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Spatial Variation and Controlling Parameters of $\delta^{18}O$ and $\delta^{2}H$ Signatures in Surface Water Resources Across Iran

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Abstract
Surface water beside groundwater is dominant in providing water supply in Iran. Hence, for better management of surface water bodies in Iran, the stable isotope technique as an accurate method has been used to study these valuable water resources. The influence of moisture sources on surface water has been reviewed by comparing stable isotope signatures in surface water resources with Iran's MWLs, GMWL, and EMMWL. In addition, the contribution percentage of each air mass (precipitation events originate from each air mass) in the recharge of main rivers across Iran was calculated using the mixing model "Simmr-package" in R. In the Southern Zagros region, the role of cT air mass was dominant, while in the Western Zagros, the role of cP air mass was significant. However, the roles of cP and mP air masses were dominant in the North of Iran. Besides moisture origin, the evaporation effect on surface water resources was also studied. Plotting the average stable isotope content of surface water resources in each mega basin on Iran meteoric water line (IMWL) showed that surface water sources belonging to the Caspian Sea and Urmia lake basins had the most depleted isotope values. However, the surface water resources in the Persian Gulf and the Oman Sea basin as well as the Eastern border basin showed enriched stable isotope values and deviation from IMWL due to the extreme evaporation effect. In conclusion, stable isotopes in surface water resources across Iran were affected simultaneously by evaporation and precipitation moisture source variations.

Introduction
Iran is a large country with an area of 1648195 km^2 located in southwestern Asia. It is situated in an arid and semi-arid region of the world. Iran receives an average annual precipitation of 341mm (Alijani, 2000), and its hydrological year, according to previous studies (Modarres and Sarhadi, 2009; Pourasghar et al., 2012; C. Balling et al., 2016), is classified to dry (May to October) and wet periods (November to April). Due to the vast land area that Iran covers and the existence of several large nearby water bodies (like the Persian Gulf, the Oman Sea, the Caspian Sea, and the Mediterranean Sea), this country is under the influence of five main air masses, each air mass dominantly influences some parts of the country (Alijani, 2000; Karimi &

Farajzadeh, 2011). The continental tropical known as Sudan air mass (cT), the continental polar known as Siberian air mass (cP), the maritime polar air mass (mP), and the Mediterranean air mass (MedT) influence Iran during the wet period. However, the maritime tropical air mass (mT) influences this country during the dry period (Alijani, 2000; Heydarizad, 2018; Heydarizad et al., 2019b) (Fig. 1).

In addition to the low precipitation amount, an uneven distribution of precipitation across the country is also observed (Heydarizad, Raeisi, Sori, & Gimeno, 2018). It could be due to the large variations in topography, latitude, vegetation coverage area, nearby water bodies, and various moisture sources and air masses in Iran (Heydarizad, et al., 2018).

During the last decades, Iran has faced a challenging situation in providing water needs for its inhabitants due to various events such as significant population increase, notable agricultural and industrial growth, and prolonged climatological droughts (Yang et al., 2003; Abbaspour et al., 2009). Therefore, the pressing matter in this situation is applying accurate techniques for monitoring available water resources, which is faced with big challenges in water resources management. In addition to groundwater resources which play a dominant role in water supply in Iran, surface water resources also play a great role, although both sources have faced intense shortages mainly during the recent decades (Madani, 2014; Mirzavand and Bagheri, 2020).

Iran consists of 6 main mega basins with various hydrological and climatological characteristics (Fig. 2).

Some of these basins, including the Persian Gulf and the Oman Sea basin, which drains the Zagros mountain, and the Caspian Sea basin, which drains the Alborz mountain range, have a significant role in surface water sources across Iran. However, other basins, like the Eastern border and the Central plain basins, have minimal surface water resources. Although the surface water sources' potential is negligible in these basins, these limited sources have a significant role due to the scarcity of available water resources. Furthermore, surface water sources in the Eastern border basin have another particular importance since they are located in the boundary zone between Iran, Afghanistan, and Pakistan. Thus, surface water resources located in each mega basin should be studied carefully. Table (1) shows some of the hydrogeological and geographical characteristics of these basins.

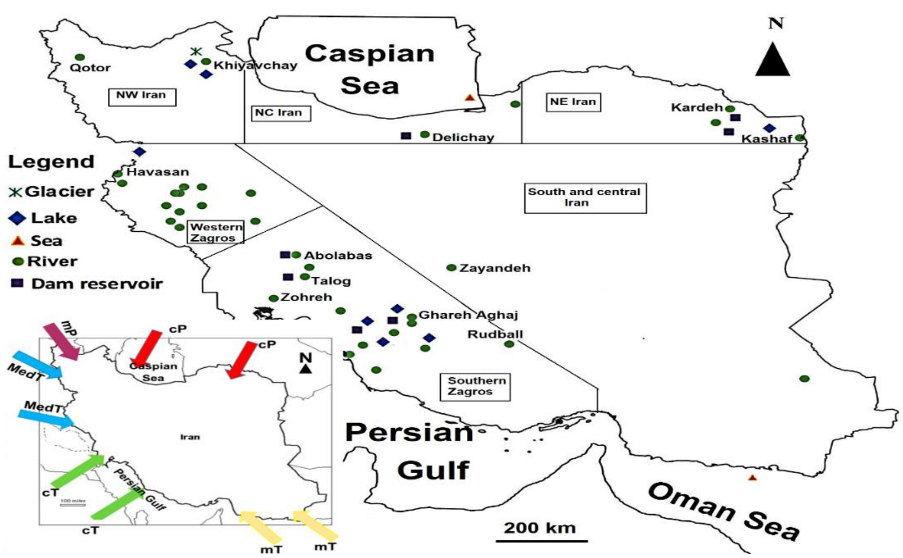

Fig. 1- The spatial distributions of the studied surface water resources (rivers, dam reservoirs, glaciers, seas, and lakes) as well as the main air masses influence Iran

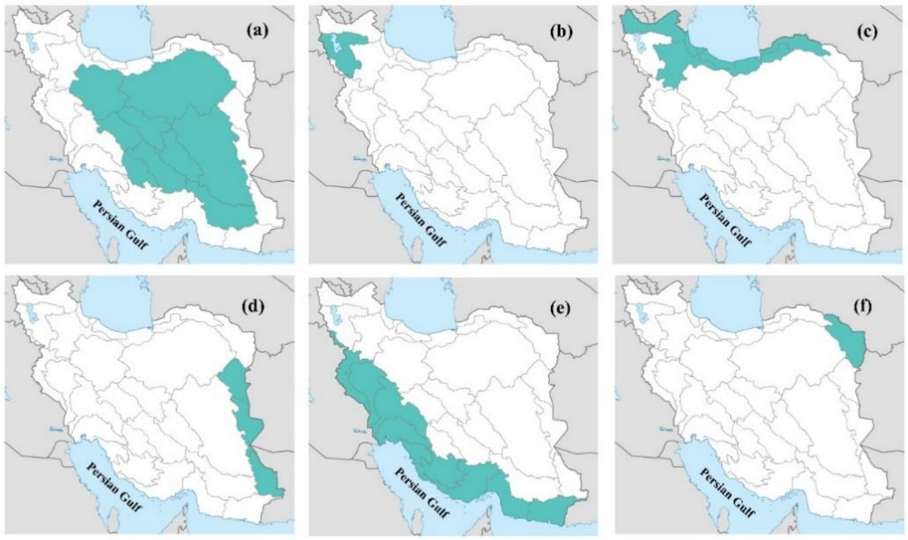

Fig. 2- The mega basins in Iran. (a) Central plain, (b) Urmia lake, (c) Caspian Sea, (d) Eastern border (e) Persian Gulf and the Oman Sea, and (f) Ghareh Ghom

Table 1- The main hydrological and geographical parameters in each mega basin

Basin	Total area (Km^2)	Precipitation (mm/year)	Potential evaporation (mm/day)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)	lc-excess (‰)
Persian Gulf and the Oman Sea	424029	542	2.73	-3.8	-19.7	10.4	-7.5
Ghareh Ghom	44295	356	4.42	-6.1	-40.4	8.4	-7.9
Caspian Sea	175060	495	3.36	-7.0	-45.0	11.5	-6.5
Urmia lake	51762	219	4.97	-7.4	-51.3	8.1	-10.1
Central plain	824611	105	6.62	-4.6	-27.7	9.1	-1.0
Eastern boarder	103183	102	4.27	-3.2	-17.7	7.5	-10.3

The Persian Gulf and the Oman Sea basin are dominant compared to other basins in providing water sources for notable inhabitants in the western part of the country. This basin covers a large surface (the second basin after the Central plain), has the highest annual precipitation, and has the lowest evaporation rate among the studied mega basins. Furthermore, large rivers, including Dez, Karoun, Karkheh, Zohreh, Jarahi, Ghareh Aghaj, etc., drain this mega basin in the western part of the country. The Caspian Sea is another essential mega basin located in the northern part of the country and receives large amounts of precipitation (mainly in the western parts of the Caspian Sea coastal area) and faces a low evaporation rate. Some large rivers that drain this mega basin are Aras, Sefud rud, Gorgan, and Atrak. In contrast, the Central plain and the Eastern border basins receive much lower amounts of precipitation and face higher evaporation rates. This is why a small number of rivers drain these basins. The main river in the Central plain is Zayandeh rud, while Hirmand is the main river in the Eastern border basin (Encyclopedia Britanica, 2020).

Among the various methods for surface water study, stable isotope techniques are considered tremendous and accurate fingerprints in hydrological studies. The application of stable isotopes of water molecules (^{18}O and ^{2}H) in water sources was started by Harmon Craig in 1961 (Craig, 1961) and has been conducted in many surveys worldwide since that time.

Stable isotope techniques also have a significant role in studying the influence of local climatic parameters such as evaporation as well as regional parameters such as moisture origins in surface water sources (Borzi et al., 2019; Hao et al., 2019; Wu et al., 2019, 2021; Mahlangu et al., 2020; McGill et al., 2020; Wallace et al., 2021; Xia et al., 2021; Yang et al., 2021).

Moisture sources dominate the stable isotope signatures in precipitation events and surface water sources (Burnett et al., 2004; Sjostrom and Welker, 2009). Precipitation events originating from water bodies with high sea surface temperature (SST) are enriched in $\delta^{18}O$ and $\delta^{2}H$ and show high d-excess values (Gat and Carmi, 1970; Zak and Gat, 1975; Clark and Fritz, 2013; Heydarizad, 2018; Heydarizad et al., 2019b). However, precipitation events originating from low SST water bodies typically show depleted $\delta^{18}O$ and $\delta^{2}H$ as well as low d-excess values (Dansgaard, 1964; Gat and Carmi, 1970).

Surface water resources in Iran are dominantly under the influence of various moisture sources of precipitation (Heydarizad, 2018; Mohammadzadeh & Heydarizad, 2019). The moisture of precipitation is provided by various water bodies, including the Mediterranean, the Caspian, the Black, the Oman, the Red, and the Arabian Seas, as well as the Persian Gulf (Alijani, 2000; Karimi and Farajzadeh, 2011; Heydarizad et al., 2018). During the wet period (November to April), moisture uptake from the Arabian Sea, the Persian Gulf, and the Mediterranean Sea is dominant, while during the dry period (May to October), the role of the Red Sea, the Caspian Sea, and the Persian Gulf intensify (Heydarizad et al., 2018). In addition to air masses and moisture sources, surface water sources are also under the influence of evaporation (Landwehr & Coplen, 2006; Wu *et al.*, 2021). Evaporation is a crucial factor influencing surface water resources, mainly in arid and semi-arid parts of the world like the Middle East and North Africa.

In the following survey, the role of the precipitation moisture sources as well as the evaporation effect on the stable isotope signatures in the main surface water resources in Iran, including rivers, lakes, glaciers, dam reservoirs, and seas, have been studied. The contribution percentage of each air mass (precipitation events originate each air mass) to the recharge of the main surface water sources has also been calculated using "Simmr-package" (Parnell et al., 2010) in R language (R core team, 2018). This package was initially developed by Parnell et al. (Parnell et al., 2010) to solve the mixing equations in a Bayesian framework. The Simmr package needs three basic inputs, such as the mixtures (the surface water samples), the endmember (source) means, and the endmember (source) standard deviation (SD) to run (Parnell & Inger, 2021). Furthermore, the role of evaporation effect on surface water sources has been studied by developing evaporation water line (EWL) as well as calculating the line-conditioned excess (lc-excess) Landwehr and Coplen, 2006 in surface water resources.

Materials and Methods

This study gathered stable isotopes (18O and 2H) data in rivers, dam reservoirs, lakes, glaciers, and seas from scientific papers, academic thesis, and reports. The ^{18}O and ^{2}H analyses of the water samples were performed in several laboratories, including Ján Veizer Stable Isotope Laboratory at Ottawa University Canada, Stable Isotope Laboratory of Waterloo University Canada, IAEA laboratories, Federal institute for geoscience and natural resources in Hannover, Germany, and several other laboratories across the world. Samples were analyzed for stable isotopes (^{18}O and ^{2}H) using Isotope Ratio Mass Spectrometer (IRMS) and Los Gatos Research (LGR) OA-ICOS techniques. Stable isotope signatures were expressed relative to Vienna Standard Mean Ocean Water (VSMOW) with the uncertainty of ±1‰ and ± 0.1‰ for ^{2}H and ^{18}O, respectively (Eq. 1).

$$\delta=1000\ (R_{Sample}-R_{VSMOW})/R_{VSMOW} \tag{1}$$

where R represents the $^{18}O/^{16}O$ or $^{2}H/H$ ratio.

Firstly, the spatial distribution maps of $\delta^{18}O$, $\delta^{2}H$, and d-excess in the surface water resources were developed using the Kriging, Inverse Distance Weighting (IDW), and Spline interpolation techniques in the Q-GIS software (desktop version: 3.14.15) (QGIS Development Team, 2021). To validate the developed maps, the root mean square error (RMSE) was calculated. The RMSE is a standard deviation of the residual, which is also known as the 'predication error', and calculated using equation (2):

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(\text{predicted i} - \text{actual i})^2}{N}} \qquad (2)$$

To study the role of various moisture sources in surface water resource recharge , surface water sources have been compared with the global meteoric water line (GMWL) (Rozanski, Araguas-Araguas and Gonfiantini, 1993), Eastern Mediterranean meteoric water line (EMMWL) (Gat and Carmi, 1970), and Iran meteoric water lines (IMWLs) (Heydarizad et al., 2019b). In addition, the Iran area has been classified into several zones according to the influence territories of various air masses as well as earth topography (Fig. 1). The whole procedure to clarify these zones has been appropriately explained in the following studies (Heydarizad, 2018; Heydarizad et al., 2019a, 2019b). The contribution percentage of each air mass (precipitation events originating from each dominant air mass) in the main rivers recharge was also calculated. Firstly, the average stable isotope signatures in precipitation events originating each air mass were obtained from previous studies (Heydarizad, 2018; Heydarizad et al., 2019b, 2019a) (Supplementary File 1). Then, the contribution percentage of the precipitation events originating from each air mass in the main rivers recharge was calculated by the stable isotopes signatures in precipitation and river samples using "Simmr-package" scripts in the R programming language (Supplementary File 2).

In addition to the moisture sources, to study the role of evaporation effect on surface water samples, lc-excess presented by (Landwehr and Coplen, 2006) has been used (Eq. 3):

$$\text{lc-excess} = {}^{2}\text{H} - a \times {}^{18}\text{O} - b \qquad (3)$$

in which *a* and *b* represent the slope and intercept of the LMWL.

In this study, the LMWLs of regions near the surface water resources have been used. The low and negative lc-excess values in surface water samples show the dominant role of evaporation. Dam reservoirs, lakes, and seas usually face stronger evaporation and show low lc-excess values. However, river water samples normally face lower evaporation and demonstrate high lc-excess values.

Results and Discussion

Stable isotope signatures and lc-excess in some of Iran's main surface water resources, including rivers, dam reservoirs, lakes, seas, and glaciers, were tabulated in Table (2). The locations of the studied surface water resources were also shown in Fig. (1).

Developing the spatial distribution maps of stable isotopes

The spatial distribution maps of δ^{18}O, δ^{2}H, and d-excess values in surface water resources were developed using various interpolation methods, including Spline, Kriging, and IDW. Then calculating the RMSE for each map showed the lowest values for the maps developed by IDW techniques confirming their higher accuracy compared to other methods (Table 3).

Table 2- Stable isotopes $\delta^{18}O$ and $\delta^{2}H$, d-excess, and lc-excess values in surface water resources

Row	Location	Sampling date	Mega basin	Zone	Symbol (source)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)	lc-excess (‰)	Ref
1	Droudzan	1996	The Persian Gulf and the Oman Sea	Southern Zagros	Dam	-1.9	-11.2	4.0	-14.2	(Niroomand and Pakzad, 1997)
2	Karoun3	2006			Dam	-6.0	-28.9	19.1	-1.6	(Zarei and Damough, 2007)
3	Cherum	1996-1997			Dam	-3.4	-10.0	17.4	-1.7	(Rezaei et al .,1998)
4	Abbaspour	2012			Dam	-4.7	-23.7	13.9	-5.9	(Kalantari and Mohamadi Behzad, 2013)
5	Kafter	2012			Lake	-4.2	-15.7	17.7	-1.9	(Kalantari and Mohamadi Behzad, 2013)
6	Taloug	2012			River	-4.9	-22.2	17.3	-2.7	(Kalantari and Mohamadi Behzad, 2013)
7	Abolabass	2010-2011			River	-4.4	-20.7	14.9	-4.8	(Zarei et al., 2014)
8	Jarahi	2009			River	-5.0	-22.0	18.0	-2.0	(Mirnejad et al., 2011)
9	Shapour	1996-1997			River	-3.1	-10.2	14.8	-4.2	(Rezaei et al., 1998)
10	Shekastyan	1996-1997			River	-0.7	2.3	7.7	-9.8	(Rezaei et al.,1998)
11	Gorg valley	1996-1997			River	-7.0	-34.6	21.4	0.2	(Rezaei et al., 1998)
12	Tanbakukar	1996-1997			River	-4.0	-20.9	10.8	-8.6	(Rezaei et al.,1998)
13	Zohreh	1996-1997			River	-4.7	-19.9	17.4	-2.5	(Rezaei et al.,1998)
14	Fahlyan	1996-1997			River	-5.6	-24.4	20.3	-0.1	(Rezaei et al., 1998)
15	Kour	1996			River	-5.2	-22.2	19.4	-0.7	(Niroomand and Pakzad, 1997)
16	Ghareh Aghag	1992			River	-4.8	-22.2	16.0	-3.9	(Pakzad, 1993)
17	Prishan	2007			Lake	2.6	11.8	-9.1	-24.6	(Mahmoudi savandi, 2008)
18	Dasht Arjan	2007			Lake	0.6	4.5	-0.2	-17.0	(Mahmoudi savandi, 2008)
19	Mharloo	1992			Lake	-4.9	-36.7	2.1	-17.8	(Pakzad, 1993)
20	Karoun	2014			River	-4.5	-20.1	15.9	-6.5	(Jalali, et al., 2019)
21	Haft Barm	2012-2013			Lake	6.6	35.0	-17.7	-28.6	(Saadat and Mohammadi, 2018)
20	Havassan	1998		Western Zagros	River	-4.0	-25.7	6.1	-8.8	(Khalaj 2013)
21	Kanishirin	1998			River	-4.1	-26.3	6.8	-8.3	(Khalaj, 2013)
22	Cahmsaree	1998			River	-3.5	-25.5	2.6	-11.7	(Khalaj, 2013)
23	Dare Zangene	1998			River	-4.0	-28.0	4.1	-10.8	(Khalaj, 2013)

24	P.Solaiman	2011-2012			River	-5.9	-34.6	12.2	-14.9	(Osati et al., 2014)
25	Aran	2011-2012			River	-6.2	-35.2	14.2	-3.3	(Osati et al., 2014)
26	Doab	2011-2012			River	-6.3	-36.0	14.0	-3.6	(Osati et al., 2014)
27	Haidar Abad	2011-2012			River	-6.0	-32.2	15.4	-1.8	(Osati et al., 2014)
28	Faraman	2011-2012			River	-5.7	-32.2	13.2	-3.7	(Osati et al., 2014)
29	Holailan	2011-2012			River	-5.1	-28.8	11.8	-4.4	(Osati et al., 2014)
30	Ramavand	2007			River	-6.6	-32.0	20.8	2.8	(Bagheri Sheshdeh, 2007)
31	Seymareh	2007			River	-5.9	-29.4	17.4	0.3	(Bagheri Sheshdeh, 2007)
32	Tangsyab	2007			River	-5.1	-28.8	12.4	-3.9	(Bagheri Sheshdeh, 2007)
33	Zarivar	2009			Lake	5.5	16.9	-27.1	-30.5	(Mohammadzadeh and Ebrahimpour, 2012)

Row	Location		Water Shed	Zone	Symbol (source)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)	lc-excess (‰)	Ref
34	Kardeh	2011	Ghareh Ghom	[1] NE Iran	Dam	-7.3	-50.4	7.8	-9.5	(Mohammadzadeh and Heydarizad, 2020)
35	Torogh	2008			Dam	-6.8	-43.7	10.7	-6.2	(Mohammadzadeh et al., 2008)
36	Kashaf	2000			River	-8.0	-32.1	32.0	14.1	(Pakzad, 2000)
37	Kardeh	2011			River	-8.7	-61.8	8.1	-10.4	(Mohammadzadeh and Heydarizad, 2020)
38	Torogh	2008			River	-7.5	-48.2	11.8	-5.7	(Mohammadzadeh, 2008)
39	Bazangan	2008			Lake	1.7	-6.2	-19.8	-29.6	(Mohammadzadeh, Robin and Khanehbad, 2008)
40	Caspian	2001	Caspian Sea	[2] NC Iran	Sea	0.3	-5.5	-7.7	-15.0	(Heydarizad, 2018)
41	Lar	1983			Dam	-8.7	-55.6	14.3	-3.5	(Office, 1983)
42	Delichay	1983			River	-9.4	-55.0	20.4	-2.2	(Office, 1983)
43	Sabalan	2005		[3] NW Iran	Glacier	-6.8	-35.9	18.3	0.1	(Porkhial, Ghomshei and Yousefi, 2010)
44	Khiyavchay	2005			River	-10.8	-67.6	19.0	-4.1	(Porkhial, Ghomshei and Yousefi, 2010)
45	Baliglu	2005			River	-11.4	-73.1	18.1	-5.7	(Porkhial, Ghomshei and Yousefi, 2010)
	Sabalan	2005			Lake	-2.5	-22.0	-2.0	-15.1	(Porkhial, Ghomshei and Yousefi, 2010)

46	Averin	2005	Urmia		River	-11.5	-74.1	18.2	-5.7	(Rahmani, 2010)
47	Darehkhan	2005			Lake	-9.3	-67.4	7.2	-4.1	(Rahmani, 2010)
48	Averin	2005			Lake	-10.6	-68.7	15.7	-7.1	(Rahmani, 2010)
50	Urmia	2012-2013			Lake	1.7	5.0	-8.6	-15.6	(Mosaffa et al., 2021)
51	Zayandeh	1994-1996	Central plain	4 C & S Iran	River	-4.6	-27.7	9.1	-1.0	(Khademi, et al., 1997)
52	Taftan/Jamchin	2005	Eastern		River	-5.9	-32.5	14.7	-2.1	(Boumeri, 2005)
53	Oman	2008	border		Sea	-0.4	-2.9	0.3	-18.5	(Heydarizad, 2018)

1-NE stands for North-eastern 2-NC stands for North-central 3-NW stands for North-western 4- C & S stands for Central and South

Table 3- The RMSE values in the developed stable isotopes distribution maps in surface water resources

Map type	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess (‰)
IDW	2.3	14.0	6.5
Spline	8.5	23.4	11.6
Kriging	7.2	44.5	13.2

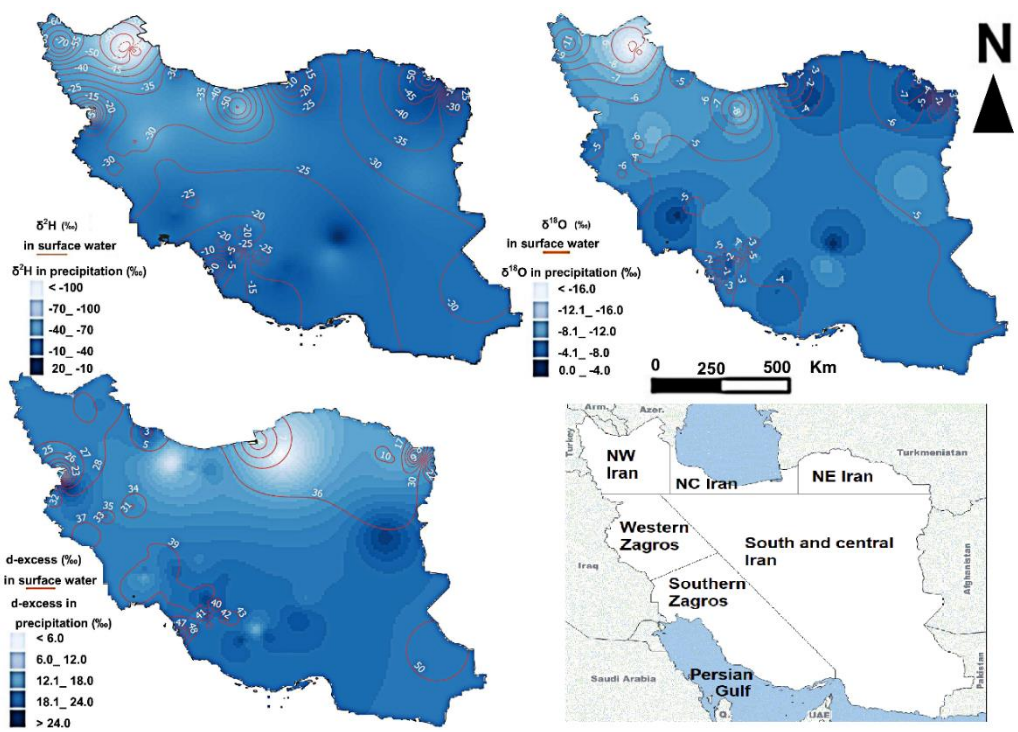

Fig. 3- The spatial distributions of $\delta^{18}O$, $\delta^{2}H$, and d-excess in surface water resources

The low RMSE showed high accuracy of the maps developed by IDW compared to the maps developed by other techniques. The spatial distribution maps of $\delta^{18}O$, $\delta^{2}H$, and d-excess in surface water resources demonstrate significant spatial variations (Fig. 3).

Studying the variations of stable isotope signatures in surface water sources and precipitation across Iran presented valuable results. Surface water resources in the North-western part of the country showed extremely depleted stable isotopes values compared to the other parts. This is because surface water resources in this region are recharged by high elevation precipitation with much depleted stable isotopes values. On the other hand, the Southern Zagros region showed highly enriched stable isotopes values compared to other areas. The Southern Zagros region normally faces high air temperatures and evaporation rates, hence precipitation and surface water resources show highly enriched stable isotope values.

The d-excess values in surface water resources also showed notable variations. Very high d-excess values were observed in surface water resources in the Southern Zagros region. The high d-excess values in surface water resources were due to high d-excess values in local precipitation events. The precipitation events in the Southern Zagros region usually originate from water bodies such as the Persian Gulf, the Red Sea, the Arabian Sea, the Mediterranean Sea, and the Oman Sea (Heydarizad, 2018; Heydarizad et al., 2019b). The precipitation events originating from these water bodies mainly show high d-excess values due to intense initial evaporation from their surfaces. On the other hand, surface water resources in the Northern part of Iran showed low d-excess values. Precipitation events in this region mainly originate from water bodies such as the Caspian Sea, the Black Sea, and the Atlantic Ocean. The precipitation events originating these water bodies normally showed low d-excess values due to weak initial evaporation from their surfaces (Heydarizad, 2018; Heydarizad et al., 2019b).

The role of various moisture sources in surface water characteristics and recharge rate

To study the role of precipitation moisture origin on surface water resources, firstly, stable isotope signatures in surface water sources have been compared with GMWL and EMMWL (Fig.4). In North-eastern Iran, most of the samples (rivers, dam reservoirs, and lakes) were mainly plotted on GMWL. Kardeh and Torogh dam reservoirs as well as Bazangan lake, deviated from GMWL due to significant enrichment of stable isotopes caused by considerable evaporation from these water bodies. In the North-central part of Iran, the Lar dam reservoir and Delichay river samples were mainly plotted on GMWL, while the Caspian Sea samples showed notable deviation from GMWL due to the significant evaporation effect. In the North-western part of Iran, surface water samples showed mild deviation toward EMMWL and plotted between EMMWL and GMWL. This is because the role of moisture originating from the Mediterranean region is stronger in the western part of Iran compared to the eastern part of the country. However, due to the evaporation effect, the Sabalan and Urmia lakes deviated from both GMWL and EMMWL (Fig.4).

In the Western Zagros region, the situation is different from the Northern part of the country as the moisture originating from the Mediterranean Sea is dominant in this region. Most of the surface water samples in the Western Zagros region were mainly plotted between EMMWL and GMWL. The precipitation events in this part of the country originated from the Mediterranean Sea as well as other regions such as the Caspian Sea (Heydarizad et al., 2019b, 2019a). In the Southern Zagros region, surface water samples were also plotted on EMMWL and GMWL due to the dominant influence of the Mediterranean Sea moisture. However, some of the dam reservoirs and lake water samples in this region deviated from both EMMWL and GMWL due to the evaporation effect (Fig.4). Finally, in the Central and South parts of Iran, the river water samples were plotted on GMWL. However, due to the evaporation effect, the Oman Sea samples showed significant deviation from both EMMWL and GMWL.

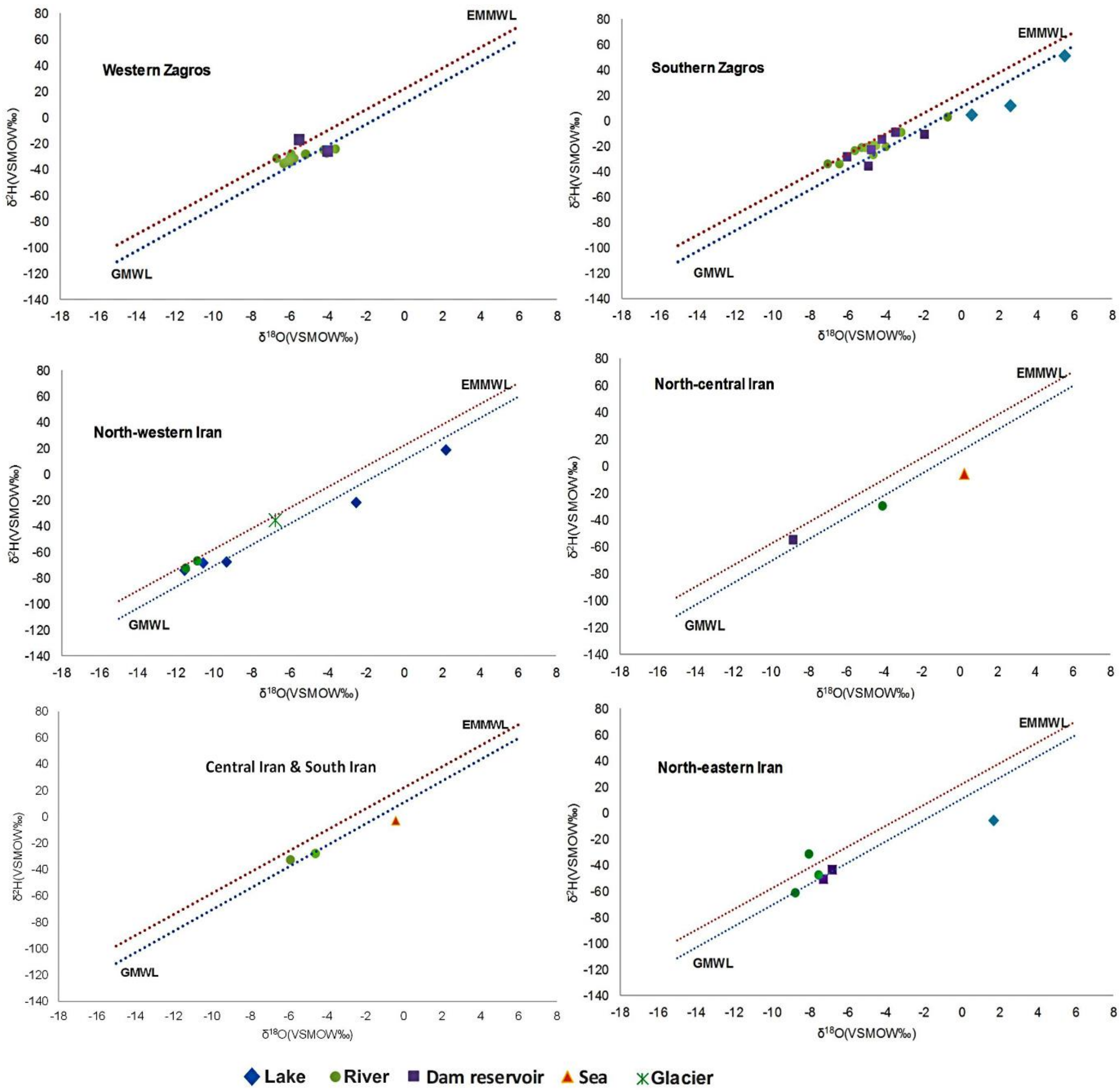

Fig. 4- Plotting the surface water samples on the global meteoric water line (GMWL) and eastern Mediterranean meteoric water line (EMMWL)

On the other hand, plotting the surface water samples on three different IMWLs (west Zagros, south Zagros, and north of Iran MWLs) also presented precious results (Fig.5). Surface water sources in the Western Zagros region were mainly plotted on West Zagros MWL (WZMWL), while surface water resources in the Southern Zagros region were mainly plotted on South Zagros MWL (SZMWL). In the North-western part of Iran, surface water resources were mainly plotted on WZMWL and North of Iran MWL (NIMWL). This is because the moisture for this region's precipitation events originates from the Mediterranean Sea with high SST and water bodies with low SSTs, such as the Caspian and the Black Seas (Heydarizad et al., 2019b, 2019a). The role of the Mediterranean Sea moisture dominantly decreased toward the country's eastern borders. This is why surface water resources in the North-central and North-eastern parts of the country were mainly plotted on NIMWL (Fig.5).

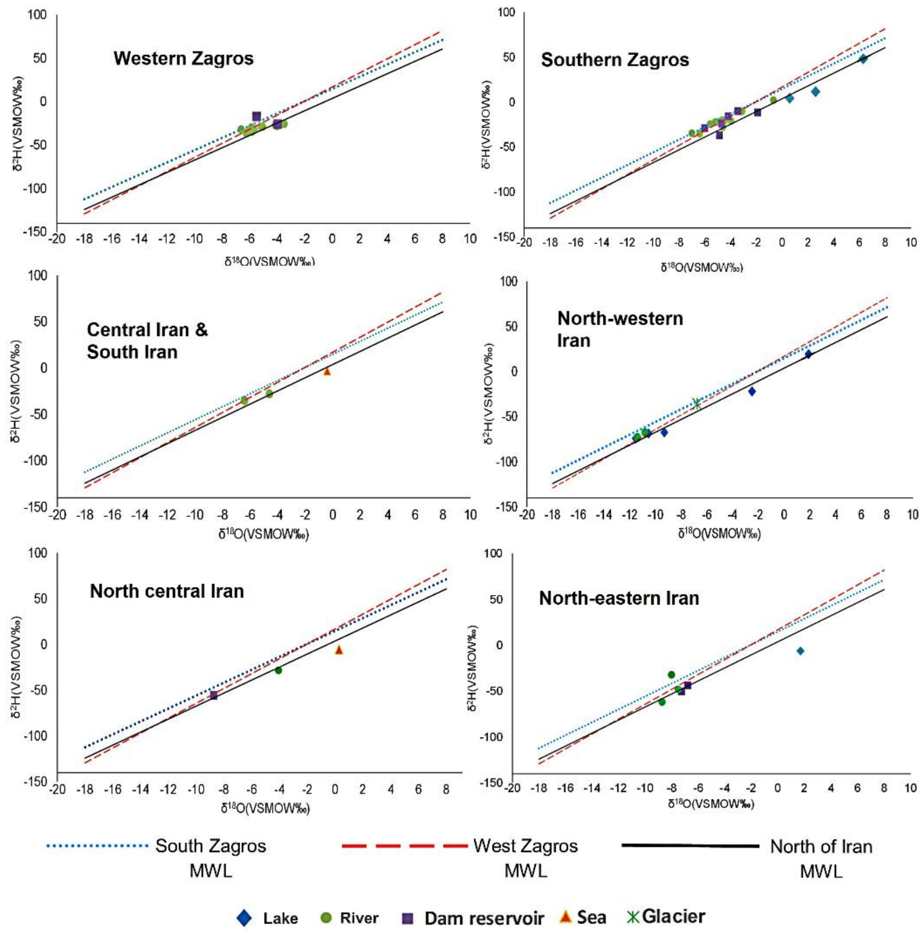

Fig. 5- Plotting surface water samples on Iran meteoric water lines (IMWLs) after (Heydarizad et al., 2019b)

Finally, the role of each dominant air mass (precipitation events originated from each air mass) in the recharge of surface water resources has been studied using stable isotopes signatures in precipitation and surface water resources and the mixing model "Simmr-package" in the R programing language. In the studied surface water sources, river water samples were selected to calculate each air mass's role in the recharge of surface water sources. Since river samples face the lowest evaporation effect, these sources were only chosen among the various surface water sources. Furthermore, among the studied rivers in this investigation, the ones with negligible evaporation effect as well as groundwater interaction (according to groundwater level near the river) were selected. It prevents the unwanted influence of groundwater mixing with river water samples. Therefore, considering all these, the author selected twelve different rivers across Iran and calculated the contribution percentage of each air mass (precipitation events originate from each air mass) in the recharge of these rivers (Table 4).

Table 4- The contribution percentage of each air mass (precipitation events originate each air mass) to the recharge of surface water resources

Air mass contribution / River	cP (%)	cT (%)	mP (%)	MedT (%)	mT(%)
Abolabas	26.4	30.8	20.5	22.2	_
Ghareh Aghaj	15.5	29.5	14.6	21.7	18.6
Havasan	40.8	25.5	15.7	18.1	_
Kardeh	36.2	23.1	22.8	17.8	_
Qotor	24.3	26.0	27.5	22.1	_
Rudball	14.3	28.0	18.5	22.9	16.3
Khiyavchay	19.7	26.4	28.7	25.3	_
Delichay	12.5	25.9	35.1	26.6	_
Talog	22.6	28.7	23.6	25.1	_
Zayandeh	34.8	25.6	18.8	20.8	_
Kashaf	31.7	23.4	24.7	20.2	_
Zohreh	22.1	33.5	20.4	24.0	_

In the Southern Zagros region, the precipitation events originating the cT air mass had a dominant role in the recharge of Abolabas, Ghareh Aghaj, Rudball, Talog, and Zohreh rivers. However, in the Western Zagros region, the precipitation events originating the cP air mass have a dominant role in the recharge of the Havasan river. In the Northern part of Iran, the precipitation events originating cP air mass had a dominant role in the recharge of surface water samples in this region, mainly the Kashaf and Kardeh rivers. However, precipitation events originating mP air mass had a significant role in the recharge of Qotor and Khiyavchay rivers in the North-western part and the Delichay river in the North-central part of Iran. Finally, in the Central part of the country, precipitation events originating cP and, to a lower extent cT air masses had a dominant role in the recharge of the Zayandeh river.

Study the role of evaporation effect on isotope signatures of surface water resources

Evaporation also has a dominant influence on stable isotope characteristics of surface water sources. Among mega basins, the Central plain shows the highest evaporation and the lowest precipitation amount. However, the Persian Gulf, the Oman Sea basin, and the Caspian Sea show the highest precipitation amount and the lowest evaporation rate (Table 1). Although the regions with low evaporation rates and high precipitation are expected to show depleted isotope values in their precipitation and water sources (Clark and Fritz, 2013), the same pattern doesn't exactly happen in this study. Since surface water sources are limited in the Central plain basin, a few samples were only taken from creeks in high-elevation mountains that faced very mild evaporation. However, in the Persian Gulf and the Oman Sea basin with numerous surface water sources (lakes, dam reservoirs, rivers), surface water sources faced stronger evaporation, mainly in lakes and dam reservoirs.

Surface water sources have been classified based on Iran mega basins, and the Iran evaporation water line (IEWL) has been developed (Fig.6 a). The results showed no apparent correlation between the lc-excess values and stable isotope content in surface water sources and mega basin divisions. However, more depleted isotope values can be observed in surface water resources in the Caspian Sea and Urmia lake basins.

Furthermore, the average stable isotope content of surface water sources in each basin has been plotted on Iran's meteoric water line (IMWL) (Fig.6 b). Surface water sources in the central plain basin are plotted on IMWL and show negligible evaporation effect, which has been confirmed by high lc-excess values -1.00‰. On the other hand, surface water resources in the Persian Gulf and the Oman Sea basin show the highest deviation from IMWL. This is why surface water resources show low lc-excess -7.5‰. However, the Persian Gulf and the Oman Sea mega basin showed the highest precipitation amount as well as the lowest potential evaporation. In addition, surface water resources in this basin showed the highest d-excess values. This is because the moisture of precipitation in this basin and the Caspian Sea basin originates from the Mediterranean Sea. As mentioned earlier in this study, the precipitation events originating the Mediterranean Sea show high d-excess values. Among the different mega basins, the surface water resources belonging to the Eastern border showed the most enriched isotope values, while the surface water resources in the Urmia lake basin showed the most depleted isotope value. The highly enriched isotope values in the Eastern border basin are because both precipitation events (due to the extreme evaporation rate and low precipitation amount) and surface water resources face heavy evaporation, which caused enrichment in stable isotope content and deviation of surface water samples from IMWL. In contrast, precipitation events do not meet considerable evaporation in the Urmia lake basin due to the tiny deviation of surface water samples from the IMWL, which has also been confirmed by the low evaporation rate (Table 1). However, surface water sources in this basin have faced significant evaporation (extreme evaporation from Urmia lake surface as well as other lakes in this basin), which low lc-excess values have also confirmed.

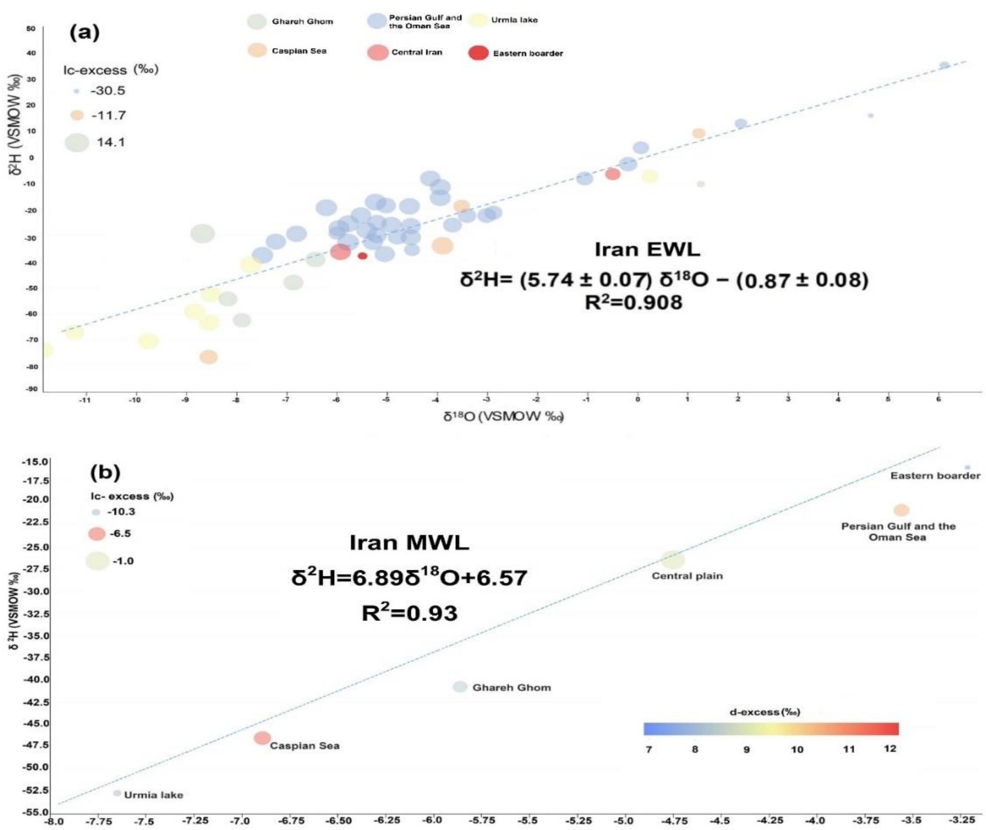

Fig. 6- Classifying surface water samples based on Iran mega basins and developing IEWL (a) as well as plotting the average stable isotope content of surface water samples (classified based on the mega basins) on IMWLs (Shamsi and Kazemi, 2014) (b)

Conclusions

Surface water resources play a dominant role in providing water supply in Iran. Stable isotope signatures in surface water sources showed large spatial variations across Iran due to moisture sources and evaporation effects. The moisture sources' influence on surface water sources has been studied by comparing stable isotope signatures in surface water resources with Iran's MWLs, GMWL, and EMMWL. Furthermore, the contribution percentage of each air mass (precipitation events originate each air mass) in the recharge of the main rivers has been studied using "Simmr-package" in R language. The results showed that the role of cP and mP air masses in the recharge of the rivers was dominant in the North of Iran. In the Southern Zagros region, the role of cT air mass was dominant, while in the Western Zagros region, the role of cP air mass was significant in the recharge of rivers. In addition to moisture origin, the evaporation effect on stable isotope content in surface water sources has been studied, and IEWL has been developed. Among Iran's mega basins, surface water sources belonging to the Caspian Sea and Urmia lake basin show the most depleted isotope values. However, the surface water resources in the Persian Gulf and the Oman Sea basin as well as the Eastern border basin showed enriched stable isotope values and deviation from IMWL due to the extreme evaporation effect.

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