

A review of research dealing with isotope hydrology in Iran and the first Iranian meteoric water line

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Abstract

For more than half a century isotopes have been employed as a powerful tool in studying various aspects of water resources in a large number of countries. However, in developing countries like Iran the application of such techniques is in its infancy. The first research in Iran was carried out in 1975 to identify the source of saline groundwaters in south Iran, and the first national conference on the application of stable isotopes was held in 2013. Altogether, there are 70 publications which fall into seven categories, including the isotopic composition of precipitation/groundwater (35.75%), sources of salinization and hydrothermal water (18.57%), natural recharge and recharge areas of springs (17.14%), informative studies and groundwater modelling (11.42%), groundwater–surface water interaction (7.14%), karst development and hydrograph separation (5.71%), and pollution and pollutant transportation (4.28%). Nationwide, there are issues which require the application of isotopes (e.g., the determination of recharge areas of important springs and the identification of the sources of groundwater pollution) but a lack of laboratory facilities does not allow scientists to tackle these problems. In this research, we have also constructed the first Iranian meteoric water line, the slope and the deuterium excess of which are 6.89 and 6.57‰, respectively.

Keywords: Iran, Isotope hydrology, Groundwater, IMWL, GMWL.

Introduction

Iran is a country with an arid-to-semiarid climate (an average precipitation of 250 mm/year), with the exception of the northern parts which receive up to 2,000 mm precipitation per year. Scarcity of surface water resources in a large part of the country is one of the main constraints in the development in both the economy as a whole and industrial sectors in particular. This has led to the overexploitation of groundwater resources in alluvial plains as well as in hard rock aquifers. Precise and comprehensive knowledge of water resources are therefore needed to enable the authorities to make proper assessments and plan in order to ensure meeting water demand. The method of study applied in the investigation of water resources, like any other study, is the most important factor in achieving the reliable evaluation of the problem at hand. Terwey (1984) states that the best way to develop a comprehensive understanding of groundwater is the use of direct data instead of data acquired from indirect methods. Isotopes (or in the other words, environmental tracers) can be referred to as the water cycle's 'fingerprints' (Kumar *et al.*, 2011; Yin *et al.*, 2011). Stable and radioactive environmental isotopes have been known for several decades as an effective tool in studying groundwater and hydrological systems (Sidle, 1998; Thomas & Rose, 2003; Aggarwal *et*

al., 2005a; Herczeg and Leaney, 2011; Sanford *et al.*, 2011). In addition, isotopes provide unique information about water resources' characteristics in a cost efficient, accurate and easy-to-use way (Aggervall *et al.*, 2005a). In groundwater hydrology, isotopes provide a direct insight into the movement and distribution processes within aquifers (Terwey, 1984). Some of the most common and important uses of stable and radiogenic isotopes in hydrological systems studies include:

- . Groundwater flow and groundwater dynamics studies (e.g., Sukhija *et al.*, 2006; Lee *et al.*, 2010; Carreira *et al.*, 2011; Majumder *et al.*, 2011; Tokunaga *et al.*, 2011).
- . Groundwater age and residence time estimation (e.g., Kazemi *et al.*, 2006; Land & Huff, 2010; Knowles *et al.*, 2010; Chen *et al.*, 2011; Bayari *et al.*, 2011).
- . Groundwater renewability investigation (e.g., Zhang *et al.*, 2005).
- . Groundwater and surface water pollution assessment (e.g., Kim, 1999; Toth and Katz, 2006; Kumar, 2013).
- . Groundwater models verification (e.g., Fekete *et al.*, 2006; Li *et al.*, 2010; Murphy *et al.*, 2011; Zuber *et al.*, 2011; Null *et al.*, 2012).
- . Local meteoric water line construction (e.g., Goni, 2006; Breitenbach *et al.*, 2010; Yin *et al.*, 2011; Danieleescu & Mac Quarrie, 2013).

- . Submarine groundwater discharge (SGD) studies (e.g., Charideh *et al.*, 2007; Bayari *et al.*, 2011; Sieyes *et al.*, 2011).
- . The evolution of leachate from landfills (e.g., Hackley *et al.*, 1996; Leung & Jiao, 2006; Mohammadzadeh *et al.*, 2006).
- . Remediation investigations (e.g., Einsiedl *et al.*, 2005; Fernandes *et al.*, 2009; Imfeld *et al.*, 2011).
- . Evaluating the mechanism of pollutant transportation (e.g., Hendry *et al.*, 2001; Pronk *et al.*, 2009; Imfeld *et al.*, 2011).
- . The source of salinization and groundwater salinity (e.g., Bouchaou *et al.*, 2008; Moller *et al.*, 2008; Horst *et al.*, 2011; Elgettafi *et al.*, 2013).
- . Identifying seawater intrusion mechanisms in coastal regions (e.g., Jørgensen *et al.*, 2001; Zakhem and Hafez, 2007; Han *et al.*, 2011).
- . Confirming interconnections between aquifers as well as groundwater–surface water interactions (e.g., Toth and Katz, 2006; Cartwright *et al.*, 2009; Dor *et al.*, 2011).
- . Hydrograph separation in surface waters (e.g., Burns 2002; Kubota and Tsuboyama, 2003; Liu *et al.*, 2008).
- . The determination of catchments and the recharge areas of springs (e.g., Matter *et al.*, 2005; Bouchaou *et al.*, 2008; Parisi *et al.*, 2011; Utting *et al.*, 2013).
- . Climate change and the evaluation of paleowaters (e.g., Goni, 2006; Zhou *et al.*, 2010; Sidle and Cvetic, 2011; Kuttel *et al.*, 2012).
- . The estimation of the water budget of lakes (e.g., Gibson, 2001; Ayenew, 2003; Horita, 2009).
- . Improvements in water resources management (e.g., Jamnik *et al.*, 2004; Nachiappan *et al.*, 2004; Herczeg *et al.*, 2007; Bouragba, 2011; Venugopal, 2011).
- . Groundwater study in permafrost regions (e.g., Hayashi *et al.*, 2004; Ireson *et al.*, 2013; Utting *et al.*, 2013).

There are a large number of environmental isotopes which can be used in hydrological studies, depending upon the aims and objectives set as well as the availability of laboratory facilities. Table 1 shows the list of such tracers. Oxygen-18 and deuterium are the most common isotopes employed in hydrology and hydrogeology for a range of goals. However, the most valuable information could be achieved by using a combination of stable isotope data with other hydrogeological methods.

This contribution provides an overview of the

current state of the art isotope hydrology studies in Iran. It is the first to collect, list and synthesize all the published materials relevant to isotope hydrology in Iran in one place. We have tried to assemble all the relevant publications: publications appearing in national and international journals and in the proceedings of national and international conferences, the internal reports of various organizations, as well as MSc and PhD theses carried out at universities, were all collected and collated. We have carried out an extensive data search and we have looked into all the databases to retrieve these publications. We also point to the gaps that need to be filled and the achievements that have been made in hydrogeology by using isotopes. It therefore can act as a benchmark paper to guide future researchers to concentrate their work in areas where more isotopic work is needed.

As the second objective, an Iranian meteoric water line (IMWL) has been constructed for Iran by using the isotopic composition of precipitation in seven cities in various parts of the country. This line is highly valuable in both surface and groundwater isotope hydrology studies. Such a line can be of much more practical value in local isotopic studies than the global meteoric water line (GMWL).

Environmental isotopes applications in Iran

Like most other developing countries, the employment of isotopes in Iran has been limited in number; the history of such studies is also recent. The first isotope hydrology study in Iran is that of Zak and Gat (1975), which was devoted to identifying the source of water salinity and residual brines in Shiraz, south Iran. Altogether, the results of 70 isotope researches have been published so far. It should be pointed out that some studies have resulted in two or more publications. For instance, the results of a graduate thesis may have been presented at a national conference and may also have been published as a journal paper. In cases like this, we have selected the journal paper as the basis and did not count the other two forms of publication.

Figure 1 shows the distribution of the isotope study sites in Iran. Based on the type of application, the studies have been divided into 13 broad fields. It should be mentioned that some studies may have had a few applications. For example, one might report on both the source of salinity and the

determination of the recharge area of springs. In such cases, the application mentioned in the title of the publication has been selected as the base. In the following section, these 13 fields are discussed in detail.



Figure 1: Distribution of the isotope study sites in Iran.

Isotope composition of precipitation, groundwater and climate change issues

The greatest number of publications are in this field - 25 publications. These are mainly internal reports of the water departments, which discuss the isotope composition of groundwater and surface water in different areas of the country (TAMAB 1982a, 1982b, 1985, 1987a, 1987b, 1987c, 1992a, 1992b, 1996, 1998, 1999, 2002, 2005a, 2005b, 2005c). In addition, Khademi *et al.* (1997) used the ^{18}O and ^2H isotope composition of precipitation in Isfahan to demonstrate the hydration mechanism of gypsum in central Iran. Likewise, the mode of decomposition of gypsum has been investigated via the application of the ^{18}O and ^2H isotopes of precipitation in Rafsanjan, eastern Iran, by Farpoor *et al.* (2004).

Khalaj Amirhosseini *et al.* (2007) investigated the isotope composition of groundwater to determine the recharge sources in the Tabas coal mining area. Similarly, the relationship between meteoric and groundwater isotope compositions in the Mashhad area, northeast Iran, was studied by Mohammadzadeh (2010). Additionally, Mirnejadat *et al.* (2011) examined the isotope composition of Marun oil field brines. Likewise, the geochemistry and ^{18}O and ^2H isotope composition of the Kardeh dam lake, northeast Iran, was investigated by Mohammadzadeh and Heydarizad (2012). The effect of temperature, quantity and elevation on the deuterium and ^{18}O concentrations of precipitation

in Tehran and Kabul city have been estimated by Mosafa and NasiriSaleh (2013). In addition, Karimi (2013a) studied the composition of ^{18}O and ^2H isotopes in West Zagros precipitation. Similarly, a local meteoric water line (LMWL) has been developed in Shahrood City, northeast Iran, by Kazemi (2013). Finally, Heydarizad and Mohammadzadeh (2011) studied climate change in Tehran by studying the concentration of ^{18}O and deuterium in local precipitation.

Sources of salinization and hydrothermal water

There are 13 publications available on this topic. Raeisi *et al.* (1999) examined the sources of salinity in Rahmat karstic springs in south Iran by using ^{18}O . Moreover, the source of salinity in the Shahpour river basin in south Iran was investigated by Hatami *et al.* (2007). In the same way, Sisakht *et al.* (2009) used ^{18}O and D isotopes to resolve the sources of salinity in maroon oil field brines. The sources of salinization in a coastal aquifer in Bousheher, south Iran, were evaluated with the use of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ isotopes (Mohammadi *et al.*, 2012). Similarly, Zarei *et al.* (2012) examined the causes of salinity in eight karstic springs in the Konarish area, south-central Iran, by applying ^{18}O and ^2H isotopes. Likewise sources of brine in the Kangan gas field have been investigated by Bagheri *et al.* (2012) by the application of isotope and hydrogeochemical approaches.

The Khoy geothermal area in the extreme northwest of Iran was studied by Balderer *et al.* (2004) via ^{18}O and ^2H isotopes. Additionally, Rajay and Asghari Moghaddam (2002) studied the hydrochemistry and geometry of mineral and thermal springs in the southeast Sabalan Mountains in northwest Iran by applying ^{18}O and ^2H isotopes. Moreover, the geothermal energy sources and mineralization in Taftan pluton, east of Iran, were investigated by Boomeri (2005), who used ^{18}O and ^2H isotopes. Furthermore, Aghazadeh and Asghari Moghaddam (2006) pinpointed the sources of the Sabalan thermal springs using hydrogeological, hydrochemical and isotope techniques. Karimi and Moore (2008) applied ^{18}O and ^2H isotopes to investigate the source and heating mechanism in the Ahram, Mirahmad and Garu thermal springs in the Zagros Mountains. Likewise, Shakeri *et al.* (2008) investigated water-rock-gas interactions in the Taftan volcanic mount using hydrochemistry and ^{18}O and ^2H isotopes. In addition, hydrochemistry

and ^{18}O and ^2H isotopes were applied to investigate the Kangan thermal spring in the Zagros region (Mohammadi *et al.*, 2010). Finally, Khojamli *et al.* (2011) examined the ^{18}O and ^2H isotopic composition of geothermal waters in the Meshkin-Shahr geothermal area in the north of Iran.

Study of natural recharge and the determination of recharge areas

There are 12 publications in this field. Ahmadipour (2002) used ^{18}O , deuterium and tritium to determine the recharge area and the role of the Sarvak formation in recharging the karstic springs of Pol-e Dokhtar, southwest Iran. The source of the Ziarat thermal spring (the north of Iran) was explored by Raghimi and Yakhkashi (2002) by the application of ^{18}O , ^2H and ^3H isotopes as well as by hydrochemical methods. Ahmadipour (2003) used ^{18}O and deuterium to evaluate the karstic spring recharge source in the Alashtar area, which is situated in the western part of Iran. Likewise, the sources of karstic springs in the western flank of the Ravandi anticline at the boundary of the Ilam and Lorestan provinces was investigated by applying ^{18}O and ^2H isotopes, hydrochemistry and a water budget by Bagheri *et al.* (2005). Karimi *et al.* (2005) employed ^{18}O and ^2H isotopes, a water budget and other hydrogeological methods to determine the karstic springs' recharge area in the Allvand basin in the west of Iran. In addition, the sources of water in the water transferring tunnel of the Seymareh dam in Ilam province have been identified by the ^{18}O and ^2H isotopes (Karimi & Tavakoli, 2007). Zarei and Damough (2010) examined the sources of water downstream the Karun-3 dam, east of Khuzestan province in southwest Iran, by using hydrochemistry and ^{18}O and ^2H isotopes. Similarly, groundwater zonation and recharge area determination were carried out by Seyedipour *et al.* (2009) at the Behesht Abad dam site in central west Iran using ^{18}O , ^3H and ^2H isotopes. Khosravi (2011) applied ^{18}O and ^2H isotopes to determine the hydraulic connection between the catchment area of the Emam Gheis spring and the adjacent aquifer in central-west Iran. The water resources and change in water quality in the Zarivar basin, Kordistan province, have been assessed using hydrochemistry and isotopic methods simultaneously by Mohammadzadeh and Ebrahimipour (2012). The catchment area of the Beshiveh karstic spring in west Kermanshah has

been mapped via ^{18}O and ^3H isotopes by Karimi (2013b). Finally, Kalantari and Mohamadi Behzad (2013) applied ^{18}O and ^2H isotopes to investigate the sources of recharge of the Sabz Ab and Bibi Talkhoon karstic springs in Khuzestan, Iran.

Informative studies and groundwater modelling

There are eight studies which deal with this subject. Sepasi (1994) has drawn attention to the applicability of environmental isotopes in assessing the hydrology of snow and ice. An example of isotope application in the evaluation of karst water resources was presented by Pakzad and Afrassiabian (1998). Additionally, Shahi and Najafi (2008) wrote one contribution detailing the methodology and application of isotope hydrology in Iran and a number of other countries. An introduction to analytical instruments in environmental isotopes has been presented by Mohammadzadeh (2009). Similarly, an introduction to the applicability of isotopes in surface water hydrology has been written by Zarei *et al.* (2013a). Furthermore, Mohammadzadeh and Shirzad (2013) wrote a contribution describing changes in the concentration of dissolved inorganic carbon (DIOC) and ^{13}C in a groundwater system. Nikghoj and Mohammadzadeh (2013) explained the applicability of ^{13}C in the separation of the hydrographs of karst springs. Finally, Heydarizad and Mohammadzadeh (2013) used PHREEQC to model isotopic separation (^{18}O and ^2H) through the Rayleigh distillation process.

Groundwater – surface water interaction

There are five publications on this subject. Pakzad and Afrasiabian (1998) employed ^{18}O , ^2H and tritium isotopes to investigate the interconnection between precipitation and karstic springs in Dashte Arzhan, south Iran. In addition, the potential of leakage at the Khersan-3 dam site, east of Lordegan city, southwest Iran, has been investigated using hydrogeological approaches and stable isotopes (Karimi Vardajani *et al.* 2007). Kazemi *et al.* (2009) used the ^{13}C isotope of methane to assess SGD into the Caspian Sea in northern Iran. Similarly, Rezaie (2010) applied ^{18}O and ^2H isotopes together with other hydrological methods to resolve the hydrogeology and hydrology of Shadkam Lake in Shiraz, south Iran. Likewise, Mohammadzadeh and Heydarizad (2011) studied the interaction between the Kardeh dam and

groundwater in Mashhad, east Iran, using ^{18}O , ^2H and hydrochemical methods.

Karst development and hydrograph separation

There are four articles dealing with this field. Maghsoodi *et al.* (2009) used tritium isotopes together with other hydrochemical and physical parameters to evaluate karst development in the Bisooton area, western Iran. Chitsazan *et al.* (2013) investigated the development of karst in the east of Iran by applying the collection of ^{18}O , ^2H , ^3H and ^{14}C isotopes. Shamloo (2002) used tritium and hydrochemistry to separate river flow and base flow in order to develop a conceptual model in the Kasilian basin in the north of Iran. Finally, Zarei *et al.* (2013b) applied stable isotopes to separate the run-off from the base flow in the Abolabbas karstic basin in southwest Iran.

Pollution and mechanisms of pollutant transportation

Three publications have been recorded in this field. Khodai *et al.* (2012) studied the origin of nitrate by applying ^{15}N and ^{18}O isotopes in the Dezful plain, southwest Iran. Similarly, sources of nitrate pollution in Shiraz groundwater have been investigated using ^{15}N and ^{18}O isotopes (Amiri & Zare, 2013). Finally, Nassery *et al.* (2013) applied ^{34}S to investigate sources of sulphate in a number of springs in the Zagros fold belt, western Iran.

Hydrogeological implications of isotopic studies in Iran

As discussed above, various researchers have applied different isotopes for a number of hydrogeological objectives. One of the main implications of the use of isotopes in Iran is the estimation of recharge amounts and the determination of the watershed areas of large important karst springs. In Iran, large karstic springs provide a considerable amount of good-quality water for a range of uses, especially for domestic water needs. The application of isotopes for evaluating the source and origin of recharge to these springs is therefore a key responsibility of hydrogeologists (e.g., Ahmadipour, 2002; Karimi *et al.*, 2005; Seyedipour *et al.*, 2009). When using isotopes in such studies, it is not necessary to analyse a huge quantity of hydrometeorological data collected over a considerable time span, which is generally inadequate or unreliable in many

regions (Charideh, 2012). The second hydrogeological issue which has been addressed by the employment of isotope techniques in Iran is the identification of sources of pollution and how solutes are transported in groundwater systems (e.g., Khodai *et al.*, 2012; Nassery *et al.*, 2013). However, this has only been carried out for a few aquifers. The third subject concerns hydrothermal waters as a new and nature-friendly source of energy, and the role of isotopic studies in exploring these resources (e.g., Balderer *et al.*, 2004; Khojamli *et al.*, 2011). Iran is potentially rich in these resources. In addition, in complicated geological and hydrological conditions, isotopes have acted as a key tool more reliably revealing the sources of natural groundwater salinization (e.g., Raeisi *et al.*, 1999; Zarei *et al.*, 2012).

Gaps

There are some gaps in our understanding of hydrogeological systems in Iran that could be filled if we were to have easier access to isotopes techniques and laboratories. For instance, Karimi and Ashjari (2010) pointed out that isotopic techniques are required to verify a mathematical flow model in a complex hydrogeological system in western Iran. Similarly, Kamali *et al.* (2010) have mentioned that the application of isotopes is a necessity to obtain further details about the capture zone and the required protective measures for the Margoon waterfall, a nationally important waterfall. In addition, Kalantari and Mohammadi (2011) have mentioned that an artificial tracer test was able to yield only general information about the relationship between sinkholes and spring discharge rates in the Alburz Mountains in northern Iran. If used, isotope techniques could yield detailed information in such studies. One of the issues that could be explored by the use of isotope techniques is the subject of fossil waters and paleowaters that are possibly hidden in extensive deserts, covering about a quarter of the land area of Iran. Constructing local meteoric water lines for different parts of the country is another issue that deserves more attention. Other gaps that could be filled by isotope studies include:

- a. Renewability studies and recharge estimations for aquifers in arid and hyper-arid parts of the country.
- b. Quantifying different causes and sources of the salinization of snow and rain.

- c. Studying the impact of nuclear power plants on groundwater resources, if any.
- d. Sources of saline waters in oil and gas fields. Saline water produced in gas fields imparts considerable costs to the wellhead facilities and pipelines.

Iran's national meteoric water line

By collecting the published data regarding the isotope composition of precipitation in seven distinct locations in Iran, an IMWL has been developed. The spatial distribution of the seven cities which are included in the construction of the Iranian water line is such that it covers a large part of the country. These cities are located in the north (Shahrood and Gorgan), south (Shiraz), west (Kerend), east (Rafsanjan) and central Iran (Tehran and Isfahan). Interestingly, the average precipitation of the seven studied cities (299 mm) is considerably similar to the average annual precipitation of the whole country, which is 250 mm. In addition, if Gorgan is excluded, the average rainfall of the six remaining cities equals 244 mm,

almost identical to the national average. There are only two samples from Gorgan, and we can therefore easily eliminate the Gorgan samples from the list without affecting the slope or the d-excess of the constructed line. Considering that the amount of precipitation is one of the important factors which controls the isotopic characteristics of precipitation, and since the average rainfall of the selected cities is close to the national average, therefore, we can confidently assert that the constructed line represents the Iranian line well.

As shown in Fig. 2 and Table 2, the countrywide isotopic composition of precipitation is within the range of -15% to 8.69% for ^{18}O and -102.7% to 67% for ^2H . The average values of ^{18}O and deuterium in precipitation are -4.95% and 27.5% , respectively. In arid conditions, the slope of the MWL is between 5 and 8 (Kazemi, 2013). As can be seen in Fig. 2, the slope of the constructed line is 6.89, which is lower than the GMWL slope (Table 3 presents the equations of various local meteoric water lines in Iran).

Table 1: Most common isotopes applied in water science

Application	Applicable isotopes
Young groundwater age dating	^{85}Kr , CFC, ^{81}Kr , ^{35}S , ^7Be , Ne, He, ^3H , ^{13}C , ^{39}Ar
Old groundwater age dating	^{238}U , ^{226}Ra , ^{13}C , ^4He , ^{36}Cl , ^{39}Ar , ^{14}C
Contaminant investigations and identification of pollution sources	^{15}N , ^{11}B , ^{37}Cl , ^{87}Sr , ^{13}C , ^{34}S , ^2H , ^{18}O , ^3H
Climate change studies	^2H , ^{18}O
Mixing and interaction between aquifers and surface water	^2H , ^{18}O , ^{13}C , ^{87}Sr , ^{88}Sr
Identification of paleowaters	^2H , ^{18}O
Groundwater dynamics	^2H , ^{18}O , ^{13}C , ^3H - ^3He , ^{37}Cl , ^{14}C
Identification of recharge areas	^{36}Cl , ^3H , ^2H , ^{18}O , ^{11}B , ^{14}C , ^{87}Sr
Dam leakage into aquifers	^2H , ^{18}O
Salinization mechanisms and sources	^{37}Cl , ^2H , ^{18}O
Water-rock interactions	^{87}Sr , ^{88}Sr , ^{34}S
Groundwater flow in geothermal systems	^{18}O , ^{34}S , ^2H , ^{87}Sr , ^{88}Sr
SGD evaluation	^{13}C , ^{223}Ra , ^{224}Ra , ^{226}Ra , ^2H , ^{18}O , ^3H , ^{87}Sr
Construction of local meteoric water line	^2H , ^{18}O
Water budget studies for lakes	^2H , ^{18}O , CFC
Natural and artificial recharge evaluation	$^{87}\text{Sr}/^{86}\text{Sr}$
Validation of groundwater flow models	^2H , ^{18}O , ^3H - ^3He , ^{36}Cl
Evaluation of leachate from landfills	^2H , ^{18}O , ^{13}C , ^3H
Identifying seawater intrusion mechanism in coastal regions	^{13}C , ^2H , ^{18}O
Hydrograph separation	^2H , ^{18}O , ^3H
Groundwater study in the permafrost regions	^2H , ^{18}O , ^{13}C , Ne, Ar, Kr, Xe

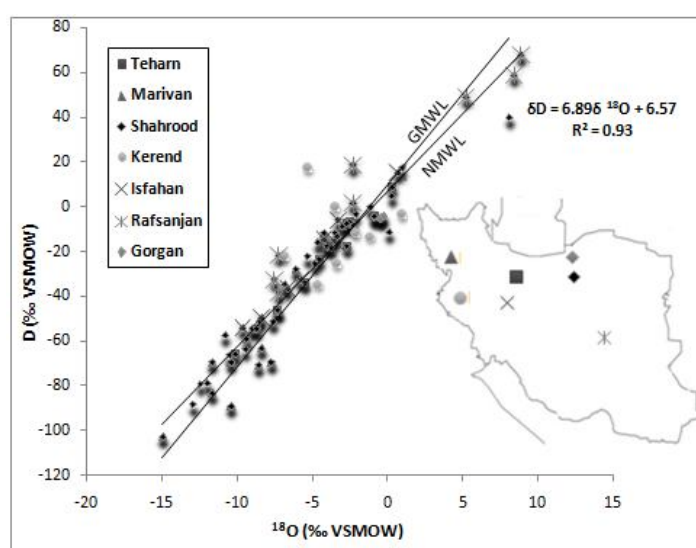
Figure 2: Deuterium and ^{18}O composition of precipitation samples in Iran and the resultant national meteoric water line.

Table 2: Isotopic composition of precipitation in Iran

Sample Location	Date (dd/mm/yyyy)	D (‰)	^{18}O (‰)	Sample Location	Date (dd/mm/yyyy)	D (‰)	^{18}O (‰)
Tehran ^a	1961-2004	-10.18	-65.75	Shahrood	07/2010	8.05	39.84
Tehran	1961-2004	-5.48	-34.2	Shahrood	10/2010	0.10	-11.40
Tehran	1961-2004	-4.095	-17.75	Shahrood	01/2010	-10.80	-57.40
Tehran	1961-2004	-4.525	-23.65	Shahrood	07/02/2011	-12.5	-79.4
Tehran	1961-2004	-2.475	-6.55	Shahrood	27/03/2011	-12.9	-88.65
Tehran	1961-2004	-2.68	-7.1	Shahrood	27/03/2011	-10.55	-66.45
Tehran	1961-2004	-0.92	-4.1	Kerend ^d	08/03/2000	-15.8	-4.6
Tehran	1961-2004	0.31	9	Kerend	16/03/2000	-34.5	-6.9
Tehran	1961-2004	-2.67	-17.9	Kerend	25/03/2000	-22.5	-5.28
Tehran	1961-2004	-3.77	-18.45	Kerend	08/03/2000	17.1	0.97
Tehran	1961-2004	-7.365	-46.05	Kerend	16/03/2000	-3.4	-2.09
Tehran	1961-2004	-8.675	-54.6	Kerend	25/03/2000	-11.8	-3.5
Marivan ^b	2010	-69.7	-7.7	Kerend	08/03/2000	-0.03	-1.2
Marivan	2010	-70.9	-8.6	Kerend	16/03/2000	-13	-3.38
Marivan	2010	-63.4	-8.4	Kerend	25/03/2000	-25.6	-4.81
Marivan	2010	-51.6	-7.6	Isfahan ^c	20/03/1994	-3.3	-6.3
Marivan	2010	-8.9	-3	Isfahan	10/09/1995	0.7	15.1
Marivan	2010	-11.8	-4.3	Isfahan	04/02/1996	-6.7	-36.3
Marivan	2010	-54.5	-9	Isfahan	06/02/1996	-9.7	-54.3
Marivan	2010	-69.6	-10.4	Isfahan	20/02/1996	-3.6	-15.2
Marivan	2010	-46.9	-7.2	Isfahan	22/02/1996	-8.4	-49.8
Marivan	2010	-8.2	-2.3	Isfahan	03/03/1996	-5.8	-32.9
Marivan	2010	-102.7	-15	Isfahan	04/03/1996	-4.3	-14.2
Marivan	2010	-59.5	-9.4	Rafsanjan ^f	02/11/1999	5.2	48.9
Marivan	2010	-83.1	-11.7	Rafsanjan	23/11/1999	-2.3	18.8
Marivan	2010	-28	-6.1	Rafsanjan	12/12/1999	-7.5	-32.8
Marivan	2010	-69.8	-11.7	Rafsanjan	09/01/2000	-7.2	-21.3
Marivan	2010	-89.1	-10.4	Rafsanjan	16/01/2000	-7.2	-38.3
Shahrood ^e	06/2009	0.29	4.85	Rafsanjan	19/01/2000	-2.3	1.7
Shahrood	02/2009	-8.54	-51.10	Rafsanjan	25/02/2000	8.9	67.79
Shahrood	03/2009	-9.44	-63.65	Rafsanjan	21/08/2001	8.4	58.6
Shahrood	04/2010	-0.90	-4.82	Gorgan ^g	10/04/2009	-0.3	-4.23
Shahrood	11/2010	-11.98	-78.62	Gorgan	10/04/2009	-0.5	-5.57
Shahrood	05/2010	-0.41	-5.03				

Source of data:

^a Based on the monthly average of data reported by the IAEA GNIP (1961-1979 and 2000- 2004)^b Mohammadzadeh and Ebrahimpoor (2012)^c Kazemi (2013)^d Karimi (2013)^e Khademi *et al.* (1997)^f Farpoor *et al.* (2004)^g Kazemi (2013)

Table 3: Correlation equations and coefficients (R^2) between deuterium and ^{18}O in precipitation of various regions of Iran

Location	Correlation equation	R^2
Tehran ^a	$\delta\text{D} = 6.46\delta^{18}\text{O} + 0.24$	0.91
Marivan ^a	$\delta\text{D} = 8.07\delta^{18}\text{O} + 11.55$	0.85
Shahrood ^c	$\delta\text{D} = 5.47\delta^{18}\text{O} - 5.5$	0.96
Kerend ^d	$\delta\text{D} = 6.53\delta^{18}\text{O} + 5.56$	0.97
Isfahan ^e	$\delta\text{D} = 7.1\delta^{18}\text{O} + 12.3$	0.97
Rafsanjan ^f	$\delta\text{D} = 5.88\delta^{18}\text{O} + 15.83$	0.96

References:

^a Based on the monthly average of data reported by the IAEA GNIP (1961-1979 and 2000- 2004)^b Mohammadzadeh and Ebrahimpoor (2012)^c Kazemi (2013)^d Karimi (2013)^e Khademi *et al.* (1997)^f Farpoor *et al.* (2004)

This can be attributed to the semi-arid/arid climate which prevails across a large part of the country. In such a climate, secondary raindrop evaporation during a rain event leads to heavy isotope enrichment. It should be noted that both the amount and intensity of precipitation are factors that govern the isotope composition of the precipitation. There is a negative correlation between the amount and intensity of precipitation and the slope of the meteoric water line (Yin *et al.*, 2012). Average precipitation in Iran is 250 mm, while the world average is 850 mm (Heydarizad & Mohammadzadeh, 2011). Fig. 2 also shows that the deuterium excess of the NMWL is 6.57, lower than the global mean which is 10. This is attributed to lower humidity in Iran compared to world average humidity.

Conclusions

The applications of environmental isotopes in hydrology and hydrogeology in Iran are mainly limited to only a few general types of applications. Of the 70 isotope hydrology publications, the majority merely describe the isotopic composition of either groundwater or precipitation. Although the

identification of recharge sources, the determination of the catchment areas of the springs and studies related to the causes of salinization have received some attention, the chief hydrogeological and hydrological implications of the isotopes remain undisclosed in Iran. This is mainly due to the lack of laboratory facilities. As a result of this, Iranian scientists are deprived of this technique, which is an effective tool in the management of water resources, particularly in arid and semi-arid regions like Iran. We have here constructed an IMWL (slope 6.89 d-excess 6.57) by using the available precipitation isotopic data of seven sites located in geographically distinct locations. Before a new line which covers larger part of the country is generated, it is recommended to use this line - instead of GWML - in future isotope hydrology studies.

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