitative studies performed on karst groundwater is given in Table 1. According to Table 1, the quantitative methods for analyze the characteristics of karst aquifers adopted in the literature including: spring hydrograph modeling, e.g., by presenting a simple conceptual model of karst system (Wu et al. 2019; Shirafkan et al. 2021); spring recession analysis (Kovács et al. 2015; Tang et al. 2016; Nurkholis et al. 2019; Olarinoye et al. 2021; Chang et al. 2021); estimation of fast-flow and baseflow recession coefficients (Nurkholis et al. 2019; Olarinoye et al. 2021); hydrograph separation (e.g., recurrent digital filtering) (Fatchurohman et al. 2018), determination of karstification degree of karst aquifer (e.g., Mangin's approach) (Fatchurohman et al. 2018; Nurkholis et al. 2019; Shamsi et al. 2019), hydrogeological simulation of karst system (using spring hydrograph analysis) (Kovács et al. 2015; Hosseini et al. 2017; Xu et al. 2018; Torresan et al. 2020); and statistical modeling the relationship between

precipitation and discharge (Hosseini et al. 2017; Chang et al. 2021). As reveals, numerous studies have employed recession analyses of karst spring hydrograph to characterize karst aquifers, evaluate aquifer properties, and predict low-flow and estimate baseflow parameters.

In comparison to more homogenous karst aquifer, higher degree of heterogeneity in karst hydraulic characteristics results in rapid changes of spring water quality (Fiorillo and Malik 2019). The mainly hydrochemical analyzes of karst groundwater used in the literature (as summarized in Table 1) including: adopting hydrogeochemical diagrams, e.g., Piper trilinear, Durov and Gibbs (Ghobadi et al. 2018; Gao et al. 2020; Davraz and Batur 2021; Hoaghia et al. 2021); development of hydrochemical indices, e.g., chloro-alkaline and saturation index (Ndoye et al. 2018; Hussien et al. 2016; Hwang et al. 2017 Sako et al. 2020); statistical methods, e.g., principle factor analysis, cross-correlation analysis, and principal component analysis (Ndoye et al. 2018; Sako et al. 2020; Vrouhakis et al. 2021); and stable isotope analysis (Ghobadi et al. 2018; Guo et al. 2019; Tang et al. 2021). It can be noted that aside from hydrograph and chemograph analysis which usually requires only spring discharge and hydrochemical time-series data, other methods including detailed site-specific speleological investigation (Ford and Williams 2007), tracer tests (Goldscheider and Neukum 2010), hydrograph analysis (Fiorillo 2014) and model ensembles (Fandel et al. 2020) are either expensive to implement, time-consuming or require more data input. These are the reasons of the karst spring recession analysis and hydrochemical data still remains a vital quantitative time-series analysis tool for estimating aquifer parameters, water-rock interactions, and geometric properties (Fiorillo 2011). The shape of spring hydrograph and temporal variations of spring water chemistry reflect the complex interplay of conduit and matrix systems, and provides insight about the characteristics of the aquifer and aquifer responses to different recharge pathways (Kovács et al. 2005).

Considering karst aquifers are prominent sources of water especially in the Zagros zone, few detailed and semi-detailed studies have been conducted on this region to give a better understand of quality and quantity characteristics of groundwater in the karst aquifers. Due to this necessity, the aim of the present study was to provide a comprehensive study on the developed methods to achieve quantification and qualification information of groundwater in karst aquifer by analysis of hydrograph and hydrochemical data of the existing springs. For application of the reviewed methods, forty-two main karst systems located in Zagros Mountains (Lorestan Province, western Iran) were studied by analysis of spring hydrograph and hydrochemistry properties. The availability and continuity of spring discharge data lead to choose these springs. Review and application of the most relevant quantifying and qualifying methods rely on

86 discharge and hydrochemical data of the karst spring is critical to increase our knowledge on the karst aquifer where
87 the precise hydrogeological data is scarce.

Table 1. Summary of the quantitative and qualitative methods to obtain karst groundwater characteristics adopted by previous studies.

a) Quantitative Investigations

Reference	Study area	Data set	Adopted Method/Analysis	Key findings
Kovács et al. (2015)	Szinva and Garadna springs, Northern Hungary	21-year daily water level of wells, discharge, temperature and conductivity data of karst spring	<ul style="list-style-type: none"> Spring hydrograph modeling Hydrograph recession curve analysis 	<ul style="list-style-type: none"> Both spring and well hydrographs indicated similar matrix block geometries. Hydrograph analysis revealed the change of flow scale.
Tang et al. (2016)	Laboratory experiments	A total of 49 experimental tests (7 groups of outlet pipes with different diameters and 7 initial water levels) were carried out in the laboratory karst aquifer	<ul style="list-style-type: none"> Spring hydrograph modeling Hydrograph recession curve analysis 	<ul style="list-style-type: none"> The saturated thickness of the aquifer has a great effect on the initial flow of the recession and recession duration, but its effect on the recession coefficient and the shape of the recession curve is slight.
Hosseini et al. (2017)	Sasan Karst aquifer, south-west Iran	21-years daily meteorological and discharge data	<ul style="list-style-type: none"> Spring hydrograph modeling Water balance model 	<ul style="list-style-type: none"> The results reveal the important role of intermediate-flow system in the hydrological modeling of karst systems during the wet period.
Xu et al. (2018)	Madison Blue Spring, Madison County, Florida	Time series of daily precipitation, spring discharge, and hydraulic head for the period from October 6, 2012 to June 6, 2017	<ul style="list-style-type: none"> Spring hydrograph modeling Hydrograph analytical methods (The Mangin, Fiorillo, and a developed model) 	<ul style="list-style-type: none"> The developed model is conceptually similar to the Fiorillo model, but has two unique features for handling the mixed-drainage stage
Fatchurohman et al. (2018)	Kakap spring, Central Java, Indonesia	Long-term discharge data series	<ul style="list-style-type: none"> Spring hydrograph modeling Determine the karstification degree Baseflow separation using digital filtering method 	<ul style="list-style-type: none"> The aquifer dominated by turbulent flow regime.
Shamsi et al. (2019)	Karstic aquifers, Lasem area, northern Iran	Springs discharge have been measured from April 2015 to June 2016	<ul style="list-style-type: none"> Spring hydrograph modeling. Hydrograph Recession Curve Analysis 	<ul style="list-style-type: none"> The main reason for discharge regime of karst springs is related to the different degree of karstification and recharge characteristics.
Jakada et al. (2019)	Miaogou karst watershed and Gaojiaping non-karst watershed, Southern China	Streamflow data from 2015 and 2016	<ul style="list-style-type: none"> Spring hydrograph modeling Hydrograph recession curve analysis 	<ul style="list-style-type: none"> The karst watershed with higher recession coefficients for successive recession limbs, transmit interflow and groundwater flow more rapidly through large cavities to springs as well as stream channels.
Nurkholis et al. (2019)	Jonggrangan Karst, Java, Indonesia	Underground river discharge recorded every 30 minutes at the time interval between 23 October 2017 and 16 May 2018	<ul style="list-style-type: none"> Spring hydrograph modeling Hydrograph recession curve analysis The analysis of the flood hydrograph component Determine the karstification degree 	<ul style="list-style-type: none"> The complex discharge is confirmed by the type of conduit, fissure, and diffuse flows, which visible on the Master Recession Curve calculations.
Wu et al. (2019)	Jinan karst aquifer, northern China	Three different artificial regulated conditions were considered as hydrological scenarios	<ul style="list-style-type: none"> Karst system simulation (laboratory experiments and numerical model) 	<ul style="list-style-type: none"> The results of laboratory experiments and numerical simulations have demonstrated how the spring hydrographs were changed under the effects of artificial regulation at different locations.
Torresan et al. (2020)	Nanto and Mossano springs, Vicenza, Italy	Springs discharge were continuously monitored, from January 2015 to June 2018	<ul style="list-style-type: none"> Spring hydrograph analysis 	<ul style="list-style-type: none"> The two monitored springs showed the same behavior as a consequence of the recharge events.

Chang et al. (2021)	Karst aquifer of the Daiye Cave, China	Precipitation and spring discharge from July 2016 to July 2018	<ul style="list-style-type: none"> Spring recession analysis Tracer Tests (using Uranine). 	<ul style="list-style-type: none"> The results show that the shape of the recession curve was changed under different rainfall conditions.
Olarinoye et al. (2021)	Three karst springs in Austria, Switzerland and Lebanon	Daily and sub-daily spring discharge time series of the selected springs were obtained from WoKaS database	<ul style="list-style-type: none"> Spring hydrograph modeling Spring recession analysis 	<ul style="list-style-type: none"> The modified extraction methods are capable of distinguishing different recession components and derived parameters.
Shirafkan et al. (2021)	Laboratory experiments	An ensemble of spring hydrographs was synthetically produced	<ul style="list-style-type: none"> Spring hydrograph analysis Karst system modeling 	<ul style="list-style-type: none"> The shape of the spring hydrograph can be influenced by the direction of the exchange flow during the recharge and recession events.

b) Qualitative Investigations

Reference	Study area	Data set	Hydrochemical Analysis/Specific software	Key findings
Hussien et al. (2016)	Um Erdhuma-Tayarat aquifer, western Iraq	24 Groundwater samples in June 2013	<ul style="list-style-type: none"> Charge balance method. Spatial analysis Hydrochemical ratios and saturation indices Hydrochemical diagrams (Piper trilinear and Durov) PHREEQC and Rockwork 14 softwares 	<ul style="list-style-type: none"> Ion exchange and reverse ion exchange were two possible processes of water-rock interaction. The mechanism controlling groundwater chemistry is originally related to geogenic process.
Hwang et al. (2017)	Rural areas of Korea for the Assessment of Groundwater Hydrochemistry in Korea.	486 groundwater samples (Pre-monsoon; 206 samples, Postmonsoon; 280 samples)	<ul style="list-style-type: none"> Hydrochemical indices and diagrams for agricultural (Wilcox diagram) and industries (Langelier saturation index and corrosion ratio) purposes Chemical processes diagrams Geochemical evolution diagrams (Gibbs and Chad diagram) 	<ul style="list-style-type: none"> The $\text{Ca}^{2+}-\text{Cl}^{-}-\text{NO}_3^{-}$ type and $\text{Ca}^{2+}-\text{HCO}_3^{-}$ type were the dominant types for the groundwater classified. The exchange of sodium and potassium from rock with magnesium and calcium in water is the main chemical processes in the aquifers.
Zheng et al. (2018)	Liulin spring, Northern China	10 groundwater samples in May 2011	<ul style="list-style-type: none"> Hydrogeochemical simulation technique (physic-chemical and mathematical models) 	<ul style="list-style-type: none"> Hydrogeochemical processes dominating chemical components of karst groundwater included lexiviation, cation exchange and mixture. Mg-Na or Ca-Na exchange prevailed along flow path but exchange types depended on ionic concentration.
Ndoye et al. (2018)	Hydrochemical assessment of Salom aquifer, southern Senegal	79 Groundwater samples in May 2012	<ul style="list-style-type: none"> Statistical methods (correlation coefficients and factor analysis) Geochemical methods (Piper trilinear plot, Wilcox diagram, US Salinity Laboratory diagram and Gibbs diagram) Hydrochemical indices (Chloro-Alkaline Indices and Saturation Indices) 	<ul style="list-style-type: none"> Results show that the groundwater in the area has generally a low hardness and appropriate for irrigation and domestic uses.
Ghobadi et al. (2018)	Dorfak karst region, Northern Iran	hydrogeochemical data from 2011 to 2014 of springs collected by the Regional Water Company of Guilan Province	<ul style="list-style-type: none"> Saturation indices Hydrogeochemical plots (Piper and Durov diagrams) and indices Stable isotopes and deuterium PHREEQC, AqQA-Rock Ware software 	<ul style="list-style-type: none"> All spring waters of the study area are of a $\text{Ca}-\text{HCO}_3$ type. There are variable water movement routes and flow-rates in the watershed between the wet and dry seasons.
Cenameri and Beqiraj (2018)	Fushë Kuqe costal aquifer, north-west Albania	14 Groundwater samples	<ul style="list-style-type: none"> Various hydrogeochemical plots and indices 	<ul style="list-style-type: none"> The geochemistry of groundwater varies from chemically immature composition up to highly evolved composition along the coastal area of the aquifer.

Guo et al. (2019)	Jinan karst system, Shandong, China	56 groundwater samples between May 2015 to October 2016 from two springs, in addition, 4 rainwater samples, and 2 river water samples in Yufu River	<ul style="list-style-type: none"> Hydrochemical and isotope analyses Hydrochemical indices AquaChem (3.7) and PHREEQC softwares 	<ul style="list-style-type: none"> The different temporal variations of hydrogeo-chemistry and stable isotope prove the springs have different recharge sources (precipitation and river water). Based on the ion ratios, the two springs experience different seasonal hydrogeochemical processes.
Sako et al. (2020)	Kodeni industrial zone, Burkina Faso.	38 groundwater samples in the dry season 2017	<ul style="list-style-type: none"> Hydrogeochemical plots (Piper and Durov) Hydrochemical indices (Saturation indices and partial CO₂ pressure) Statistical analyses (correlation coefficients and factor and principal component analysis) Global Mapper 20.0 and MINEQL+ chemical equilibrium modeling software 	<ul style="list-style-type: none"> Because of the short residence time of the groundwater and already advanced weathering stage of the aquifer materials, the aquifer is vulnerable to anthropogenic activities. Glauconite weathering during water–rock interactions within the aquifer contributed to Ca²⁺, Mg²⁺ and SO₄²⁻ loadings into the groundwater.
Wang et al. (2020)	Guizhou province, southwest China	25 Groundwater samples between 2008 and 2012	<ul style="list-style-type: none"> Hydrogeochemical analysis by fuzzy Comprehensive Evaluation Method 	<ul style="list-style-type: none"> The geochemical characteristics and the trilinear piper diagram of groundwater proved that the waters can be considered as calcium bicarbonate water and can be considered as good or excellent quality for drinking.
Gao et al. (2020)	Jinan spring, Shandong province, China	80 groundwater samples from March 2015 to July 2018	<ul style="list-style-type: none"> Hydrochemical plots (Piper diagram and Durov diagram) Statistical analysis (correlation analysis, and principal component analysis) Hydrochemical ratio and indices (saturation index) Phreeqc software 	<ul style="list-style-type: none"> The hydrochemistry of spring water is mainly controlled by the dissolution of calcite, dolomite, and gypsum, as well as the occurrence of dedolomitization in the study area. The quality of spring water is affected by anthropogenic inputs.
Davraz and Batur (2021)	Yalvaç–Gelendost Aquifer, Turkey	23 water samples were gathered from drinking water resources (spring, well) in October-2019 and July-2017	<ul style="list-style-type: none"> Hydrogeochemical analyses Hazard health risk index AquaChem 2014.2 software 	<ul style="list-style-type: none"> The main factor controlling groundwater chemistry in the study area is rock–water interaction. The dominant water type is Ca–Mg–HCO₃ in the basin.
Hoaghia et al. (2021)	14 karst water sources, northwestern Romania	14 water samples from springs from October 2019 to August 2020	<ul style="list-style-type: none"> Groundwater quality index Hydrochemical plots (Piper and Durov diagrams) XLStat software 	<ul style="list-style-type: none"> Limestone and dolostone are the main Ca and Mg sources, while halite is the main Na and Cl source. The studied karst waters is influenced mainly by the water–rock interaction and, to a more limited extent, by anthropogenic activities.
<u>Vrouhakis</u> et al. (2021)	Pinius Basin, central Greece.	153 groundwater samples and 21 surface water samples between September 2016 and April 2018	<ul style="list-style-type: none"> Hydrogeochemical plots and Multivariate statistics 	<ul style="list-style-type: none"> The progressive evolution of groundwater was further verified by the variation of the saturation indices of critical minerals. In addition, the combined use of water level measurements delineated the major pathways of groundwater flow.
<u>Tang</u> et al. (2021)	Niangziguan spring, Hebei Province, China	52 groundwater samples during 23–24 June 2014	<ul style="list-style-type: none"> Hydrochemical plots (piper diagram) Hydrochemical ratios Stable isotopes 	<ul style="list-style-type: none"> The Na⁺ in karst groundwater in the Niangziguan spring are mainly sourced from urban sewage and coal mine drainage. The hydrochemical characteristics of the area were mainly affected by dedolomitization, the dissolution of dolomite, salt, rock and gypsum.

In the following sections the study karst springs and their hydrochemical properties are presented, at the first, then, the Manging's approaches are given to analyze the recession curves of spring discharge and classification of the attributed aquifers; the statistical indices developed to show the relationship of precipitation-spring discharge data is reviewed; successively, the hydrochemical indices that used for the classification of spring water quality are given, and the finally, the obtained results from different parts are illustrated and discussed.

2. Materials and Methods

2.1. Study Area

The Zagros region with an NW – SE trend is located in the middle of the Orogenic Belt of Alpine–Himalayan (Agard et al. 2005) and extends from northern Iraq through west of Iran to the Oman (Homke et al. 2010). The Zagros orogenic belt consists of three parallel tectonic zones: 1) the Urumieh-Dokhtar Magmatic Assemblage which is known as Tertiary magmatic arc (Saccani et al. 2013); 2) the Sanandaj-Sirjan Zone which is composed of Mesozoic and rarely Paleozoic rocks (Horton et al. 2008); and 3) the Zagros Simply Folded and Thrust Belt which is a result of deformation of the Zagros Orogenic Belt passive margin sediments (Alavi 1994). The belt is located at the northeastern edge of the Arabian platform and contains a folded sequence of Phanerozoic sediment with a thickness of 10 km (Stocklin 1968). Which is divided into two distinct structural parts, one is the high Zagros Thrust belt (fracture zone) and the other is the folded belt, which are separated by a long Zagros fault (Falcon 1969).

Lorestan province is one of the western provinces of Iran. It has a temperate and mountainous climate with an average annual precipitation of 550 mm, which starts in early autumn and continues until late spring, and during the whole summer, the amount of precipitation reaches almost zero. The province has an area of about 28,294 km², which is located between 46 degrees and 51 minutes to 50 degrees and 22 minutes north latitude (Fig. 1). Oshtorankoo with 4,150 meters in height is the highest point of Lorestan and the lowest point is located in the southernmost region of the province and its height is 500 meters above sea level. Lorestan is located in the middle part of the Zagros, most of which is folded in the Zagros, the general trend of which is in parallel with the Thrust zone and is northwest-southeast. The other part of Lorestan is located in the high or Thrust Zagros. This zone, with a width of 10 to 65 km, is a narrow strip that forms the highest part of the Zagros Mountains and for this reason, it is sometimes referred to as the High Zagros. Also, a part of the eastern part of Lorestan is located in the Sanandaj-Sirjan zone, which includes from the

north of Boroujerd to the south of Doroud. This region is one of the most dynamic tectonic zones in Iran. Most of the studied springs are located in the Thrust Zagros belt, a smaller part in the folded Zagros and a few of them in Sanandaj-Sirjan zone. These springs are located in Dez and Karkheh sub-basins in the Great Karoun basin (Fig. 1). Most of the exposed rocks of Sanandaj-Sirjan zone in Lorestan province are sedimentary rocks, magmatic (Ghorbani 2019). Jurassic rocks belonging to the Thrust Zagros in Lorestan province represent two different facies. Limestone, dolomite and silty shales of Neyriz Formation have been left in shallow environments with the tidal environment and hard and dense limestone of Surmeh Formation. In the folded Zagros zone, between the folded areas, the bolson plains are formed as lowlands covered with Quaternary alluvium. Limestone units of Sarvak and Asmari Formations have been dissolved due to infiltrated acidic surface waters and while developing karst regimes, they contain many dissolution cavities (Fig. 2).

2.2. Data Set

Hydrochemical data and hydrographs of karst springs of Lorestan province and precipitation of climatological stations related to these springs were provided by the Regional Water Company of Lorestan and Iran's Water Resources Management Company. Then, among these karst springs, 42 springs due to the length of the common statistical period (from 1988 to 2017) were selected for quantitative and qualitative analyzes. To describe the quantitative parameters of spring discharge, the most important indicators of spring variability are based on the data of spring time series (Table 2). A 1:100,000-scale geological map prepared by Iran's Geological Survey was used to obtain lithological information of the study area (Fig. 2). Also, to create an ombrothermic diagram of the study area, precipitation, temperature and geographical data of 20 climatological stations in a 49-year statistical period from 1969 to 2018 that were collected from the Regional Water Company of Lorestan. For this purpose, the gradient method (correlation between elevation with precipitation and elevation with temperature) was used. According to the diagram (Fig. 3), February with -0.09 °C has the minimum temperature and July with 25.95 °C has the maximum temperature. The dry season starts in mid-May in the region and lasts until mid-October.

2.3 Hydro-Chemical Characteristics of Study Springs

Estimation of spring's discharge variability is important for potential utilization of spring water and regional hydrogeological processes of the associate aquifers (Stevanovic 2015). The ratio of $Q_{\max}/Q_{\min}$ can be considered as a stability measure of spring discharge and known as the index of variability I_v (Slovak technical standard SÚTN 2009). That according to preliminary calculations based on quantitative discharge data, the highest average annual discharge with 893.76 L/S is related to Robat spring and the lowest average annual discharge is related to Sabour, Gousheh and Reftkhan springs equal to 26 L/S. The highest and lowest standard deviations are related to Zoz springs (935.81) and Gousheh (13.19), respectively. Index of variability I_v is the simplest measure of spring's discharge variability is the ratio of maximal and minimal recorded discharge ($Q_{\max}/Q_{\min}$) (Kresic 2007), Springs with high discharge variability show quick response of the karst system to recharge and thus, a high degree of transport process of flow within the aquifer (Stevanovic 2015). The value of this index for these 42 springs varies between 7 (for Toudehzan, Honam and Amir springs) to 997 (for Zoz spring). The coefficient of spring discharge variability is based on the ratio of discharges with 10 % to 90 % exceedance; and the spring coefficient of variation parameter can be calculated from the standard deviation and average of spring discharge (Springer et al. 2004). The highest calculated SVC value is equal to 147.57 related to Zoz spring and the lowest value equal to 2 is related to Amir spring. And the maximum and minimum SCVP values calculated are equal to 1.53 for Darehsaki spring and 0.27 for Amir spring, respectively.

Also, the most important quality parameters calculated for these springs include Total dissolved solids (TDS), The highest value of this parameter is equal to 407.3 mg/l related to Daryab spring and the lowest value equal to 234.2 mg/l is related to Golombahri spring; Sodium Adsorption Ratio (SAR), The value of this parameter varies between 0.05 mg/l (for Daryab spring) to 0.60 mg/l (for Sarnamak spring).

Table 2. Descriptive statistics of the measured parameters in the studied karst springs.

Spring ID	Spring Name	UTM		Lithology name	$\bar{Q}_{\text{Average}}$ (L/S)	Q_{STDEV} (L/S)	I_v (L/S)	SVC (L/S)	SCVP (L/S)	TDS (mg/l)	SAR (mg/l)
		X	Y								
1	Motahari	255162	3708105	Q	513.76	483.32	506	19.24	0.94	330.8	0.251
2	Golestan	254803	3707248	Q	527.18	289.94	32	4.13	0.55	327.7	0.276
3	Doure	223605	3717543	Q+Eo as	193.03	223.82	313	33.60	1.16	317.9	0.183
4	Changae	246570	3706715	Q	392.10	170.17	9	3.10	0.43	325.7	0.150
5	Robat	250085	3726025	M	893.76	749.72	28	5.78	0.84	306.8	0.195
6	Goushe	246680	3697502	Eo as	21.46	13.19	33	3.50	0.61	378.9	0.260
7	Reftkhan	209556	3731321	Kn	21.66	28.46	98	7.83	1.31	304.7	0.194
8	Sarnamak	269508	3715559	K I	58.95	70.06	51	6.00	1.19	241.1	0.058
9	Darae	250085	3726025	Q	294.11	178.93	19	4.50	0.61	307.5	0.496
10	Nawekash	232428	3713793	Qc2	683.37	438.82	21	6.26	0.64	369.9	0.265
11	Sabour	244039	3698642	Eo as	21.66	28.46	98	7.83	1.31	355.4	0.195
12	Golomsabz	332150	3705239	Q+OMI	492.26	716.72	367	20.28	1.46	262.1	0.110

13	Shirkhan	332933	3701215	OMI	209.62	298.98	211	11.12	1.43	264.4	0.136
14	Zaghe	285825	3708587	Qc1	143.49	214.69	166	14.64	1.50	279.8	0.117
15	Bidhel	268298	3731745	Q	261.66	282.26	478	16.47	1.08	249.6	0.127
16	Darehsaki	276953	3716843	K I	141.64	216.73	246	8.14	1.53	253.2	0.068
17	Darab	271320	3720263	K I	128.43	171.90	171	13.46	1.34	259.8	0.128
18	Mosivandi	269921	3725841	K I	178.32	265.26	138	14.03	1.49	243.3	0.101
19	Zoz	252818	3749961	Q	690.31	935.81	977	147.57	1.36	275.0	0.133
20	Honam	251101	3744030	EI	427.03	183.40	7	3.27	0.43	290.4	0.088
21	Amir	246910	3753032	Q	473.71	128.29	7	2.00	0.27	333.5	0.436
22	Chenareh	243697	3746392	Q	270.86	128.03	38	2.49	0.47	296.5	0.104
23	Papi	247787	3747171	Q	83.23	66.22	114	9.30	0.80	292.3	0.077
24	Cheshmeh Barghi	249060	3751380	Q	28.10	19.85	112	7.00	0.71	275.3	0.155
25	Laghari	226562	3764220	Qt	320.67	414.09	208	8.95	1.29	272.7	0.074
26	Abdolhosseini	235114	3771595	KI 2	188.53	117.86	39	4.25	0.63	262.1	0.134
27	Niyaz	239988	3767879	Qal	295.60	141.40	13	3.84	0.48	277.6	0.141
28	Teymour	225588	3782182	Qal+K I2	193.38	114.64	25	4.86	0.59	279.9	0.101
29	Golombahri	224116	3781332	Qal	229.97	173.89	53	7.02	0.76	234.2	0.067
30	Saliyaneh	230412	3772075	QpI	27.00	24.12	135	11.20	0.89	280.8	0.119
31	Darband	372964	3694980	Qt2	351.65	228.22	409	6.18	0.65	243.0	0.061
32	Toudehzan	278033	3760402	Qt	160.08	80.00	7	2.92	0.50	263.1	0.274
33	Kertil	275877	3760574	M	465.58	165.23	15	2.30	0.35	297.5	0.142
34	Karbalae Vali	288157	3747016	P	197.55	95.20	36	4.95	0.48	276.0	0.186
35	Neyze	288157	3747041	P	129.54	69.55	48	6.58	0.54	291.3	0.258
36	Kiyoureh	289234	3744118	Jk	223.88	135.09	24	7.92	0.60	279.0	0.151
37	Bouryabaf	289823	3742302	Jk	86.04	70.88	35	18.91	0.82	276.2	0.174
38	Golomsouz	279601	3742711	Qc1+JKr	389.85	311.74	42	9.99	0.80	262.1	0.110
39	Safarali	290847	3731204	E I	190.06	110.45	88	6.38	0.58	308.2	0.270
40	Azizabad	346671	3703494	Q	243.15	248.60	131	27.55	1.02	363.3	0.403
41	Daryab	350151	3726058	Jph	366.70	220.19	61	6.20	0.60	407.3	0.609
42	Absardeh	287427	3742270	Jk	362.63	366.31	59	18.43	1.01	312.1	0.213

$\bar{Q}_{Average}$: Arithmetical mean of spring discharge values, Q_{STDEV} : Standard deviation of spring discharge values,
 I_v : Index of variability, SVC: Spring variability coefficient, SCVP: Spring coefficient of variation parameter, TDS: Total dissolved solids, SAR:
Sodium Adsorption Ratio, GQI_{mix} : Mixed groundwater quality index, GQI_{dom} : Domestic groundwater quality index.

2.4 Recession Analysis of Spring Discharge Using Mangin's Approach

Mangin (1975) indicated that the karst spring discharge at time t , $Q(t)$ during recession can be defined as

$$Q(t) = q^f(t) + q^b(t) \quad (3)$$

where $q^f (m^3/s)$ is infiltration (fast) flow function which reflects the effect of surface recharge through the unsaturated zone of karst setting, maybe it passages through the saturated zone, $q^b (m^3/s)$ is base flow function. Mangin (1975) used an empirical expression of q^f as the following homographic function:

$$q^f(t) = q_o^f \times y(t) ; y(t) = \frac{(1 - \eta \cdot t)}{(1 + \varepsilon \cdot t)} \quad (4)$$

where q_o^f (m^3/s) is the initial infiltration (fast) flow rate, ε (day^{-1}) is the flow heterogeneity factor and η (day^{-1}) is the infiltration velocity. The q_o^f is computed by the difference between the total discharge Q_0 at t_0 (start of recession) and q_0^b the extrapolated value of initial discharge of the phreatic zone at t_0 . The parameter of ε controls the concavity of the infiltration part of recession curve and allows to estimate moderating capacity of the unsaturated zone upon infiltration. $\varepsilon > 1$ indicates that fast infiltration flow is dominant during recession (Padilla et al. 1994). For the karst aquifers that carbonate rocks cover with sediments or snow, the parameters of η and ε being small (<0.1) and leads to a slow or delayed infiltration rate. The function of $q^f(t)$ is defined during fast flow ($t = 0 \rightarrow t_i$). The function of $y(t)$ varies between 0 (for $t = t_i$) and 1 (for $t = 0$).

Maillet's expression of q^b is usually used as the following exponential form (Manging 1975):

$$q^b(t) = q_o^b \times e^{-\alpha_b \cdot t} \quad (5)$$

where q_o^b (m^3/s) is initial spring discharge of the baseflow (phreatic zone) at t_0 (start of recession), α_b (day^{-1}) is baseflow recession coefficient. The initial volume of stored water, available for draining during the base flow period (V_0^b in m^3) can be computed by integrating the baseflow function (Eq. 5) from the start of recession (t_0) (Marsaud 1997):

$$V_0^b = 86400 \times \frac{q_o^b}{\alpha_b} \quad (6)$$

Where 86,400 is used for conversion of unit ($day \rightarrow sec$). Likewise, the volume of initial quantity of stored water, available for discharge during the fast (infiltrated) flow period (V_0^f in m^3) can be calculated by integration of homographic function of Eq. 4 respect to time from $t_0 \rightarrow t_i$:

$$V_0^f = \frac{q_o^b}{\varepsilon} \times \left[\ln(1 + \varepsilon \cdot t_i) \times \left(1 + \frac{\eta}{\varepsilon} \right) - 1 \right] \quad (7)$$

Thus, total initial volume drained during recession period (V_0^t) is calculated by $V_0^t = V_0^f + V_0^b$. The V_0^t also known as dynamic volume of the aquifer (V_d), the volume drainable by gravity toward the spring outlet at the beginning of recession, t_0 .

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2.4.1 Manging's Method for Classification of Karst Aquifers

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Mangin (1975) considered two indices in the classification of karst systems: i) regulating power of the phreatic zone of the aquifer (k), and ii) infiltration delay (i) which characterizing the phreatic zone extent and infiltration conditions, respectively, as follow:

$$k = \frac{V_d}{V_t} \quad (8)$$

V_d (Eq. 6) is usually calculated for each recession, separately; then, the maximum value of obtained V_d during long time-series is considered in Eq. 8 to calculate the parameter k .

In the Eq. 8, V_t (m^3/yr) is the average annual volume of water flowing through the phreatic zone. Index of k equivalent to the mean water residence time of infiltrated flow within saturated zone of aquifer, t_r (yr). For the karst aquifers the k is lower than 0.5 (i.e. mean residence time of aquifer is 6 months), while $k < 0.5$ for porous and fractured aquifers (Marsaud 1997). However, the greater value of k (up to 2) are also reported in the Middle East (e.g. El-Hakim and Bakalowicz 2007).

Mangin (1975) proposed the value of infiltration delay (i.e. parameter i) equal to the value of $y(t)$ function in Eq. 4, at $t=2$. For the karst aquifers with a slow or delayed infiltration, the value of i has a tendency towards unit ($i \rightarrow 1$), whereas for the aquifers with fast infiltration $i \rightarrow 0$. According to the i and k values calculated from various karst systems across Europe, Mangin (1975) defined five fields (Fig. 4). These zones are the following (El-Hakim and Bakalowicz 2007): zone I ($k < 0.5$ and $i > 0.5$): domain of complex karst systems consist of several sub-systems; zone II ($k < 0.5$ and $0.25 < i < 0.5$): domain of conduit karst system which well developed in the upper part of phreatic zone, and characterized by a slow infiltration due to either coverage by sediment or snow layer, or non-karstic terrains; zone III ($k < 0.1$ and $0 < i < 0.25$): highly karstified systems in both infiltration and phreatic parts; zone IV ($0.1 < k < 0.5$ and $0.1 < i < 0.25$): systems with a well-karstified upper zone, a flooded phreatic zone with an extended conduit network; and zone V ($k > 0.5$): porous and fissured aquifers.

2.4.2 Relationships of Precipitation and Discharge Data

Karst spring hydrograph reflects the accumulated amount of infiltrated precipitation into the karst terrain during the previous time-steps (Fiorillo 2009). The meteorological drought on the karst area caused by either low rainfall, or short rainy season, or increasing temperature will drop the spring discharge known as hydrological drought (Tallaksen and

Van Lanen 2004). In this study, the time-series of karst spring discharge have been considered to evaluating the temporal trends of spring discharge and rainfall variations.

The standardized value of annual precipitation (P_s) is calculated from the precipitation value (P_i) using the following equation:

$$P_s = \frac{P_i - \bar{P}}{S_p} \quad (9)$$

with $\bar{P}$ and S_p are the average and the standard deviation of the annual rainfall data, respectively. Similarly, the annual mean values of the spring discharges (Q_i) have been standardized (Q_s) by the following equation:

$$Q_s = \frac{Q_i - \bar{Q}}{S_Q} \quad (10)$$

with $\bar{Q}$ and S_Q are the average and the standard deviation of the discharge data series, respectively. To highlight the trend in the time series of P_s and Q_s , the rescaled adjusted partial sums (*RAPS*) introduced by Garbrecht and Fernandez (1994) have been used. The *RAPS* of time series P_s and Q_s ($RAPS_p$ and $RAPS_Q$) is defined as:

$$RAPS_p(k) = \sum_{t=1}^{k \leq n} \frac{P_t - \bar{P}}{S_p} \quad (11)$$

$$RAPS_Q(k) = \sum_{t=1}^{k \leq n} \frac{Q_t - \bar{Q}}{S_Q} \quad (12)$$

where n is the number of data in the series, k is the counter limit of the current summation. Any decreasing (increasing) trend in the $RAPS_p$ or $RAPS_Q$ is the result of below-average (above-average) values of P_s or Q_s , respectively.

2.5 Hydrochemical Analyses of Springs Data

2.5.1 Groundwater Quality Index (GQI)

Mixed groundwater quality index (GQI_{mix}), Domestic groundwater quality index (GQI_{dom}). Groundwater quality indices developed by Tomaszewicz et al. (2014) are considered in this study to combine hydrochemical data of various ions:

$$GQI_{\text{mix}} = \left[\frac{Ca^{2+} + Mg^{2+}}{TC} + \frac{HCO_3^-}{TA} \right] \times 50 \quad (13)$$

$$GQI_{\text{dom}} = \left[\frac{Na^+ + K^+}{TC} + \frac{HCO_3^-}{TA} \right] \times 50 \quad (14)$$

Where TC and TA are concentrations of total cations and anions in spring water, respectively. The concentrations of ions in Eqs. (1) and (2) are *meq/l*. The lower and upper limits of GQI_{mix} and GQI_{dom} are 0 (representing saline water and Ca - Cl water type, respectively) and 100 (representing fresh water and Na- HCO_3 water type, respectively).

2.5.2 Chloro-Alkaline Indices (CAI)

The alkaline-chlorine indices show the chemical reactions occurs between groundwater and the aquifer materials through the period of residence or movement of water in karst aquifer (Raju et al. 2011). Schöeller (1962) developed Chloro-Alkaline Indices (CAI) to identify the ion-exchange between groundwater and its surroundings materials as follows:

$$I_1 = \frac{[Cl - (Na + K)]}{Cl} \quad (15)$$

$$I_2 = \frac{[Cl - (Na + K)]}{SO_4} + HCO_3 + CO_3 + NO_3 \quad (16)$$

Depending on the exchange of magnesium and calcium in the water with sodium and potassium in the rock, the CAI can be positive or negative (Kumar et al. 2014; Reyes-Toscano et al. 2020). A positive (negative) value of CAI indicates that the origin of bicarbonate ions in water is the weathering of silicate minerals (carbonate minerals or from human activities) (Chidambaram et al. 2011).

2.5.3 Water Typology

The Piper (Piper 1994), Gibbs (Hoaghia et al. 2021), and Durov (Durov, 1948) diagrams were used to assess the spring water typology. The Piper diagram is a ternary plot of major anions (Cl^- , $CO_3^{2-} + HCO_3^-$, SO_4^{2-}) and cations (Ca^{2+} , Mg^{2+} , $Na^+ + K^+$) and representing information on the relationship between the water composition and rock types (Ghobadi et al. 2018). The Durov diagram is a composite plot of the same major cations and anions on two ternary diagrams, reveals the geochemical processes that affect the groundwater (Hoaghia et al. 2021). The Gibbs diagram and the scatterplots showing the relationship between the major ions were represented using. In this study, the AqQA-software was used to depict the Piper and Durov, and MS Excel (version 2016) was used to depict the Gibbs diagram.

3. Results and Discussion

3.1 Recession analysis of hydrographs

While two flow components during recession (infiltration and base flow) are observed for the most of the studied springs (76%), there is no fast flow (only base flow) during recession of 10 springs (24% of total). Therefore, for the last springs the calculation of the aquifer characteristics (given in Tables 3 and 4) are computed only by Maillet's analysis (Eqs. 3 and 4) which is valid for the base flow. The absence of fast-flow component in 10 springs indicates that the water filters slowly in the associated aquifers, maybe due to poorly developed network of channels in the upper zone (unsaturated zone).

The results given in Table 4 let us to conclude that the limestone aquifers located in Lorestan Province have dominant baseflow storage (between 80.0% to 100% of total storage), while during the period of fast-flow only small quantity of total dynamic water is drained (between 0.0% to 21%). The base flow discharge lasts 3.0 to 8.83 months (on average 5.06 months). While the duration of the fast (infiltration) flow is averagely less than 2.0 months (Table 4). These findings reveal that the saturated zone of the studied aquifers provides the prominent influence on the flow of springs. The speed of flow drainage (fast and base flow) by the studied springs quantified by the recession coefficients (α_f and α_b). While the values of α_f for the studied springs relies in the range of 0.11 day^{-1} to 1.72 day^{-1} (on average 0.55 day^{-1}), the base flow discharged in much lower slope as 0.006 to 0.73 day^{-1} (0.17 day^{-1}).

Based these results, existence of a network of karstic conduits for the springs (for almost 60% of springs with a fast flow recession coefficient greater than 0.50 day^{-1}), is responsible for higher values of the recession coefficients and indicates a rapid drainage reaction through these networks.

Properties of the infiltration (fast) flow and baseflow of the study karst systems are given in Table 3. The dynamic storage of the study karst systems is in the range of 0.01 to $1.23 \times 10^6 \text{ m}^3$. The average residence time of groundwater in the phreatic zone of the study karst aquifers (i.e. k index) are in the range of 0.01 yr ($<4 \text{ day}$) to 2.01 yr (on average 0.41 yr , ~ 5 months). The maximum value of k index is obtained for the spring #1 with the highest discharge ($\sim 6272 \text{ lit/s}$). Karst aquifers with large storage volumes in the phreatic zone, responsible for high value of residence times ($k > 1 \text{ yr}$). The index i relies in the range of 0.45 and 0.92 (on average 0.67) and means that slow infiltration in these aquifers is predominant. The long delay in infiltration may be due to snow coverage of karst surface. The carbonate karst aquifers in Lorestan province as representative of carbonate aquifers in the Zagros Mountain, display large

regulating power as shown by the indices of k and i in Table 3. These aquifers contain in their phreatic zones frequent karst features, developed in relation with the rising of the karst drainage base level, due to either the formation of basins subsiding since the Neogene in a continental environment.

3.2 Classification of karstification degree of aquifers

According to the Mangin (1975) classification based on indices of k and i , three groups of springs may be considered (Fig. 5): $k < 0.5$, $0.25 < i < 0.5$ (zone II): including one spring (#16) that displays a fairly low value of residence time ($k = 0.053 \text{ yr} \sim 20 \text{ days}$). It discharges groundwater from Sarvak and Asmari lime formations of Lorestan Province. $k < 0.5$, $i > 0.5$ (zone I): this group brings together 33 springs (78.5%), which mainly emerging from Carbonate rocks in hard and dense Jurassic limestones, Neyriz and Surmeh formations of Lorestan with average residence time of $k = 0.22 \text{ yr}$ ($\sim 80 \text{ days}$). $k > 0.5 \text{ yr}$ (zone V): including eight springs ($\sim 20\%$), characterized as karst systems with a deep phreatic zone, restricted by impervious sediments, and largely developed during previous karstification periods which is also named “non-functional karst systems” (Marsaud 1997). These karst systems have a complex drainage structure responsible for very long residence times. However, the paleo-conduit networks developed in their phreatic zone remain relatively active to reduce the residence time.

By classification of the study karst systems based on indices of k and i obtained from the recession analysis based on Mangin (1975), it was found that the i index for almost all springs was more than 0.5 and indicates a lag in the filtration rate to saturated zone due to the snow regime in the area, and also the value of the k index for springs that is greater than 0.5, most of them include springs located in the west and southwest of the study area, places where the grade of lime is reduced and the marl and shale interlayered in the lithology of the region has been exposure (such as the Gurpi Formation) and the degree of development of these karst systems has decreased.

The classification of the studied springs based on the average value of α_b coefficient for each spring (values given in Table 3) is performed and shown in Fig. 6. The results revealed that 27% of the springs with a coefficient α_b of between 0.2 and 0.6 are located in the central areas of the study area. These springs have the highest degree of karstification (between 7 and 8), formed by large open faults and conduits. For such karst systems, the transmission of significant part of groundwater is mainly via preferred pathways of conduits. Moreover, discharge regime of these springs is a combination of one exponential flow component and two or more linear flow component.

Table 3 Summary of the main parameters characterizing the infiltration (fast flow) and baseflow of the study karst systems. Each value is obtained based on analysis of more than 12 recession curves for each karst spring*.

Spring ID	Infiltration Flow (Fast Flow)					Base Flow				
	α_f (day ⁻¹)	q_o^f (lit/s)	η (day ⁻¹)	ε (day ⁻¹)	i index (-)	q_o^b (lit/s)	α_b (day ⁻¹)	V_d (MCM)	V_t (MCM)	k index (yr ⁻¹)
1	0.53	2123.39	0.096	0.174	0.600	429.95	0.13	0.28	1.33	0.21
2	0.29	782.02	0.021	0.197	0.687	405.61	0.05	0.64	1.37	0.47
3	0.60	867.96	0.077	0.246	0.566	150.17	0.12	0.11	0.50	0.22
4	0.50	649.81	0.077	0.098	0.708	371.22	0.09	0.34	1.02	0.34
5	0.36	2,735.38	0.062	0.140	0.684	799.78	0.07	0.95	2.40	0.40
6	-	-	0.086	0.050	0.753	45.94	0.10	0.02	1.52	0.01
7	0.48	149.70	0.102	0.114	0.647	16.62	0.11	0.01	0.06	0.23
8	0.89	777.76	0.103	0.235	0.539	42.47	0.23	0.04	0.06	0.66
9	0.28	554.95	0.067	0.092	0.731	256.20	0.08	0.27	0.15	1.74
10	0.35	1,003.16	0.031	0.094	0.789	713.30	0.05	1.24	0.76	1.62
11	0.38	76.66	0.111	0.052	0.705	18.17	0.15	0.01	1.77	0.01
12	0.75	4,501.00	0.146	0.217	0.493	175.77	0.21	0.07	0.06	1.28
13	0.65	1,784.88	0.119	0.217	0.532	114.33	0.16	0.06	1.28	0.05
14	0.75	1,612.03	0.125	0.239	0.507	84.77	0.22	0.03	0.54	0.06
15	0.88	3,828.70	0.131	0.186	0.539	240.16	0.35	0.06	0.37	0.16
16	0.89	2,118.67	0.127	0.326	0.451	92.22	0.22	0.04	0.68	0.05
17	0.69	1,176.55	0.136	0.199	0.521	69.18	0.26	0.02	0.37	0.06
18	0.87	2,045.08	0.128	0.215	0.520	70.99	0.21	0.03	0.33	0.10
19	-	-	0.135	0.121	0.588	6,272.27	0.58	0.93	0.46	2.01
20	-	-	0.061	0.026	0.836	834.13	0.14	0.51	1.79	0.28
21	-	-	0.027	0.016	0.916	682.87	0.07	0.82	1.11	0.74
22	-	-	0.069	0.024	0.823	455.94	0.18	0.22	1.23	0.18
23	-	-	0.098	0.013	0.784	211.48	0.20	0.09	0.70	0.13
24	-	-	0.042	0.073	0.799	66.07	0.18	0.03	0.22	0.15
25	0.57	2,733.75	0.096	0.116	0.656	214.61	0.20	0.09	0.07	1.29
26	0.33	414.34	0.071	0.138	0.672	175.21	0.09	0.17	0.83	0.21
27	-	-	0.054	0.223	0.618	622.91	0.15	0.36	0.49	0.74
28	0.34	401.52	0.106	0.055	0.710	157.78	0.12	0.11	0.77	0.15
29	0.55	910.24	0.065	0.176	0.643	216.05	0.12	0.15	0.50	0.31
30	0.51	98.12	0.106	0.100	0.657	20.53	0.15	0.01	0.60	0.02
31	0.54	489.93	0.084	0.200	0.595	132.34	0.32	0.04	0.91	0.04
32	0.49	328.02	0.074	0.110	0.699	151.23	0.12	0.11	0.41	0.27
33	0.33	615.39	0.027	0.127	0.755	482.55	0.08	0.54	1.21	0.45
34	-	-	0.066	0.043	0.799	289.79	0.14	0.18	0.51	0.35
35	0.26	178.15	0.059	0.096	0.740	168.26	0.12	0.12	0.34	0.36
36	0.49	323.10	0.052	0.168	0.670	175.78	0.10	0.15	0.58	0.27
37	0.37	154.04	0.066	0.134	0.685	72.51	0.10	0.07	0.22	0.29
38	0.48	1,546.73	0.095	0.117	0.656	436.37	0.14	0.28	1.01	0.27
39	-	-	0.095	0.011	0.792	432.23	0.22	0.17	0.49	0.35
40	0.60	1,570.06	0.131	0.154	0.564	236.69	0.30	0.07	0.63	0.11
41	0.32	449.02	0.087	0.071	0.723	358.11	0.13	0.25	0.95	0.26
42	0.46	2,172.08	0.079	0.161	0.637	592.41	0.13	0.38	0.94	0.41

* Karst systems of # 6, 19-24, 27, 34, and 39 have single flow regime (i.e. base flow) during recession.

Table 4 Values of the initial volume of stored fast flow (V_0^f) and base flow (V_0^b). Each value is obtained based on more than 12 recession curves for each karst spring.

Spring ID	Infiltration (fast) flow			Base flow		
	V_0^f (MCM)	V_0^f (%)	D_f (month)	V_0^b (MCM)	V_0^b (%)	D_b (month)
1	1.92	15.84	3.44	10.20	84.16	5.72
2	1.65	14.97	3.14	9.38	85.03	5.79
3	0.54	14.09	2.78	3.30	85.91	5.72
4	0.48	11.12	1.00	3.85	88.88	3.00
5	3.11	15.26	3.00	17.27	84.74	5.33
6	0.00	0.00	0	0.66	100.00	5.65
7	0.11	15.94	5.00	0.57	84.06	8.83
8	0.13	12.74	2.40	0.90	87.26	5.90
9	1.14	18.62	3.43	4.97	81.38	4.07
10	1.85	14.64	2.00	10.78	85.36	3.83
11	0.06	16.71	2.67	0.31	83.29	4.17
12	0.63	16.00	2.75	3.29	84.00	4.50
13	0.46	16.45	3.11	2.34	83.55	4.83
14	0.32	15.83	2.92	1.70	84.17	4.92
15	0.78	14.35	2.50	4.64	85.65	5.00
16	0.32	14.09	2.71	1.98	85.91	5.64
17	0.25	15.65	2.83	1.37	84.35	4.92
18	0.21	14.69	2.33	1.25	85.31	4.50
19	0.0	0.0	0.0	121.89	100.00	7.50
20	0.0	0.0	0.0	14.48	100.00	6.70
21	0.0	0.0	0.0	11.11	100.00	6.28
22	0.0	0.0	0.0	6.49	100.00	5.50
23	0.0	0.0	0.0	3.01	100.00	5.50
24	0.0	0.0	0.0	1.12	100.00	6.63
25	0.73	15.57	2.62	3.95	84.43	4.50
26	0.54	14.84	2.40	3.13	85.16	4.50
27	0.00	0.00	0.0	8.71	100.00	5.40
28	0.72	21.00	3.50	2.69	79.00	3.10
29	0.73	14.63	2.60	4.25	85.37	5.00
30	0.09	18.80	3.20	0.37	81.20	3.90
31	0.43	16.24	2.50	2.21	83.76	4.00
32	0.29	12.02	1.50	2.15	87.98	4.00
33	1.38	13.10	2.20	9.13	86.90	5.10
34	0.00	0.00	0.0	4.50	100.00	6.00
35	0.44	11.79	2.00	3.26	88.21	5.50
36	0.32	11.68	1.40	2.41	88.32	3.90
37	0.23	15.25	2.40	1.25	84.75	4.30
38	1.24	16.68	2.20	6.22	83.32	3.30
39	0.0	0.0	0.0	6.94	100.00	6.20
40	0.85	16.51	2.78	4.31	83.49	4.28
41	1.24	16.68	2.67	6.18	83.32	4.00
42	1.79	13.47	2.33	11.51	86.53	5.17

3.3 Precipitation-discharge relationships

The time series of RAPS for the average annual spring discharge (Fig. 7a) which described by successive values of Q_s above or below (high-flow and low-flow period, respectively) the average. The lowest values of 1999 and 2014, show the most severe droughts, as well as other droughts of 1993, 1997 and the recent period 2007–2008. After 1998 all the series evidently show a decline in discharge values, which is interrupted only during 2007 and 2009. Thus, there are two periods of discharge peak for all springs, one from 1993 to 1997 and the other period is 2005 and 2006. According to the RAPS of the annual rainfall (Fig. 7b), this increase in discharge is due to increased rainfall in these periods. This characteristic is observed in all the series. Recent long-negative trend of the RAPS is present in all spring discharge time series.

RAPS of the annual rainfall (Fig. 7b) present similar trends of the spring discharge, showing that the rainfall control the spring discharge. The discharge response to rainfall fluctuations was simultaneous in all springs in the region and did not have a significant lag-time to rainfall fluctuations. Which is due to the development of karst system in these springs.

3.4 Hydrochemical Analyses

The highest calculated value of GQI_{mix} index equal to 90.89 is related to Laghari spring and the lowest value equal to 68.52 is related to Daryab spring. And the maximum and minimum values of GQI_{dom} calculated are equal to 48.62 for Reftkhan spring and 48.62 for Daryab spring, respectively (Table 5). The average value of GQI_{mix} and GQI_{dom} indexes respectively is 85.70 and 41.80 for all springs, according to Table 6: Hydrochemical domains using of GQI_{mix} and GQI_{dom} Piper diagram illustrating general classifications of groundwater types (Tomaszkiewicz et al. 2014), the water quality index of springs is in excellent class. And representing fresh water and $Ca - HCO_3$ water type, respectively.

Table 5. Long-term average values of GQI_{mix} and GQI_{dom} calculated for the study springs.

Spring ID	Spring Name	UTM		GQI_{mix} (-)	GQI_{dom} (-)	Spring ID	Spring Name	UTM		GQI_{mix} (-)	GQI_{dom} (-)
		X	Y					X	Y		
1	Motahari	255162	3708105			22	Chenareh	243697	3746392	80.76	44.10
2	Golestan	254803	3707248	83.96	41.33	23	Papi	247787	3747171	88.85	42.33

3	Doure	223605	3717543	82.51	40.54	24	Cheshmeh Barghi	249060	3751380	90.02	43.75
4	Changaee	246570	3706715	87.00	42.51	25	Laghari	226562	3764220	85.07	40.60
5	Robat	250085	3726025	88.60	42.85	26	Abdolhosseini	235114	3771595	90.89	43.40
6	Goushe	246680	3697502	86.15	42.00	27	Niyaz	239988	3767879	88.34	42.88
7	Reftkhan	209556	3731321	85.38	41.96	28	Teymour	225588	3782182	89.12	43.86
8	Sarnamak	269508	3715559	78.62	48.62	29	Golombahri	224116	3781332	88.80	42.36
9	Daraee	250085	3726025	90.23	42.49	30	Saliyaneh	230412	3772075	89.21	42.12
10	Nawekash	232428	3713793	79.44	44.02	31	Darband	372964	3694980	88.29	42.33
11	Sabour	244039	3698642	85.23	42.43	32	Toudehzan	278033	3760402	90.30	42.94
12	Golomsabz	332150	3705239	86.56	41.55	33	Kertil	275877	3760574	80.81	40.04
13	Shirkhan	332933	3701215	87.87	41.80	34	Karbalaee Vali	288157	3747016	84.24	38.02
14	Zaghe	285825	3708587	86.36	41.27	35	Neyze	288157	3747041	84.74	40.30
15	Bidhel	268298	3731745	88.25	42.23	36	Kiyoureh	289234	3744118	83.27	41.40
16	Darehsaki	276953	3716843	87.88	42.71	37	Bouryabaf	289823	3742302	86.95	41.77
17	Darab	271320	3720263	89.54	42.10	38	Golomsouz	279601	3742711	84.86	40.37
18	Mosivandi	269921	3725841	87.55	42.40	39	Safarali	290847	3731204	87.87	41.80
19	Zoz	252818	3749961	88.52	42.40	40	Azizabad	346671	3703494	79.69	37.84
20	Honam	251101	3744030	86.47	41.26	41	Daryab	350151	3726058	76.66	37.64
21	Amir	246910	3753032	90.07	43.35	42	Absardeh	287427	3742270	68.52	33.37

Table 6. Hydrochemical domains using GQI (mix) and GQI (dom) (Tomaszkiewicz et al. 2014)

Domain	GQI piper (mix)	GQI piper (dom)	Groundwater types
I	50–100	25–75	$Ca - HCO_3$
II	0–50	25–75	$Na - Cl$
III	25–75	50–75	$Ca - Na - HCO_3$
IV	25–75	25–50	$Ca - Mg - Cl$
V	25–75	0–25	$Ca - Cl$
VI	25–75	75–100	$Na - HCO_3$

Generally, the Durov diagram shows that the main hydrochemical processes included in the spring water chemistry is ion exchange, reverse ion exchange, simple dissolution and mixing (Ravikumar et al. 2015). For the studied karst spring waters, the Durov diagram (Fig. 8) shows that the most of waters are alkaline with TDS, approving the influence of limestone lithology on the spring water chemistry through either dissolution or water recharge in limestone. The Piper diagram (Fig. 9) showed that the sum of alkaline earth elements (Ca + Mg) is higher than the sum of alkali elements (Na + K). Similarly, the sum of weak acid radicals ($HCO_3^- + CO_3^{2-}$) is higher than the sum of strong acid radicals ($SO_4^{2-} + Cl^-$). Most of the studied karst water samples have similar Ca-Mg-HCO₃. Type hydrogeochemical facies, confirming that most of the studied springs discharge from a carbonate-type aquifer.

The Gibbs (Gibbs 1970; Lyu et al. 2019) diagram is another tool for evaluating the hydrogeochemical evolution of karst and for identifying the predominant processes of groundwater chemistry. With high values of TDS between 193 and 550 mg /L, and low values of $Na/(Na + Ca)$ or $Cl^-/(Cl^- + HCO_3^-)$ the Gibbs diagram (Fig. 10) suggesting that rock weathering was the main hydrochemical process influencing the chemical composition of the spring waters.

In Fig. 11, all the samples were classified according to the ternary diagram ($Cl^- - HCO_3^- - SO_4^{2-}$) described by Giggenbach (1988). Shows distinct zones of alkaline, volcanic, and nutra chloride water. As shown in Fig. 11, all water samples were located in the alkaline water zone.

The results of CAI indices show that all but two springs (S10 and S28) in this work have positive CAI values. This reveal the ion exchange and a bicarbonate ion source for silicate minerals. However, in these two springs, the origin of bicarbonate ions was carbonate minerals (Fig. 12).

Based on the quantification and qualification analyses performed in this study, the springs were classification and the results are presented in Fig. 13. The results revealed that the springs with the highest degree of karstification are located in the center of the study area and in the Thrust Zagros belt. These springs are located in hard and dense Jurassic limestones (Neyriz and Surmeh formations) and discharge from a carbonate-type aquifer. Their groundwater type is fresh water and Ca-HCO₃ water type.

4. Conclusion

A holistic review on the qualitative and quantitative repeatable methods rely on the discharge and hydrochemical data of springs are presented in this study. The application of the reviewed methods was carried out on the 42 main karst springs in Zagros Mountain region. Results of this study could be summarized as follows:

- Recession analysis of hydrographs reveal that both flow components during recession (infiltration and base flow) are observed for the most of the studied springs (76%), while there is no fast flow (only base flow) during recession of 10 springs (24% of total).
- The Mangin's approach proved that the karstification degree of the Karst system 33 springs (78.5%) have a well-developed system, which mainly emerging from Carbonate rocks in hard and dense Jurassic limestones (Neyriz and Surmeh formations of Lorestan).

- The RAPS pattern is the same for all springs and there are two discharge peak periods for all springs, one from 1993 to 1997 and the other from 2005 and 2006, that according to the RAPS annual rainfall, this increase in discharge was due to the increase in rainfall during these periods, and discharge response of springs did not have a significant lag-time to rainfall fluctuations.
- The Durov and by the Piper diagrams showed that the chemical composition of the spring waters is typical of karst waters as it is dominated by HCO_3 and Ca, and the most of waters are alkaline with TDS between 193 and 550 mg /L. Confirming the influence of limestone lithology on the water composition. The results of CAI indices show that all but two springs in this work have positive CAI values and the groundwater quality index (GQI) representing fresh water and $\text{Ca} - \text{HCO}_3$ water type and are of excellent quality for domestic and agricultural purposes. The results of the present study show the importance of optimal management of excellent-quality karst waters in this part of Zagros Mountain especially during the water scarcity periods.

The study springs as representative of the karst springs in the Thrust Zagros belt, indicate good quality suitable for domestic and agricultural uses. Regarding the high degree of karstification of these karst settings, the protection of these water resources from surface contaminates are highly recommended.

Finally, characterizing the hydrogeological characteristics of karst aquifers in the absence of site-specific logging-data and speleological investigations is a challenging task due to they usually exhibit complex structure with extremely high spatial heterogeneity. In such environments, hydrochemical and discharge data of spring can be used to identify the inner structure of karst systems and help to depict more reliable picture of hydrological functionality of karst aquifers.

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Fig. 1 Spatial distribution of the studied springs located in the sub-basins Dez and Karkheh in Lorestan Province, western Iran.

Fig. 2 Geological map of the study area.

Fig. 3 Long-term average monthly variations of precipitation and temperature over the study area.

Fig. 4 Mangin's Diagram of infiltrated (fast) and base flow components of the recession curve. Refer to the text for definition of the variables.

Fig. 5 Classification of the study karst systems based on indices of k and i obtained from the recession analysis based on Mangin (1975). Zone I: well developed system, II: well developed system speleological network whit large downstream flood plains, III: upstream Karstification with retarded infiltration, IV: complex system and V: poorly developed system.

Fig. 6 Spatial distribution of studied springs based on α_b coefficients.

Fig. 7 Rescaled adjust partial sums of monthly discharge, RAPS_Q (a) and precipitation, RAPS_P (b).

Fig. 8 Durov diagram of the water samples collected from the Regional Water Company of Lorestan Province.

Fig. 9 Piper diagram for spring water samples.

Fig. 10 Gibbs diagrams for spring water samples collected from the Regional Water Company of Lorestan Province.

Fig. 11 Ternary diagram ($Cl-HCO_3-SO_4$) of the spring water samples.

Fig. 12 The graph of chloro-alkaline indices *CAI1* (a) and *CAI2* (b) for the spring water samples.

Fig. 13 Classification of the study area based on the Mangin's approach and hydrochemical indices considered in this study.