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

Abdollah Shamsi*, Gholam A Kazemi
Faculty of Earth Sciences, University of Shahrood, Shahrood, Iran
**Corresponding author, e-mail: a.shamsi@shahroodut.ac.ir*
(*received: 15/02/2014 ; accepted: 06/07/2014*)

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 (Aggerval *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; Tothand 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; Danielescu & Mac Quarrie, 2 013).

. 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.

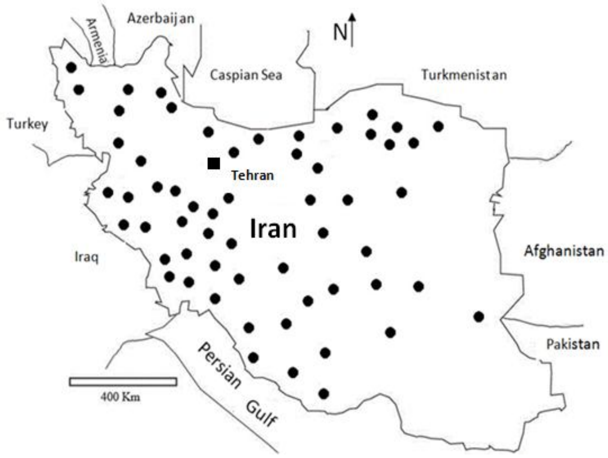

Figure 1: Distribution of the isotope study sites in Iran.

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 ^{2}H 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 ^{2}H 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, Mirnejadet *et al*. (2011) examined the isotope composition of Marun oil field brines. Likewise, the geochemistry and ^{18}O and ^{2}H 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 ^{2}H 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 δ^{18}O and δ^{2}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 ^{2}H 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 ^{2}H 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 ^{2}H isotopes. Moreover, the geothermal energy sources and mineralization in Taftan pluton, east of Iran, were investigated by Boomeri (2005), who used ^{18}O and ^{2}H 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 ^{2}H 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 ^{2}H isotopes. In addition, hydrochemistry and ^{18}O and ^{2}H 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 ^{2}H 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, ^{2}H and ^{3}H 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 ^{2}H isotopes, hydrochemistry and a water budget by Bagheri *et al*. (2005). Karimi *et al*. (2005) employed ^{18}O and ^{2}H 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 ^{2}H 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 ^{2}H 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, ^{3}H and ^{2}H isotopes. Khosravi (2011) applied ^{18}O and ^{2}H 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 Ebrahimpoor (2012). The catchment area of the Beshiveh karstic spring in west Kermanshah has been mapped via ^{18}O and ^{3}H isotopes by Karimi (2013b). Finally, Kalantari and Mohamadi Behzad (2013) applied ^{18}O and ^{2}H 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 ^{2}H) through the Rayleigh distillation process.

Groundwater – surface water interaction

There are five publications on this subject. Pakzad and Afrasiabian (1998) employed ^{18}O, ^{2}H 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 ^{2}H 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, ^{2}H 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 Bisotoon area, western Iran. Chitsazan *et al*. (2013) investigated the development of karst in the east of Iran by applying the collection of ^{18}O, ^{2}H, ^{3}H 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 Dezfull 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 ^{2}H. 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	Appilicable isotopes
Young groundwater age dating	^{85}Kr , CFC, ^{81}Kr,^{35}S, ^{7}Be,Ne,He, ^{3}H, ^{13}C,^{39}Ar
Old groundwater age dating	^{238}U, ^{226}Ra, ^{13}C, ^{4}He, ^{36}Cl,^{39}Ar, ^{14}C
Contaminantion investigations and identification of pollution sources	^{15}N, ^{11}B, ^{37}Cl, ^{87}Sr, ^{13}C, ^{34}S, ^{2}H, ^{18}O, ^{3}H
Climate change studies	^{2}H, ^{18}O
Mixing and interaction between aquifers and surface water	^{2}H, ^{18}O, ^{13}C, ^{87}Sr, ^{88}Sr
Identification of paleowaters	^{2}H, ^{18}O,
Groundwater dynamics	^{2}H, ^{18}O, ^{13}C,^{3}H–^{3}He, ^{37}Cl, ^{14}C
Identification of recharge areas	^{36}Cl, ^{3}H, ^{2}H,, ^{18}O, ^{11}B, ^{14}C, ^{87}Sr
Dam leakage into aquifers	^{2}H, ^{18}O,
Salinization mechanisms and sources	^{37}Cl, ^{2}H, ^{18}O
Water-rock interactions	^{87}Sr, ^{88}Sr, ^{34}S
Groundwater flow in geothermal systems	^{18}O, ^{34}S, ^{2}H, ^{87}Sr, ^{88}Sr
SGD evaluation	^{13}C, ^{223}Ra, ^{224}Ra, ^{226}Ra, ^{2}H, ^{18}O, ^{3}H, ^{87}Sr
Construction of local meteoric water line	^{2}H, ^{18}O,
Water budget studies for lakes	^{2}H, ^{18}O, CFC
Natural and artificial recharge evaluation	$^{87}Sr/^{86}Sr$,
Validation of groundwater flow models	^{2}H, ^{18}O, ^{3}H–^{3}He, ^{36}Cl
Evaluation of leachate from landfills	^{2}H, ^{18}O, ^{13}C, ^{3}H
Identifying seawater intrusion mechanism in coastal regions	^{13}C, ^{2}H, ^{18}O,
Hydrograph separation	^{2}H, ^{18}O, ^{3}H
Groundwater study in the permafrost regions	^{2}H, ^{18}O, ^{13}C, Ne, Ar, Kr , Xe

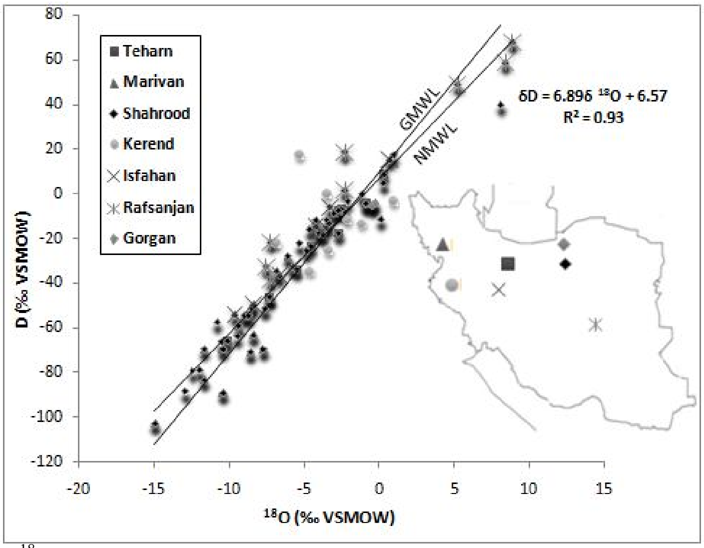

Figure 2: Deuterium and ^{18}O composition of precipitation samples in Iran and the resultant national meteoric water line.

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[e]	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[c]	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]	$\delta D=6.46\delta^{18}O+0.24$	0.91
Marivan[a]	$\delta D= 8.07\delta^{18}O+11.55$	0.85
Shahrood[c]	$\delta D=5.47\delta^{18}O-5.5$	0.96
Kerend[d]	$\delta D= 6.53\delta^{18}O+5.56$	0.97
Isfahan[e]	$\delta D= 7.1\delta^{18}O+ 12.3$	0.97
Rafsanjan[f]	$\delta D= 5.88\delta^{18}O+ 15.83$	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.

Acknowledgements

The authors greatly acknowledge the efforts of Ms. F. Jafari from the Institute of Water Research, WRI, Tehran, for her kind assistance in providing the internal reports of the WRI.

References

Aggarwal, PK., Froehlich, K., Gonfiantini, R., Gat, JR., 2005a. Isotope hydrology: a historical perspective from the IAEA. In: Aggarwal, PK., Gat, JR., Froehlich, K., (eds) Isotopes in the water cycle: past, present and future of a developing science. Springer, Berlin, pp 3–8.

Aghazadeh, N., Asghari-Moghaddam, A., 2006. Hydrogeological and hydrochemical evolution of Sabalan thermal springs. Proceedings of the 10th Symposium of Geological Society of Iran, August 2006, Tehran, Iran, pp 142–152.

Ahmadipour, M.R., 2002. The role of Sarvak formation in supplying Pol–e Dokhtar town (Iran) with drinking water. Acta carsologica, 31: 93–103.

Ahmadipour M.R., 2003. Karst springes of Alashtar., Iran. Acta carsologica, 32: 245–254.

Amiri, H., Zare, M., 2013.investigation of nitrate pollutant sources in Shiraz city groundwater aquifer by application of nitrogen and oxygen stable isotopes. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 48–53.

Ayenew, T., 2003.Environmental isotope–based integrated hydrogeological study of some Ethiopian rift lakes. Journal of Radioanalytical and Nuclear Chemistry, 257: 11–16.

Bagheri, R., Nadri, A., Raeisi R., Kazemi G.A., Eggenkamp H. G. M., Montaseri A., Origin of brine in the Kangan gasfield: isotopic and hydrogeochemical approaches. Environmental Earth Sciences. (2013), dio: 10.1007/s12665-013-3022-7.

Bagheri, R., Raeisi, E., Mohammadi, Z., Bahadory, F., 2007. Source of the eastern part of Ravandi anticline springs using 2H–18O Isotopes., hydrochemistry and water budget. Proceedings of the 11th Symposium the Geological Society of Iran. Mashhad, Iran, pp 21–29.

Balderer, W., Leuenberger, F., Khalaj, Amirhossainee, Y., Hatami, F., Jahani, H.R., Kulkarni, K.M., 2007. Characterization of the Khoy geothermal area NW Iran based on isotope and chemical investigations. Proceeding Sympposium Advance in Isotope hydrology and its role in sustainable water resource management.vol 2. IAEA, Vienna, pp 621–630.

Boomeri, M., 2005.Assessment of geothermal energy and mineralization in Taftan volcano using stable isotopes in water. Geography and Development Iranian Journal 3:25–40 [In Persian., with abstract in English].

Bouchaou, L., Michelot, J.L., Vengosh, A., Hsissou, Y., Qurtobi, M., Gaye, C.B., Bullen, T.D., Zuppi, G.M., 2008. Application of multiple isotopic and geochemical tracers for investigation of recharge., salinization., and residence time of water in the Souss–Massa aquifer., southwest of Morocco. Journal of Hydrology, 352:267– 287.

Bouragba, L., Mudry, J., Bouchaou, L., Hsissou, Y., Krimissa, M., Tagma, T., Michelot, J.L., 2011. Isotopes and groundwater management strategies under semi–arid area: Case of the Souss upstream basin (Morocco). Applied Radiation and Isotopes, 69:1084–1093.

Breitenbach, S.F.M., Adkins, J.F., Meyer, H., Marwan, N., Kumar, K.K., Haug, G.H., 2010. Strong influence of water vapor source dynamics on stable isotopes in precipitation observed in southern Meghalaya., NE India. Earth and Planetary Science Letters, 292:212–220.

Burns, D.A., 2002. Storm flow hydrograph separation based on isotopes: the thrill is gone what's next? Hydrological Processes, 16:1515–1517.

Carreira, P.M., Marques, J.M., Marques, J.E., Chamine, H.I., Fonseca, P.E., Santos, F.M., Moura, R.M., Carvalho, J.M., 2011. Defining the dynamics of groundwater in Serra da Estrela Mountain area., central Portugal: an isotopic and hydrogeochemical approach. Hydrogeology Journal, 19:117–131.

Cartwright, I., Hall, S., Tweed, S., Leblanc, M., 2009.Geochemical and isotopic constraints on the interaction between saline lakes and groundwater in southeast Australia. Hydrogeology Journal, 17:1991–2004.

Charideh, A., 2012. Recharge rate estimation in the Mountain karst aquifer system of Figeh spring, Syria. Environmental Earth Sciences, 65:1169–1178.

Charideh, A., Rahman, A., 2007. Environmental isotopic and hydrochemical study of water in the karst aquifer and submarine springs of the Syrian coast. Hydrogeology Journal, 15:351–364.

Chen, Z., Wei, W., Liu, J., Wang, Y., Chen, J., 2011. Identifying the recharge sources and age of groundwater in the Songnen Plain., Northeast China) using environmental isotopes. Hydrogeology Journal, 19: 163–176.

Chitsazan, M., Karimi, Vardajani, H., Karimi, H., Mohamadi Z., 2013.Karst development evolution in Iran's west desert regions by application of stable isotopes. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 132–141.

Danielescu, S., MacQuarrie, T.B.K., Nitrogen and oxygen isotopes in nitrate in the groundwater and surface water discharge from two rural catchments: implications for nitrogen loading to coastal waters. Biogeochemistry (2013), doi:10.1007/s10533–012–9823–z.

Dor, N., Syafalni, S., Abustan, I., M.T.A., Nazri, M.A.A., Mostafa, R., Mejus, L., 2011. Verification of surface–groundwater connectivity in an irrigation canal using geophysical., water balance and stable isotope approaches. Water Resources Management, 25:2837–2853.

Einsiedl, F., Maloszewski, P., Stichler, W., 2005.Estimation of denitrification potential in a karst using the 15–N and 18–O isotopes of Nitrate. Biogeochemistry, 72:67–86.

Elgettafi, M., Elmandour, A., Himi, M., Casas, A., The use of environmental markers to identify groundwater salinization sources in a Neogene basin., Kert aquifer case., NE Morocco. International Journal of Environmental Science and Technology (2013), doi:10.1007/s13762–012–0164–1.

Fekete, B.M., Gibson, J.J., Aggarwal, P., Vorosmarty, C.H.J., 2006.Application of isotope tracers in continental scale hydrological modeling. Journal of Hydrology, 330:444–456.

Fernandes, P.G., Carreira, P.M., Nunes, D., 2009. Environmental isotopes (15N and 18O. in the assessment of groundwater degradation: Aveiro Quaternary aquifer (NW Portugal). Journal of Radioanalytical and Nuclear Chemistry, 281:157–160.

Gao, X., Wang, Y., Wu, P., Guo, Q., 2010. Trace elements and environmental isotopes as tracers of surface water–groundwater interaction: a case study at Xin'an karst water system., Shanxi Province., Northern China Environmental Earth Sciences, 59:1223–1234.

Gibson, J.J., 2001. Forest–tundra water balance signals traced by isotopic enrichment in lakes. Journal of Hydrology, 251:1–13.

Goni, I.B., 2006.Tracing stable isotope values from meteoric water to groundwater in the southwestern part of the Chad basin. Hydrogeology Journal,14:742–752.

Hackley, K.C., Liu, C.L., Coleman, D.D., 1996.Environmental isotope characteristics of landfill leachates and gases. Ground Water, 34:827–836.

Han, D., Kohfahl, C., Song, X., Xiao, G., Yang, J., 2011.Geochemical and isotopic evidence for palaeo–seawater intrusion into the south coast aquifer of Laizhou Bay, China.Applied Geochemistry Journal, 26:863–883.

Hatami, F., Khalaj Amirhosseini, Y., Kuhpor, M., 2007. Examination source of salinity in water resource using isotope technique: a case study., water resource of Shapor River basin. Proceeding Sympposium Advance in Isotope hydrology and its role in sustainable water resource management, Vol 1. IAEA, Vienna, pp 667–673.

Hayashi, M., Quinton, W.L., Pietroniro A., Gibson, J.J., 2004. Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. Journal of Hydrology 296:81–97.

Hendry, M.J., Wassenaar, L.I., 2011. Millennial–scale diffusive migration of solutes in thick clay–rich aquitards: evidence from multiple environmental tracers. Hydrogeology Journal, 19:259–270.

Herczeg, A.L., Leaney, F.W., 2011. Environmental tracers in arid–zone hydrology. Hydrogeology Journal, 19:17–29

Herczeg, A.L., Love, A.J., Harrington, G.A., 2007. A practical approach to radiocarbon dating of groundwater. Proc. Symp. Adv. Isotope hydrology and its role in sustainable water resource management IHS–2007., vol 2. IAEA–CN–151/135., IAEA., Vienna., pp 193–201.

Heydarizad, M., Mohammadzadeh, M., 2013.Modeling of isotopic separation of by PHREQC software in Rayleigh distillation procedures. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 48–53.

Heydarizad, M., Mohammadzadeh, H., 2011. Investigating climate changes using stable isotopes (18O., 2H) composition of Tehran precipitation. Proceedings of the 7th Iranian Conference of Engineering Geology and Environment., August 2011 Shahrood., Iran, pp 256.

Horita, J., 2009. Isotopic evolution of saline lakes in the low–latitude and polar regions. AquatGeochem 15:43–69.

Horst, A., Mahlknecht, J., Zavala MLAP Mayer B., 2011. The origin of salinity and sulphate contamination of groundwater in the Colima State., Mexico., constrained by stable isotopes. Environmental Earth Sciences 64:1931–1941.

IAEA/WMO., 2013. Global Network of Isotopes in Precipitation.Available via http://isohis.iaea.org. Accessed 16 June 2013.

Imfeld, G., Pieper, H., Shani, N., Rossi, P., Nikolausz, M., Nijenhuis, I., Paschke, H., Weiss, H., Richnow, H.H., 2011. Characterization of groundwater microbial communities., dechlorinating bacteria., and In Situ Biodegradation of chloroethenes along a vertical gradient. Water Air Soil Pollut, 221:107–122.

Ireson, A.M., Kamp, G., Ferguson, G., Nachshon, U., Wheater, H.S., 2013. Hydrogeological processes in seasonally frozen northern latitudes: understanding., gaps and challenges. Hydrogeology Journal, 21:53–66.

Jamnik, B., Urbanc, J., 2004. Isotope investigations a tool for water resource management in Ljubljana City., Slovenia). Proc. Symp. Isotope hydrology and integrated water resources management., 2003., IAEA–CN–104/P–24 Vienna., pp 148–149.

Jirakova, H., 2011. Isotope hydrogeology and geothermal application to clarify the origin., the sustainability and the character of groundwater flow. Ph.D. thesis university of Bordeaux.

Jorgensen, N.O., Banoeng–Yakubo, B.K., 2001. Environmental isotopes (18O., 2H., and 87Sr/86Sr) as a tool in groundwater investigation in the Keta basin., Ghana. Hydrogeology Journal, 9:190–201.

Kalantari, N., Mohamadi Behzad, H., 2013. investigation source of recharge to Sabzab and Bibi Talkhon karstic springes by application of 18O and 2H stable isotopes. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 96–103.

Kalantari, N., Mohamadi, R., 2013. A dye-tracing investigation in the Poshte-Naz Karstic aquifer., Alburz Mountain., northern Iran. SpeleogenesisEvol Karst Aquifers10: 52–59.

Kamali, M., Mahmoudi–Sivand, S., Affrasiaban, A., 2010. Investigation Of Margoun water fall spring's catchment area and protection radius by applying tracer technique. Proceedings of The First Iranian National Conference on Applied Research in Water Resources., May 2010., Kermanshah., pp 131-138.

Karimi, H., 2013a. Differentiation of spring catchment area using isotope data., Case study: Beshiveh Plain springs., Kermanshah. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 104–109.

Karimi, H., 2013b. Investigating composition of 18O and 2H stable isotopes in precipitations of West Zagros. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 110–115.

Karimi, H., Ashjari j., 2009.., Periodic breakthrough curve of tracer dye in the Gelodareh Spring., Zagros., Iran. Cave Karst Sci 36:5–10.

Karimi, H., Farid Moore F.,., 2008. The source and heating mechanism for the Ahram., Mirahmad and Garu thermal springs., Zagros Mountains., Iran. Geothermics 37: 84–100.

Karimi, H., Tavakoli M., 2007. Examination sources of water appears at water transportation tunnel for power plant of Seymareh dam., Ilam. Journal of engineering geology, 2: 301–322 [In Persian., with abstract in English].

Karimi, H., Raeisi E., Bakalowicz M., 2005. Characterizing the main karst aquifers of the Alvand basin., northwest of Zagros., Iran, by a hydrogeochemical approach. Hydrogeology Journal, 13:787–799.

Karimi Vardajani, H., Keshavarz T., Mohammadi Z., Raeisi E., 2007. Potential leakage at the Khersan 3 Dam Site., Iran: a hydrogeological approach. Bull Eng Geol Env 66:269–278.

Kazemi, G.A., 2013. Isotope composition (18O and 2H) in precipitations of Shahrood area. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 54–60.

Kazemi, G.A., Komatsu., D.K., Tsunogai, U., 2009. The application of tracers to study submarine groundwater discharge into Gorgan Bay., Northern Iran. In: Dulati Ardejani F (ed) Proceedings of the International Conference on Water Resources: Emphasis on regional development., Shahrood University of Technology., Shahrood., Iran, pp 148–152.

Kazemi, G.A., Lehr, J.H., Perrochet, P., 2006.Groundwater Age: John Wiley And Sons. Hoboken., NJ 325 pp.

Khademi, H., Mermut, A.R., Krouse, H.R., 1997. Isotopic composition of gypsum hydration water in selected landforms from central Iran. Chem Geol 138: 245– 255.

Khalaj Amirhosseini, Y., Hatami, F., Kuhpor, M., 2007. Isotope studies of water resources (Tabas area case study) Proceeding Sympposium Advance in Isotope hydrology and its role in sustainable water resource management. vol 2. IAEA, Vienna, pp 387–393.

Khodaie, K., Mohammadzadeh, H., Nassery, H.R., Shahsavari, A.A 2012.Investigation of groundwater nitrate in Dezfull–Andimeshk and examining sources of them with application of 15N and 18O isotopes. Iranian Journal of Geology, 6:93–11. [In Persian., with abstract in English].

Khojamli, A., Doulati Ardanjani, F., Moradzadeh, A., Porkhial, S., 2011.Isotopic study of the thermal springs in NW Sabalan., Meshkinshahr. Proceedings of the 4th Iranian Mine Engineering Conference, October 2010, Tehran, Iran, pp 22–28.

Khosravi, R., 2011. Investigating the presence or lake of hydraulic connection between catchment area of karst Emam Gheis spring and adjacent aquifer. MSc thesis, Shahrood University of Technology.

Kim, K., 1999. Geochemical evolution of groundwater along a flow path determined from oxygen isotope analysis in a carbonate free, silicate aquifer. Geosciences Journal, 3:191 – 200.

Knowles, L.J., Katz, G.B., Toth, D.T., 2010. Using multiple chemical indicators to characterize and determine the age of groundwater from selected vents of the Silver Springs Group, central Florida, USA. Hydrogeology Journal, 18:1825–1838.

Kubota, T., Tsuboyama, Y., 2003. Intra and inter storm oxygen–18 and deuterium variations of rain, through fall, and stem flow, and two components hydrograph separation in a small forested catchment in Japan. Journal of Forest Research, 8:179–190.

Kumar, P., 2013. Multi isotopic approach to study temporal variation of groundwater quality in coastal aquifer of Saijo Plain, Shikoku Island, Japan. Water Resources 40:208–216.

Kumar, M., Someshwar Rao, M., Kumar, B., Ramanathan, A., 2011. Identification of aquifer recharge zones and sources in an urban development area (Delhi, India), by correlating isotopic tracers with hydrological features. Hydrogeology Journal, 19:463–474.

Kuttel, M., Steig, J.E., Ding, Q., Monaghan, A.J., Battisti, D.S., 2012. Seasonal climate information preserved in West Antarctic ice core water isotopes: relationships to temperature, large scale circulation and sea ice. Climate Dynamics, 39:1841–1857

Land, L., Huff, G.F., 2010. Multi–tracer investigation of groundwater residence time in a karstic aquifer: Bitter Lakes National Wildlife Refuge., New Mexico., USA. Hydrogeology Journal, 18:455–472.

Lee, J., Jung, B., Kim, J.M., Ko, K.S., Chang, H.W., 2010. Determination of groundwater flow regimes in underground storage caverns using tritium and helium isotopes. Environmental Earth Sciences, 63:763–770.

Leung, C.M., Jiao, J.J., 2006.Use of Strontium Isotopes to Identify Buried Water Main Leakage Into Groundwater in a Highly Urbanized Coastal Area. Environmental Science & Technology, 46:6575–6579.

Li, S.L., Liu, C.O., Lang, Y.Ch., Zhao, Z.Q., Zhou, Z.H., 2010. Tracing the sources of nitrate in karstic groundwater in Zunyi, Southwest China: a combined nitrogen isotope and water chemistry approach. Environmental Earth Sciences, 60:1415–1423.

Liu, Y., Fan, N., An, Sh., Bai, X., Liu, F., Xu, Z., Wang, Z., Liu, Sh., 2008. Characteristics of water isotopes and hydrograph separation during the wet season in the Heishui River, China. Journal of Hydrology, 353:314–321.

Maghsoodi, M., Karimi, H., Safari, F., Charrahi, Z., 2009. Karst development evaluation in Perova–Bisoton karstic area with application of breakthrough coefficient., dead time of spring and analysis of hydrochemical and isotopic data. Natural Geography Investigation, 69:51–65 [In Persian, with abstract in English].

Majumder, R.K., Halim, M.A., Saha, B.B., Ikawa, R., Nakamura, T., Kagabu, M., Shimada, J., 2011.Groundwater flow system in Bengal Delta, Bangladesh revealed by environmental isotopes. Environmental Earth Sciences, 64:1343–1352.

Matter, J.M., Waber, H.N., Loew, S., Matter, A., 2005. Recharge areas and geochemical evolution of groundwater in an alluvial aquifer system in the Sultanate of Oman Juerg. Hydrogeology Journal, 14:203–224.

Mirnejad, H., Sisakht, V., Mohammadzadeh, H., Amini, AH., Rostron, B.J., Haghparast, G., 2011. Major Minor elements chemistry and oxygen and hydrogen isotopic compositions of Marun oil–field brines, SW Iran: Source history and economic potential. Geological Journal, 46:1–9.

Mohammadi, Z., Zare, M., Sharifzade, B., Delineation of groundwater salinization in a coastal aquifer, Bousheher, South of Iran.Environmental Earth Sciences. (2012), doi:10.1007/s12665–012–2143–8.

Mohammadi, Z., Bagheri, R., Jahanshahi, R., 2010. Hydrogeochemistry and geothermometry of Changal thermal springs, Zagros region, Iran. Geothermics, 39: 242–249.

Mohammadzadeh, H., Shirzad, Z., 2013. change in dissolved mineral carbon and 13C of groundwater. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 48–53.

Mohammadzadeh, H., Ebrahimpoor, S., 2012. Application of stable isotopes and hydrochemistry to investigate sources and quality exchange Zarivar catchment area. Journal of Water and Soil 26:1018–1031 [In Persian, with abstract in English].

Mohammadzadeh, H., Heydarizad, M., 2012. Investigating geochemistry and the stable isotope (δ 18O & δ 2H) composition of Karde Carbonate Lake water (NE Iran). Proceedings of the Goldschmidt Conference 2012, (abstract).

Mohammadzadeh, H., Heydarizad, M., 2011.Hydrochemical and isotopic (δ2H and δ18O) investigation of Andrekh karstic area NE, Iran. Earth Science Researches, 5:56–69.

Mohammadzadeh, H., 2009. Analyzing environmental stable isotopes (sampling, preparing samples, standards and measuring instruments).Proceedings of the 1th Conference on Hydrogeology, Behbahan, Iran, November 2009, pp 16.

Mohammadzadeh, H., Clark, I.D., Aravena, R., Bourbonnais, A., Lue, I., Mi ddlestead, P., 2006. Isotopic analysis of ammonium (δ15N, Nitrate (δ18O, δ15N) and dissolved carbon (δ13C) in landfill leachate plum. 2ed International Conference on Environmental Science and Technology, Houston, Texas, USA, pp 145–150.

Moller P., Weise, S.,M., Tesmer, M., Dulski, P., Pekdeger, F., Bayer, U., Magri, F., 2008. Salinization of groundwater in the North German basin: results from conjoint investigation of major, trace element and multi–isotope distribution. International Journal of Earth Sciences, 97:1057–1073.

Moore, W., 2003.Sources and fluxes of submarine groundwater discharge delineated by radium isotopes. Biogeochemistry, 66:75–93.

Mosafa, M., Nasiri-Saleh, F., 2013.Investigating effect of temperature, altitude and amount of precipitation on isotope concentration in Tehran and Kabul cities precipitation. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 124–131.

Murphy, S., Ouellon, T., Ballard, JM., Lefebvre, R., Clark, I.D., 2011. Tritium–helium groundwater age used to constrain a groundwater flow model of a valley–fill aquifer contaminated with trichloroethylene (Quebec., Canada. Hydrogeology Journal, 19:195–207.

Nachiappan, R.M.P., Someshwar-Rao, M., Kumar, B., Navada, S.V., Satyanarayana, Y., 2004. Chemical and isotopic techniques for development of groundwater management strategies in a coastal aquifer: Krishna River Delta., South India. Proceeding Symposia on Isotope hydrology and integrated water resources management, 2003, IAEA, Vienna, pp 42–45.

Nassery, H., Mohammadzadeh, H., Salami, H., 2013.investigation of sulfate sources in some sulfuric springs in folded Zagros by using of 34S isotope. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 168–175.

Nikghoj, Y., Mohammadzadeh, H., 2013. application of 13C isotope in hydrograph separation of karstic springs. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 48–53.

Null, K.A., Dimova, N.T., Knee, K.L., Esser, B.K., Swarzenski, P.W., Singleton, M.J., Stacey, M., Paytan, A., 2012. Submarine groundwater discharge–derived nutrient loads to San Francisco Bay: Implications to future ecosystem changes. Estuaries and Coasts, 35:1299–1315.

Pakzad, M., Afrasiaban, A., 1998.Application of isotope techniques in karst water recourses in Iran. Proceedings of the 2nd international Symposium on karst water resources, July 1998, Kermanshah, Iran, pp 415–426.

Parisi, S., Paternoster, M., Kohfahl, C., Pekdeger, A., Meyer, H., Hubberten, H.W., Spilotro, G., Mongelli, G., 2011. Groundwater recharge areas of a volcanic aquifer system inferred from hydraulic., hydrogeochemical and stable isotope data: Mount Vulture, southern Italy. Hydrogeology Journal, 19: 133–153.

Pronk, M., Goldscheider, N., Zopfi, J., 2009.Microbial communities in karst groundwater and their potential use for biomonitoring. Hydrogeology Journal, 17:37–48.

Raeisi, E., Zare, M., Rezaie, M., 1999. Use of oxygen–18 isotopes in determining the sources of salinity in the Rahmat karstic springs. Proceedings of the Third Symposium of Geological Society of Iran, August 1999, Shiraz, Iran, pp 285–290.

Raghimi, M., Yakhkashi, M.E., 2002.The origin of thermal water of Ziarat, Gorgan by hydrochemistry and isotopc studies. Journal of Agricultural Sciences and Natural Resources, 19:29–40 [In Persian, with abstract in English].

Rajay, M., Asghari Moghaddam, A., 2002.Hydrochemistry and geometry of mineral and thermal springs in south east hilside of Sabalan (Sareyin and Boushali). Proceedings of the 5th Symposium of Geological Society of Iran, August 2001, Tehran, Iran, pp 365–368.

Rezaie, A., 2010. Hydrological and hydrogeological investigation of Shadkam Lake. MSc Theses., Department of Earth Sciences., Shiraz University.

Sanford, W.E., Aeschbach–Hertig, W., Herczeg, A.L., 2011. Preface: Insights from environmental tracers in groundwater systems. Hydrogeology Journal, 19:1–3.

Sepasi, M., 1995.Isotpes application in hydrology of snow and ice.Proceedings of the 1st Conference of Snow and Ice Hydrology.January 1995, Urmia, Iran, pp170–186.

Serdar Bayari, C., Nur Ozyurt, N., Oztan, M., Yalin Bastanlar, Y., Varinlioglu, G., Koyuncu, H., Ulkenli, H., Hamarat, S., 2011. Submarine and coastal karstic groundwater discharges along the southwestern Mediterranean coast of Turkey. Hydrogeology Journal, 19:399–414.

Seyedipour, M., Karimi, H., Ebrahimi, B., 2009.Application of stable and unstable environmental isotopes in hydrogeologic zoning of Beheshtabad dam and reservoir. Proceedings of the 12th Symposium the Geological Society of Iran, August 2009, Ahwaz, Iran, pp 368–373.

Shahi, S., Najafi, M., 2008.Experiments and application of isotope hydrology in water resources in Iran and some other countries.Proceedings of the 2nd National Congress on nuclear technology in agricultural and natural resources.June 2008, Karaj, Iran, pp 306–3015.

Shakeri, A., Moore, F., Kompani–Zare, M., 2008.Geochemistry of the thermal springs of Mount Taftan, southeastern Iran. Journal of Volcanology and Geothermal Research, 178:829–836.

Shamloo, R., 2002. Source determining of river flow for hydrograph separation by chemical and isotope tracer and graphical modeling.MSc thesis, Mazandaran University.

Sidle, W.C., Cvetic, V., 2011. Stable water isotope climate archives in springs from the Olympic Mountains., Washington. Environmental Earth Sciences, 62:569–580.

Sidle, W.C., 1998. Environmental isotopes for resolution of hydrology problems. Environmental Monitoring and Assessment, 52:389–410.

Sieyes, N.R., Yamahara., K.M., Paytan A., Boeh, A.B., 2011. Submarine groundwater discharge to a high–energy surface zone at Stinson Beach California, Estimated Using Radium Isotopes. Estuaries and Coasts, 34:256–268.

Sisakht, V., Mirnejad, H., Amini, A., V, Mohammadzadeh, H., Haghparast, G., 2009.determinate origin of Marun Oil fields with isotopic and chemical data. Proceedings of the 12th Symposium the Geological Society of Iran, August 2009, Ahwaz, Iran, pp 90–94.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P., Bhattacharya, S.K., Jani, R.A., Kumar, D., 2006.Characterization of recharge processes and groundwater flow mechanisms in weathered–fractured granites of Hyderabad (India) using isotopes. Hydrogeology Journal, 14:663–674.

TAMAB., 1982a. Report of initial study of relationship between Kardeh limestone well's and Mashhad plains by isotope analysis, 6 pp.

TAMAB., 1982b. Report of isotope study in Torbat–e Hidarieah area,10 pp.

TAMAB.,1985. Isotope study of water resource in Yazd and Ardakan plains,30pp.

TAMAB., 1987a. Isotope study of water resource in Jiroft, 30 pp.

TAMAB., 1987b. Isotope study of water resource in Kazerun area, 49 pp.

TAMAB., 1987c. Isotope study and tracing in Kamshak karst basin in Bandarlengeh, 26 pp.

TAMAB., 1992. Isotope study of water resources in Maharloo lake basin, Shiraz, 143 pp.

TAMAB., 1992. Isotope study of water resources in Shahpoor river basin, 47 pp.

TAMAB., 1996. Isotope study in hard rock formations in south of Gorgan, 19 pp.

TAMAB., 1998. Isotope and tracer study in Roodbar dam and power plant foundation in Lorestan, 36 pp.

TAMAB., 1999. Isotope and tracer study in Shemiran dam foundation in Tangea Shemiran,72 pp.
TAMAB., 2002. Semi–detail study of Siah kouh karst project in Yazd area, 150 pp.
TAMAB., 2005a. Report of semi–detail study of karst of Dareh Anjir project in Bafgh–Kermen, 68 pp.
TAMAB., 2005b. Isotope and tracer study in Glorde Neka dam foundation, 41 pp.
TAMAB., 2005c. Report of Semi–detail study of Meymea karstic basin, Morchekhort, 60 pp.
Terwey JL., 1984. Isotopes in groundwater hydrology.Proceedings of the Challenges in African hydrology and water resources Harare Symposium, Netherland 1984, IAHS, pp 155–160.
Thomas, J.M., Rose, T.P., 2003. Environmental isotopes in hydrogeology. Environmental Geology, 43:532.
Tokunaga, T., Shimada, J., Kimura, Y., Inoue, D., Mogi, K., Asai, K., 2011. A multiple–isotope (δ37Cl., 14C., 3H) approach to reveal the coastal hydrogeological system and its temporal changes in western Kyushu., Japan. Hydrogeology Journal, 19:249–258.
Toth, D.J., Katz, B.G., 2006. Mixing of shallow and deep groundwater as indicated by the chemistry and age of karstic springs. Hydrogeology Journal, 14:1060–1080.
Utting, N., Lauriol, B., Mochnacz, N., Aeschbach–Hertig, W., Clark I.D., 2013. Noble gas and isotope geochemistry in western Canadian Arctic watersheds: tracing groundwater recharge in permafrost terrain. Hydrogeology Journal, 21:79–91.
Venugopal, V., 2011. Societal applications of nuclear technology in health care., industry and water resource management in India. Energy Procedia, 7:553–559.
Yin, L., Hou, G., Su, XS., Wang, D., Dong, J., Hao, Y., Wang, X., 2011. Isotopes (δD and δ18O) in precipitation., groundwater and surface water in the Ordos Plateau., China: implications with respect to groundwater recharge and circulation. Hydrogeology Journal, 19:429–443.
Zak, I., Gat, J,R., 1975. Saline waters and residual brines in the Shiraz Sarvistan basin, Iran. Chemical Geology, 16: 179–188.
Zakhem, B.A and Hafez, R., 2007. Environmental isotope study of seawater intrusion in the coastal aquifer (Syria) Environmental Geology, 51:1329–1339.
Zarei, H., Akhondali, A., Mohammadzadeh, H., Radmanesh, F., 2013a. Application of 18O and 2H isotopes in hydrology of surface water. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 89–95.
Zarei, H., Akhondali, A., Mohammadzadeh, H., Radmanesh F., 2013b. Base flow separation from runoff by applying isotope technique in Abolabbas karstic basin. Proceedings of the 1st National Conference on Application of Stable Isotopes, Mashhad, Iran, pp 89–95.
Zarei, H., Damough, N., 2010. Investigation source of water at downstream of Karun 3 dam with application of isotope and hydrochemistry. Proceedings of the 13th Symposium of Geological Society of Iran and 27th Anniversary of Geoscience., August 2010., Urmia., Iran,., 6 pages published in CD).
Zarei, M ., Raeisi, E., Merkel B.J., Kummer, N.A Identifying sources of salinization using hydrochemical and isotopic techniques, Konarsiah, Iran. Environmental Earth Sciences. (2012) dio:10.1007/s12665–012–1591–5.
Zhang, Y., Wu, Y., Su, J., Wen, X., Liu, F., 2005.Groundwater replenishment analysis by using natural isotopes in Ejina Basin., Northwestern China. Environmental Geology, 48:6–14.
Zhou, Y., Zwahlen, F., Wang, Y., Li, Y., 2010.Impact of climate change on irrigation requirements in terms of groundwater resources. Hydrogeology Journal, 18: 1571–1582.
Zuber, A., Różański, K., Kania, J., Purtschert, R., 2011. On some methodological problems in the use of environmental tracers to estimate hydrogeologic parameters and to calibrate flow and transport models. Hydrogeology Journal, 19:53–69.