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Full Length Article

Identifying sources of groundwater and recharge zone using stable environmental isotopes in the Erbil basin-northern Iraq

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ABSTRACT

The Dashty-Hewler basin is a groundwater basin located in Erbil in northern Iraq. It comprises three distinct sub-basins (Kapran, Central, and Bashtapa) covering a total basin area of 2,660 km^2. It is bounded by the greater Zab river to the north and the little Zab to the south. The groundwater in this catchment has never been investigated using modern environmental isotope evidence. Since the groundwater in this basin serves as both drinking water and a source of irrigation, its management is crucial. Recently, due to the increase in population, excessive pumping has taken place, which has led to a decline in the water table. Accordingly, it is necessary to address the issues of where the groundwater will recharge and what the source of the recharge will be. For this purpose, 27 groundwater samples from different wells and two river water samples were analyzed for stable isotopes ($\delta^{18}O$ and $\delta^{2}H$). The distribution of $\delta^{18}O$ and $\delta^{2}H$ over the study area was utilized by inverse distance weighted (IDW) interpolation within ESRI ArcGIS (10.8). The results indicated that the relationship between $\delta^{18}O$ and $\delta^{2}H$ in the groundwater samples ($\delta^{2}H = 6.59\ \delta^{18}O + 7.48‰$) showed relative shifts of both the slope and the deuterium excess when compared to the Iraq meteoric water line ($\delta^{2}H = 7.66\ \delta^{18}O + 14.19‰$). The deviation of data points from the meteoric line can be attributed to high evaporation both during the rainy season and through run-off on the ground surface before infiltration. Most of the groundwater samples had a deuterium excess above 10‰ between 12.14 and 22.72‰, suggesting the precipitation present in the groundwater comes from the Mediterranean sector. Based on local isotopic gradients ($\delta^{18}O$, −0.22/100 m), in combination with topographic and geologic criteria, the recharge areas were identified as being between 400 m and 1,100 m above sea level.

Introduction

The field of isotope hydrology developed into a scientific and practical approach in the late 1950s and early 1960s. Clark and Fritz (2013) suggested that the use of environmental isotopes in conjunction with the hydrogeology of the watershed could prove to be an effective method for identifying places where groundwater recharge occurs. The fluctuations in the oxygen and hydrogen signatures of precipitation provide the variable input functions that are helpful for tracing groundwater. The ^{18}O and ^{2}H data of groundwater frequently reflect the height and temperature of precipitation that infiltrates into the subsurface. Based on this, stable isotope analyses of water can be used to find the average height of the catchment basin. Knowledge of the distribution pattern of the compositions of environmental isotopes in rainfall is an indispensable parameter when using these isotopes as natural tracers in hydrological and hydrogeological investigations. The isotope compositions can also prove the movement of groundwater, supported by the altitude of the recharge area and the known water table.

Several studies have been carried out regarding this, including (Terwey, 1984): in Sudan, who investigated the main applications of groundwater movement through an aquifer using its distribution process and surface water. The origin of the water, along with the location, period, and recharge processes, can be identified if the deuterium and oxygen-18 concentrations do not alter inside the aquifer. If the isotope concentration of the groundwater changes, this can be used to reconstruct the history of the water involved in the mixing, salinization, and discharge processes. Hager and Foelsche (2015) investigated the compositions of stable isotopes in the precipitation of Austria. The Austrian meteoric water line was ($\delta^{2}H = 7.5\ \delta^{18}O + 3.2‰$) and the altitude effect was −0.19‰ per 100 m increase in elevation. Demiroğlu (2017) selected

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the boundary of the Yenicikri basin in Turkey. The $\delta^{18}O$ changing rate for increasing elevation was determined to be −0.32‰ per 100 m rise in altitude.

Mawlood (2003) researched the underground water resources with the support of both stable and radioactive isotopes. This study was the first step in the management of water resources in the Kurdistan region of Iraq, especially in Erbil province. Different isotope analyses, like ^{18}O (Oxygen-18), ^{2}H (Deuterium) and ^{3}H (Tritium), were conducted at the Austrian Research and Testing Centre Arsenal in Vienna. The results showed that the large compositions of isotopes in water were due to the effects of altitude above sea level and temperature, as well as precipitation and evaporation changes. Furthermore, this study cited the estimated altitude effect for the Damascus Region, which was about −0.19‰ per 100 m for the $\delta^{18}O$ gradient. Liu et al. (2006) analyzed the isotope of spring water of the Huaishahe basin located northwest of Beijing. Based on $\delta^{18}O$, the altitude of the recharge area of the spring water was −0.24‰ per 100 m rise in altitude. Zhou et al. (2017) in Zhanjiang (China), evaluated 95 groundwater samples to identify the recharge sources. The values of the stable isotopes ^{18}O and ^{2}H indicated where groundwater recharge occurred in a multilayered aquifer system. Unconfined groundwater is produced by local current precipitation, while confined groundwater is produced by the current precipitation in the northwest mountain range. Hssaisoune et al. (2022) determined the mean elevation of groundwater recharge zones in Morocco using the relationship between oxygen-18 and altitude in rainwater. The regression line of the rainfall data adopted an altitudinal gradient of +0.18‰ per 100 m. Al-Naseri et al. (2022) studied the environmental isotopic characteristics of 240 precipitation samples covering 16 Iraqi provinces between 2011 and 2022. The Iraqi meteoric water line (MWL) is defined as ($\delta^{2}H = 7.66\ \delta^{18}O + 14.19‰$), which is due to the continental effect, which involves lower humidity and higher temperatures than the Mediterranean region. The d-excess (14.19‰) was lower than that of the MWL (22‰) in that region. The milder slope of the Iraqi MWL would suggest that secondary sub-cloud evaporation (the evaporation of raindrops during rainfall) is common in the area. The slope may be affected by changes in the amount of precipitation and relative humidity. The northern region, including Erbil province, receives almost all of the precipitation, based on the higher altitude, as it has a relatively cool climate, which encourages frequent and heavier precipitation as well as lower temperatures overall. The isotopic traces of the precipitation were found to be considerably influenced by the altitude. It was calculated that the altitude gradient of ^{18}O in Iraqi precipitation was −0.5‰ per 100 m elevation. Additionally, it was determined that the Mediterranean Sea and the Black Sea were the two main moisture supply areas. These two seas elicit a huge quantity of moisture, resulting in heavy rainfall in the area.

The main objective of this research is to promote the environmental isotope technique as a tool that can be used to ensure the effective management and development of the Dashty-Hewler aquifer systems at Erbil. This will involve an appropriate evaluation of the recharge site and the sources of groundwater in wells. This investigation is important as the groundwater in this region is used for irrigation and drinking water. It should also be noted that the recent population growth has necessitated over-pumping, which has caused the water table to drop.

Materials and methods

Study site and sampling points

The Erbil, or (Dashty-Hewler) basin is a groundwater reservoir in Erbil province of the Kurdistan region. This region is located in the northern part of Iraq, as shown in Fig. 1 a. The study area covers an area of 2,660 km^2 (see Fig. 1b). This basin is bordered by the greater Zab river in the northwest (with a volume of 13.25 billion m^3) and the little Zab in the southeast (with a volume of 5.74 billion m^3). Supplying drinking and irrigation water are the major functions of the Erbil basin. Usually, groundwater is recharged by precipitation and snowmelt. However, it can be renewed in specific topographical locations by leakages from rivers or lakes.

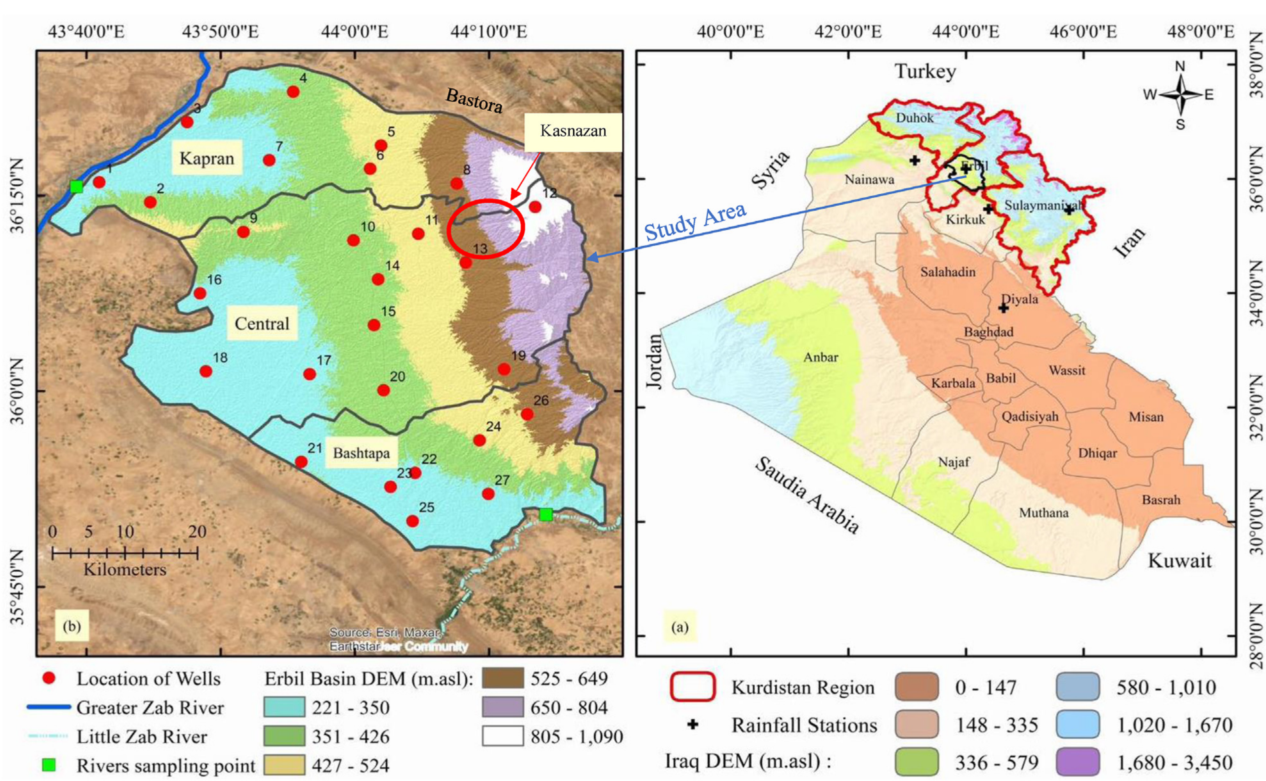

Fig. 1. a) The location of the study area in the Kurdistan region of Iraq. b) The location of the wells from which samples of Erbil groundwater were drawn.

The Erbil basin is divided into three sub-basins based on the local hydrological and geological characteristics obtained from deep wells. Kapran, which lies in the north, with a 720 km^2 catchment area, is bounded by Bastora and the greater Zab. Bashtapa lies in the south, with a 625 km^2 catchment area near the little Zab. The Central sub-basin has a catchment area of 1315 km^2, and it largely serves urban areas. Erbil province is divided into two climatic regions, both of which have a varied climate. The north and northeast sections have a Mediterranean climate, with an average annual rainfall of 600–800 mm, while the south and southwest sections have a warm climate with an approximate average annual rainfall of 500 mm. The average volume of precipitation over this basin is 1.28 billion m^3. Based on the total amount of precipitation, 55% evaporates, 24.23% permeates into the soil to recharge the groundwater, and 20.77% flows as surface water (Dizayee, 2018). While (Mawlood, 2019) focused on the impact of groundwater on the aquifer sustainability in the Erbil basin, finding that the depth of the water table had dropped by approximately 1.24 m annually.

The significant physical characteristics of the semi-arid climate of the plains are distinctive. The average temperature is between 1 °C in December to February and up to 44 °C in July and August (Hamad, 2022). The elevation of the Erbil basin is between 221 and 1090 m above sea level. The Kasnazan district is located in the eastern part of the study area (as circled in red) starting at an elevation of about 570 m. This area includes some catchment areas in Kapran and the Central sub-basin, where the Bakhcha hills lie opposite the village of Mam-joghan.

For this investigation, a total of 27 wells at different positions were sampled and two river water samples were drawn. The coordinates and elevations of each were taken. The main parameters that need to be measured in the field are the temperature and static water depth in the wells. Between the 17th of July and the 2nd of August 2022, a 1-L sample was drawn from each site. Each sample was collected and stored in well-sealed plastic bottles to ensure safe transfer to the laboratory. During sampling, storage, and shipping, the key concern was to avoid isotopic fractionation due to evaporation or diffusive loss of water vapor, as well as any isotope exchange with the environment and the bottle material (Clark and Fritz, 2013).

(Ali et al., 2015; Al-Naseri et al., 2022) conducted studies surveying the rainwater isotopic data for Iraq. Precipitation stations in the Kurdistan region, as well as stations adjoining the Kurdistan border, were used, as shown on the Iraq map. The weighted mean isotopes in the precipitation were recorded and can be seen in Table 1. For the current study, the online isotopes in the precipitation calculator (OIPC, 2022) were used and were compared with those of (Ali et al., 2015).

Isotope analysis

The overall data that was measured in the field as well as the results of the stable isotopes found in the water samples are shown in Table 2. This study focused on the stable isotopes found in water molecules. Experiments of isotope analysis were carried out in the (Devlet Su Isleri-DSI) laboratory in Ankara./Turkey. A (Patrick, 2021) Cavity Ring-down Spectrometer with high-precision readings was used to analyze the water samples for stable isotope elements. This instrument provides a platform for advanced research into all aspects of the water cycle: water vapor, liquid water, or water trapped in solids (Dennis, 2014). The determination of the isotope compositions ^{18}O and ^{2}H were made according to Equations (1) and (2) below, and reported as parts per thousand (ppt or per mil-‰) regarding the Vienna Standard Mean Ocean Water (V-SMOW) using the (δ) notation where:

$$\delta^2\text{H ‰} = \frac{(\delta^2\text{H}/\delta^1\text{H})_{\text{sample}} - (\delta^2\text{H}/\delta^1\text{H})_{\text{standard}}}{(\delta^2\text{H}/\delta^1\text{H})_{\text{standard}}} \times 10^3 \quad (1)$$

$$\delta^{18}\text{O ‰} = \frac{(\delta^{18}\text{O}/\delta^{16}\text{O})_{\text{sample}} - (\delta^{18}\text{O}/\delta^{16}\text{O})_{\text{standard}}}{(\delta^{18}\text{O}/\delta^{16}\text{O})_{\text{standard}}} \times 10^3 \quad (2)$$

The deuterium excess (d-excess) was the main parameter describing isotope fractionation occurring under almost equilibrium conditions covering the change of atmospheric vapor to the liquid phase, and it was calculated according to the formula: (d-excess = δ^2H – 8 $\delta^{18}O$).

Geological map of the Erbil basin

For this investigation, the Erbil basin geological map was sketched as shown in Fig. 2 a. From the hydrogeological perspective, the basin is a low-folded zone which is heavily influenced by its geological surroundings and the Erbil area is primarily covered by conglomerate aquifers (Sissakian and Fouad, 2015). Section (S–S) in Fig. 2 b shows that a Pliocene (the upper and lower Bakhtiary) formation covers a large part of the Erbil basin. This formation consists of gravel and conglomerates, with some sand and clay beds. The quaternary deposits that overlie the upper Bakhtiary, is an alluvium formation (from the Pleistocene to recent ages) which consists mainly of alluvial fan deposits, gravel, sand and silty clay.

Generally, the Bakhtiary and alluvium aquifers are unconfined, meaning that precipitation infiltrates directly into them. However, in some parts of the study area, because of a covering of thick clay, the aquifers become semi-confined or confined. Bashtapa is mostly dominated by the upper Bakhtiary formation. This sub-basin is characterized by two different types of aquifer systems: unconfined and semi-confined. The semi-confined aquifers consist of silty materials that are interbedded with thin fine-grained sandstone strata and are amalgamated with clay layers, whereas the unconfined aquifers mainly consist of interbedded clay beds with some silt.

Results

The most pressing issues including the zone of recharge area, or the origin of the water that forms the basin recharge, and the direction of the groundwater with stable isotopes ($\delta^{18}O$) are described below.

Distribution of deuterium and ^{18}O in the groundwater

The ^{2}H and ^{18}O compositions serve as a basis for geodata in the construction of spatial distribution maps. The inverse distance weighted (IDW) method was used for interpolation within the ESRI ArcGIS (10.8). This is an exact method based on an iterative finite difference technique that assumes the data that are close together are more similar than those that are farther apart (Amroune et al., 2020). The isotopic compositions of $\delta^{18}O$ and $\delta^{2}H$ were analyzed for the 27 different wells in the study

Table 1
Precipitation sampling stations and weighted mean stable isotopes.

Station Name	Coordinates (DD[a])		Altitude (m.asl)	Ali et al. (2015)		OIPC (2022)	
	Longitude	Latitude		Mean $\delta^{18}O$ (‰)	Mean δ^2H (‰)	Annual $\delta^{18}O$ (‰)	Annual δ^2H (‰)
Erbil	36.175342	44.000394	950	−7.20	−43.96	−7.1	−43
Kirkuk	35.473583	44.383978	234	−5.84	−33.12	−5.3	−30
Sulaymaniyah	35.400553	46.504147	1050	−7.25	−45.00	−6.6	−40
Nainawa	36.326275	43.130975	350	−5.94	−33.90	−5.7	−32
Diyala	33.741769	44.641183	212	−5.42	−28.00	−4.8	−24

[a] DD: decimal degree.

Table 2
Field data and the isotope analyses for wells and river water samples of the study area.

Sample no.	Position Name	Coordinate in Decimal Degrees (DD)		Elevation (m.asl)	Well Depth (m)	Depth to GW (m.bgl)	Sample Temperature (°C)	PH	EC (μS/cm)	$\delta^{18}O$ (‰)	uncertainty (±)	δ^2H (‰)	uncertainty (±)
		Longitude	Latitude										
1	Kalak	43.682505	36.267223	266	*	58.6	28.8	7.30	817	−5.95	0.1	−32.58	0.48
2	Big Chaluk	43.746069	36.241502	380	210	56.3	27.3	7.73	774	−4.70	0.1	−25.46	0.47
3	Kawrgosk	43.791708	36.343966	298	300	65	28.2	8.10	705	−6.35	0.1	−37.52	0.46
4	Grdachal	43.923523	36.382746	384	300	39.6	28.4	7.74	516	−6.09	0.1	−31.97	0.46
5	Bahirka	44.032496	36.314119	470	400	88.1	28.4	8.24	487	−7.58	0.1	−43.58	0.46
6	Grd-Jutyar	44.018933	36.284339	440	300	64.3	28.2	7.98	416	−5.69	0.1	−29.42	0.47
7	Qalanchoghan	43.893633	36.295335	350	250	49.5	32.2	7.70	587	−5.73	0.1	−29.38	0.46
8	Pirash-kulk	44.126508	36.265475	620	**	92.2	29.0	7.61	464	−6.50	0.1	−34.72	0.43
9	Kani-Qrzhala	43.861610	36.203631	433	370	125	27.9	8.09	1022	−7.00	0.1	−43.36	0.36
10	Minara	43.998310	36.192836	403	*	91.2	27.5	7.93	311	−9.15	0.1	−50.48	0.36
11	New-Hawler	44.078781	36.201199	483	300	96.2	26.2	7.51	445	−6.86	0.1	−37.44	0.36
12	Mam-joghan	44.224023	36.235640	910	280	44.1	26.2	8.31	463	−7.97	0.11	−43.98	0.36
13	Bnaslawa	44.137725	36.164450	533	235	74.1	27.9	7.68	393	−6.02	0.1	−31.96	0.37
14	Eng. College	44.028943	36.143044	419	300	96.9	27.9	7.73	395	−5.64	0.1	−29.34	0.36
15	Grda-Rasha	44.023798	36.084592	414	300	61.1	28.0	8.09	436	−6.37	0.1	−34.20	0.36
16	Yarmija	43.807674	36.125026	297	200	27.3	28.1	7.96	827	−5.76	0.1	−31.42	0.36
17	Pir-Dawud	43.943946	36.021862	351	230	38.5	26.4	8.01	756	−7.42	0.1	−42.82	0.37
18	Aliyawa	43.815069	36.025499	310	242	29.4	26.3	8.01	3670	−5.49	0.14	−29.52	0.43
19	Bistana	44.185308	36.028027	591	276	26.2	26.4	7.70	698	−6.36	0.14	−33.14	0.39
20	Qushtapa	44.035666	36.001250	393	300	160	26.9	7.87	545	−5.77	0.14	−30.05	0.39
21	Qurshaghlu	43.933479	35.909905	340	103	35.3	28.5	7.76	1350	−5.49	0.14	−28.10	0.39
22	Dolabakra	44.074842	35.895814	360	300	68.5	26.9	8.11	744	−5.74	0.14	−29.88	0.39
23	Tatarawa	44.044353	35.877940	345	218	33.3	28.3	8.00	830	−6.80	0.14	−37.39	0.39
24	Puricha	44.154898	35.937425	425	253	51	27.2	8.23	730	−5.16	0.14	−25.34	0.39
25	Shekhanan	44.071761	35.834122	301	306	19.6	28.2	8.28	377	−5.03	0.13	−24.71	0.39
26	Rulka	44.213925	35.970671	522	200	49.9	26.3	7.48	604	−5.15	0.14	−24.53	0.39
27	Grda-sur	44.165909	35.852736	322	300	62.1	26.4	8.14	536	−5.81	0.14	−30.96	0.39
28	Greater Zab	43.654182	36.261526	246	–	–	26.2	7.35	279	−8.91	0.14	−49.22	0.35
29	Little Zab	44.237359	35.842590	337	–	–	32.2	7.87	304	−5.43	0.14	−27.22	0.26

* Missing data at governmental office, ** Illegal well, asl: above sea level, bgl: below ground level, GW: is groundwater.
Sampling no. 1 to 27 are of groundwater but samples no. 28 and 29 are of river water.

area. As shown in Fig. 3, the analyzed data were interpolated for $\delta^{18}O$ and the higher values ranged between (−6.03 to −4.70‰). These covered largely the southern Bashtapa sub-basin.

The same results were found in the spatial distribution of deuterium contents over the Bashtapa sub-basin as shown in Fig. 4. The range of enriched δ^2H for the aforementioned catchment area was between (−32.2 to −24.5‰). It can be seen that the groundwater became progressively enriched in both $\delta^{18}O$ and δ^2H in the Bashtapa sub-basin.

The temperature of groundwater samples that came from the aquifer system changed the stable isotope content distributions. Higher sample temperature conditions can be attributed to subsurface formation events, including water and rock interactions, some areas of the aquifer being covered with recent quaternary sediments.

Deuterium excess (d-excess)

Based on the global atmospheric water vapor that occurs at a humidity of roughly 85%, the deuterium excess value is d = 10‰. As shown in Fig. 5, for groundwater at the Dashty-Hewler basin, the deuterium excess ranged between 12.14 and 22.72‰, indicating that the precipitation in the groundwater came from the Mediterranean sector.

Meanwhile, the greater and little Zab river (samples no. 28 and 29) d-values are 22.06‰ and 16.22‰, respectively. Lower values of d-excess were found in the groundwater at wells no. 2, 16, and 18. The low d-excess values are enriched with $\delta^{18}O$ indicates that these waters have undergone evaporation to different extents before recharging. Conversely, the higher values calculated for the groundwater at wells (no. 10 and 12), affected the depletion in $\delta^{18}O$ in these wells because they were recharged directly from precipitation.

The meteoric water line of groundwater in the Erbil basin

Fig. 6 shows the δ^2H correlated with the $\delta^{18}O$ values. This illustrates how various meteoric water lines were plotted to describe the isotopic data for various sources of water in the research area. A (Mawlood, 2003) discovered for the first time, the local MWL (MMWL) in Erbil with a slope of 8 and 20‰ y-intercept, which is the baseline of any hydrological study with stable isotopes. Additionally, for this study, the regional MWL for the groundwater at the 27 sampling points in the Erbil basin was obtained. The equation describing the relationship between $\delta^{18}O$ and δ^2H for Erbil groundwater is ($\delta^2H = 6.59\ \delta^{18}O + 7.48$‰) which suggests that the samples plot slightly below the MMWL. This indicated that the soil water, which evaporates before infiltration, had restored the groundwater. This measurement was also located below the eastern MWL (EMWL: $\delta^2H = 8\ \delta^{18}O + 22$‰) and above the global MWL (GMWL: $\delta^2H = 8\ \delta^{18}O + 10$‰).

Identifying groundwater recharge zones

The spatial distribution of environmental isotope compositions in rainfall is a crucial parameter, one which works as a natural tracer in hydrological and hydrogeological investigations. The $\delta^{18}O$ in atmospheric precipitation versus the altitude of the sample stations is presented in Fig. 7. The regression line of the rainfall data (OIPC, 2022) enveloped 23 wells, (i.e., 85.2%) of the groundwater samples. The altitude relationship with $\delta^{18}O$ and δ^2H yields Equations (3) and (4), with a decreased gradient of −0.22 and −1.76‰ per 100 m elevation above the sea level, respectively.

$$\delta^{18}O = -0.0022 \times \text{Altitude} - 4.694 \qquad (R^2 = 0.87) \tag{3}$$

$$\delta^{2}H = -0.0176 \times \text{Altitude} - 23.981 \qquad (R^2 = 0.86) \tag{4}$$

The $\delta^{18}O$ and altitude relationship agrees with the atmospheric precipitation for the countries surrounding Iraq. For instance, the estimated altitude effect for the Damascus region was about −0.23‰ and −1.65‰

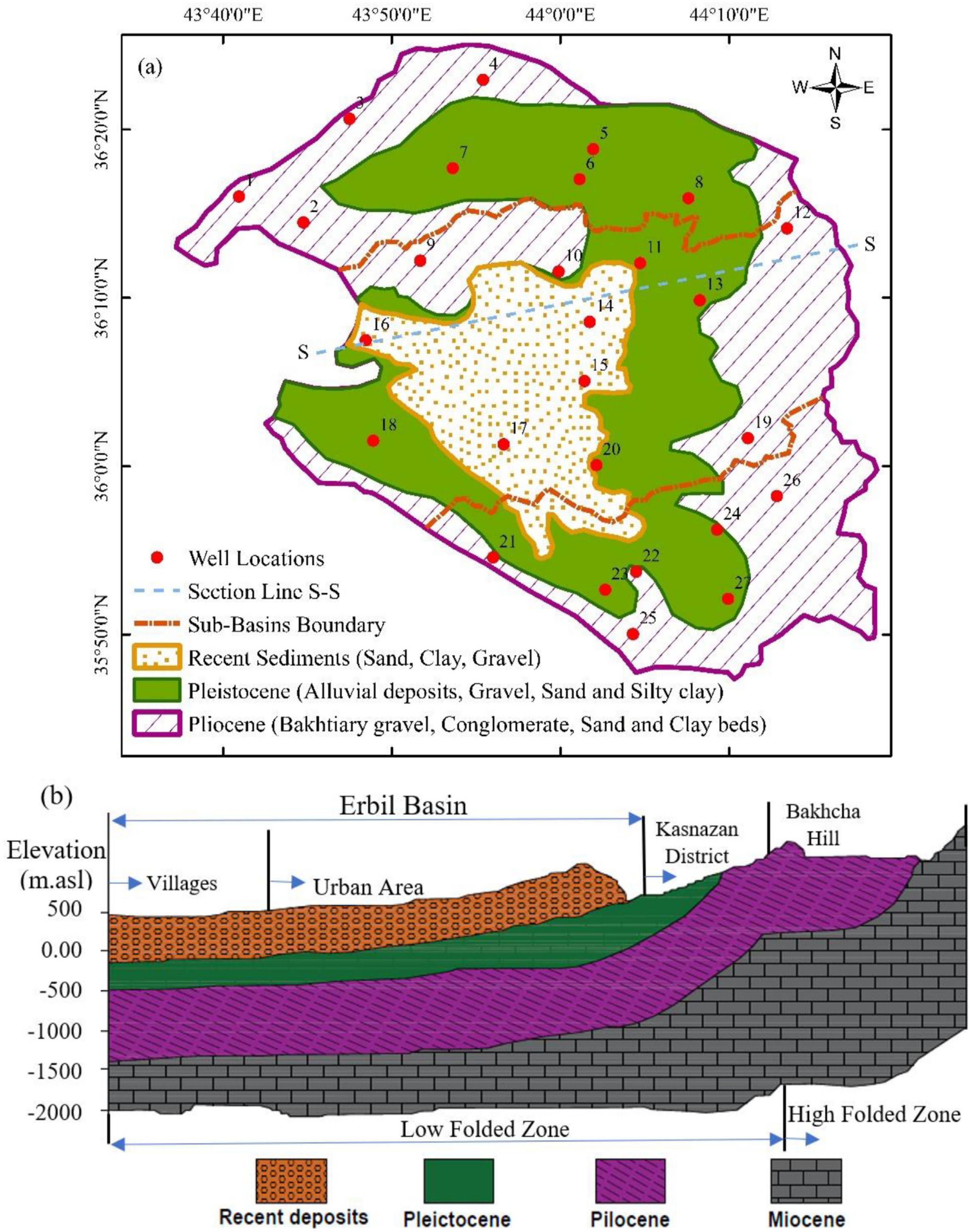

Fig. 2. a. A geological map of the Erbil basin. b. A simplified cross-section (section S–S).

per 100 m for a $\delta^{18}O$ and δ^2H gradient (Kattan, 1994). For Jordan, precipitation gradients of about −0.26 and −1.31‰ per 100 m were found for $\delta^{18}O$ and δ^2H, respectively. For the Yenicikri basin in Turkey, the $\delta^{18}O$ changing rate for an increasing elevation has been determined as −0.32‰ per 100 m rise in altitude (Demiroğlu, 2017). The range of $\delta^{18}O$/altitude coefficients of (−0.15 to −0.50) ‰ 100 m^{-1} has been established for the isotopic composition of precipitation (Taylor et al., 1989), with higher coefficients applying in colder climates where temperature/altitude gradients are steeper. Also (Clark and Fritz, 2013), have reported that the changing rate in δ^2H isotope concentration varies

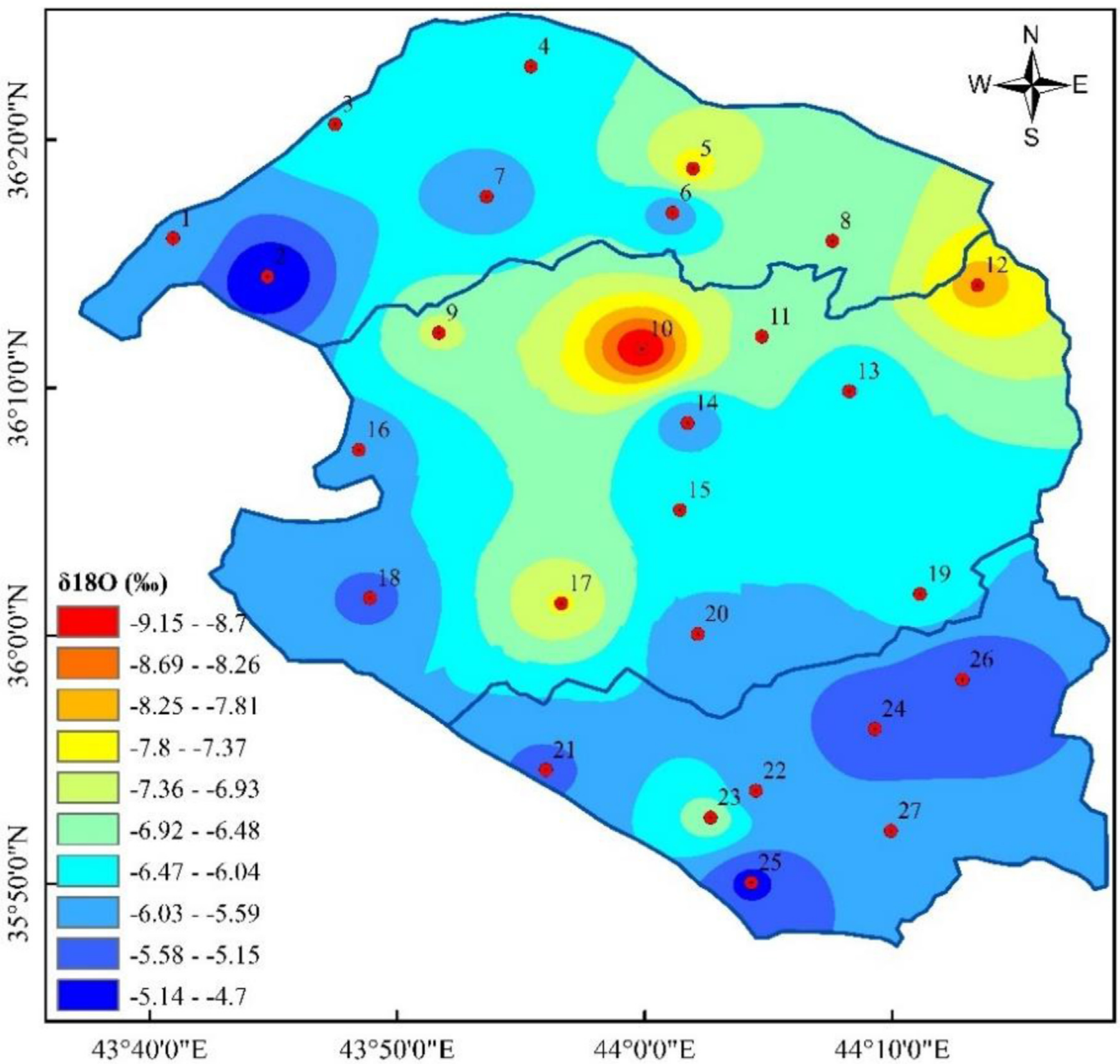

Fig. 3. $\delta^{18}O$ distribution in groundwater of the Erbil basin.

between (−1 to −4) ‰ per 100 m rise in altitude.

Groundwater flow direction

The groundwater flow direction was based on the static water level for different wells. For the Erbil basin, the static water level was measured in 27 selected wells. SURFER software (V.8) was developed to translate the 'XYZ' data into a clear surface and contour map to support a better understanding of the overall flow regime across the study area. The spatial distribution of the groundwater level map for the wells in the Kapran, Central and Bashtapa sub-basins is shown in Fig. 8. This water table map shows that the flow vectors drop from the east and northeast toward the west and southwest of Erbil. The stable isotopes were used to measure the groundwater flowing from the highest altitude of the well recharge area (with the lowest $\delta^{18}O$ values) toward the lower elevations (with the highest $\delta^{18}O$ values) is illustrated with the slope of line in Fig. 7. These findings match measurements of groundwater flow using a conventional method, as mapped in Fig. 8.

The range of pH values in the 27 groundwater samples was (7.3–8.31), and their mean value was 7.89. The higher values were recorded near the Bashtapa sub-basin at wells (no. 22, 24, 25 and 27). This was also the case for wells in the Central sub-basin: (wells no. 9, 12, 15, 16, 17 and 18). On the other hand, the greater and little Zab rivers' pH values were recorded as 7.35 and 7.87, respectively.

Electrical conductivity (EC) is commonly used for estimating the salinity of groundwater. EC can flow more freely in water with a larger concentration of dissolved salts. The EC of the groundwater at wells (no. 18 and 21) was 3,670 and 1,350 μS/cm, respectively. The local population does not depend on the groundwater as their source of drinking water because the salinity originates at well (no. 18) from Aliyawa, a village with an enriched $\delta^{18}O$ value of (-5.49 ± 0.14) ‰. Given that the groundwater in the research area flows from east to west, the longer the groundwater is in touch with the rock, the more ions dissolve and the higher the conductivity is achieved. The (IAEA, 2001) has indicated that the stable isotopic composition has not undergone any significant changes with regarding EC. However, the presence of mixing or evaporation processes essentially causes sensitive changes in the stable isotopic contents.

Discussion

The different $\delta^{18}O$ contents show that one of the sources of groundwater recharge is local precipitation, with annual isotopic values of ($\delta^{18}O = -7.1$‰) over the study area. The catchment areas with $\delta^{18}O$ ranged between (−7.36 and −6.93) ‰ were suggested to be the result of vertical infiltration directly from precipitation, which occurred passing through the different layers of the groundwater aquifer basin in these regions. This location includes the Bakhcha hills (910 m.asl) toward the

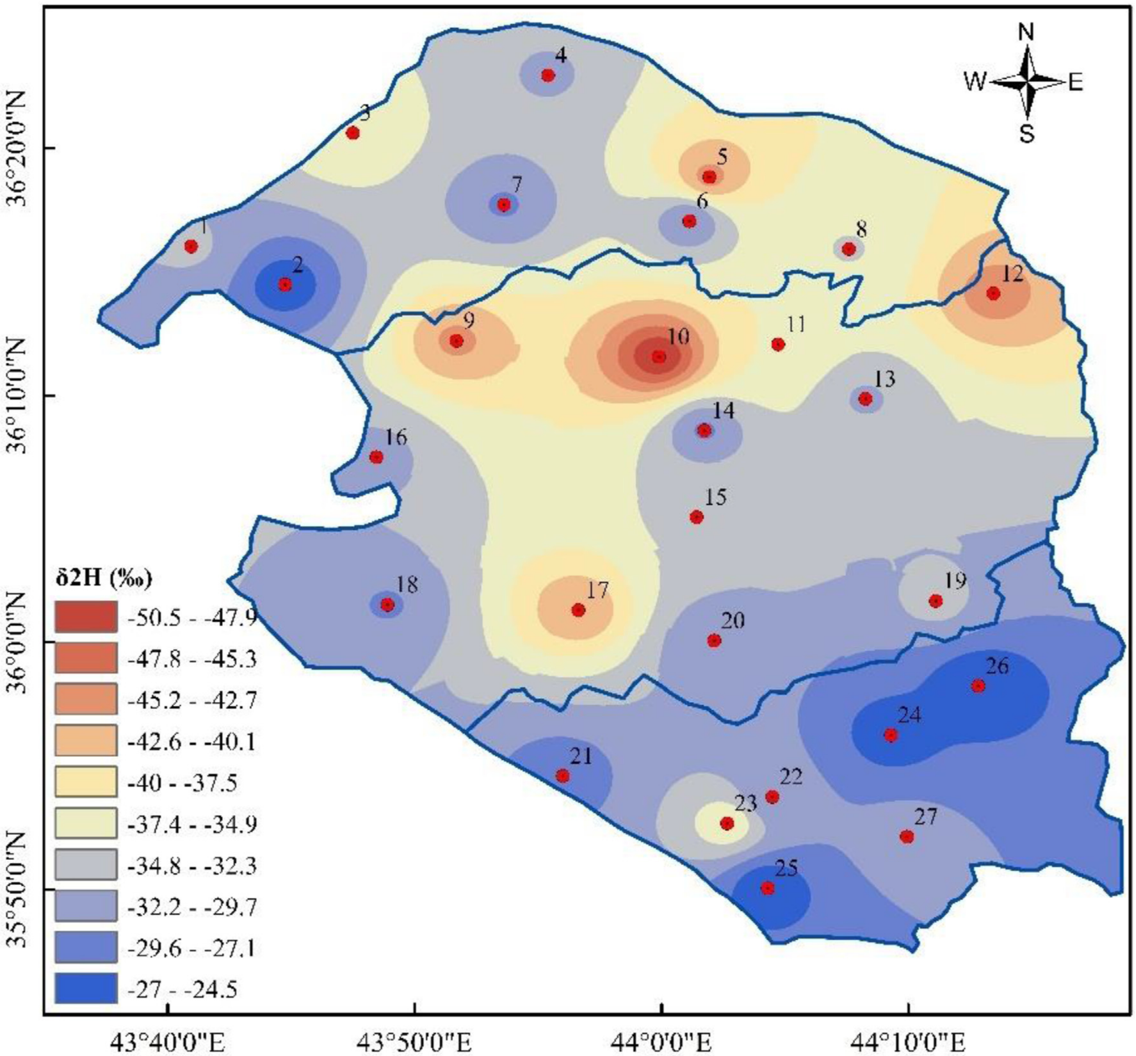

Fig. 4. δ^2H distribution in the groundwater of the Erbil basin.

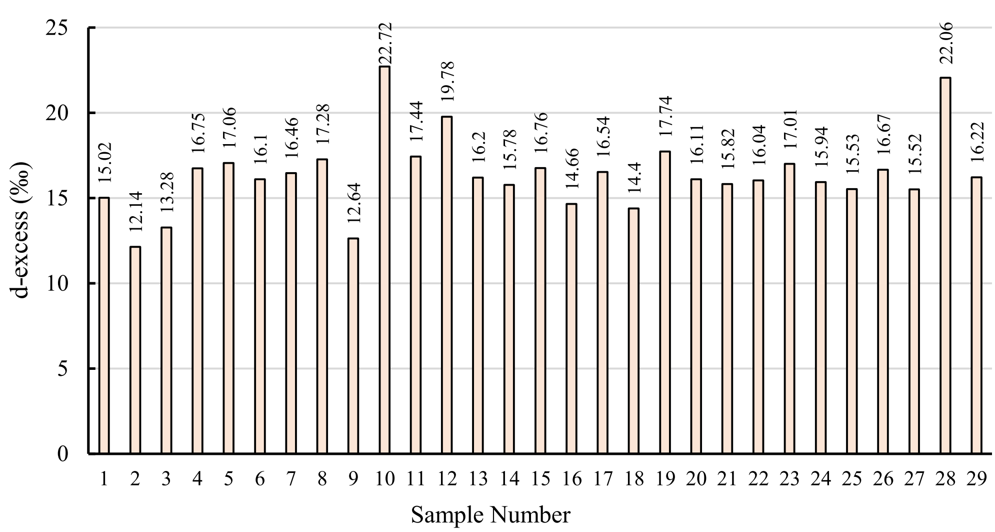

Fig. 5. The deuterium excess levels in the groundwater and river waters.

district of Kasnazan and the catchment areas around the center of Erbil, near well (no. 10).

Since the groundwater at the wells in Bashtapa is affected by partial evaporation from the little Zab river, the enrichment of heavy oxygen isotopes will be present. These findings concluded that the river water, with ($\delta^{18}O = -5.43$‰) infiltrates through the Bakhtiary gravel, sand and

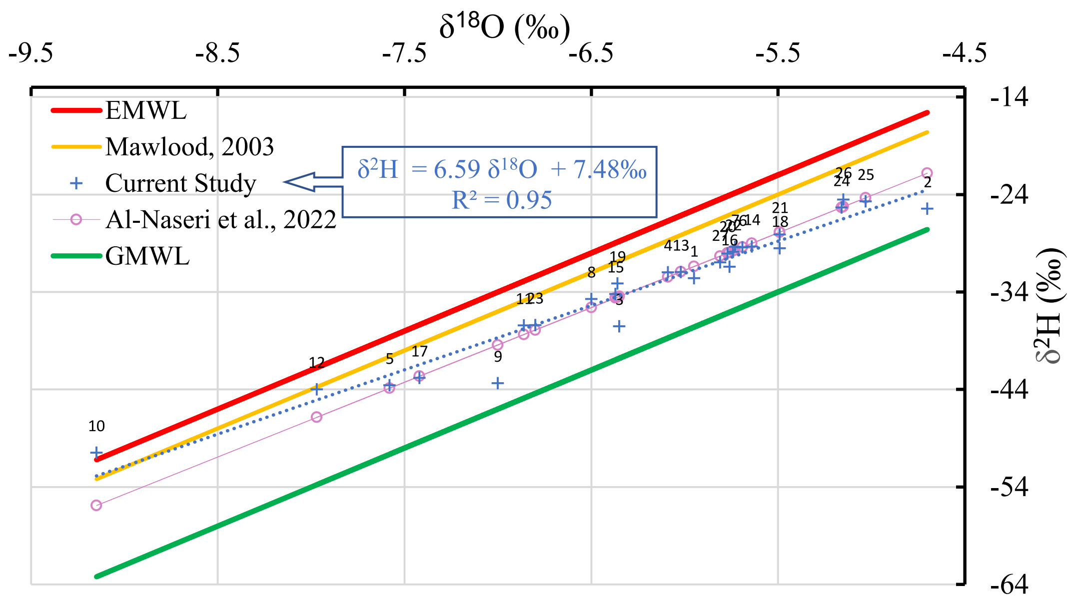

Fig. 6. The relationship between the $\delta^{18}O$ and δ^2H for the wells in the Erbil basin.

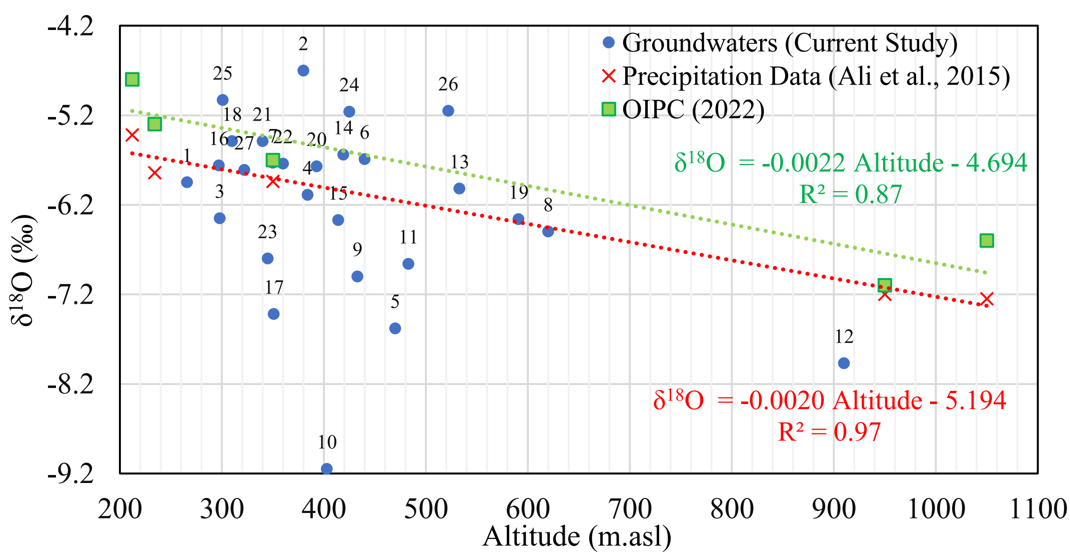

Fig. 7. The relationship between $\delta^{18}O$ and altitude for the wells in the Erbil basin.

conglomerate formations of Bashtapa near the eastern boundary of the Erbil basin. Furthermore, the recharged water at Bashtapa, with $\delta^{18}O >$ $-6.03‰$ (which is near to the value of river water), flows from the southeast, with its higher water table, toward the southwest of this sub-basin.

Wells (no. 16 and 18) which are located at the villages of Yarmija and Aliyawa, supply water for irrigation of 33 and 50 acres of land, respectively. The enriched values of their $\delta^{18}O$ may be due to the agricultural return flow which has been subjected to evaporation before infiltration. The same findings appear at wells (no. 1 and 2) located at Kalak and Chaluk villages. The enriched $\delta^{18}O$ at Kalak is due to the return flow of water from about 60 acres of farmland. The land use in Chaluk is also for agricultural purposes.

The weak convergence between river water and groundwater in the wells in the Kapran sub-basin (well no. 1 and 2) shows the $\delta^{18}O$ of the greater Zab river sample is ($-8.91‰$) compared to the water drawn near the western boundary of the sub-basin. This gives rise to two issues; First, it is better to take numerous samples of river water from different sections so that the $\delta^{18}O$ value of the greater Zab river can be measured exactly. Second, it must be noted that the elevation of the well points in the sub-basin decreases from east to west. This means that the river sample point at 20 m.asl is lower than the lowest well located at Kalak. It should also be noted that the direction of the flow of groundwater over the study area flows from east to west (see Fig. 8).

The d-excess values of all the groundwater samples and the two main rivers at the Dashty-Hewler basin was higher than the average global value, which is 10‰. This represents the evaporation from the surface of the water. Cejudo et al. (2020) concluded that the d-excess of lower than 10‰ could be due to the convective systems or low-pressure precipitation events. Conversely, a d-excess higher than 10‰ might involve precipitation from the air that has undergone more than one condensation, moisture originating from forward events, or convective recycled moisture (Clark et al., 2015).

The composition of the hydrogen and oxygen isotopes from the Erbil basin varies in both slope and d-excess values regarding the local meteoric water, because the groundwater that infiltrates underground contributes to various effects, including evaporation, altitude above the sea level, temperature, humidity, the quantity of precipitation and the

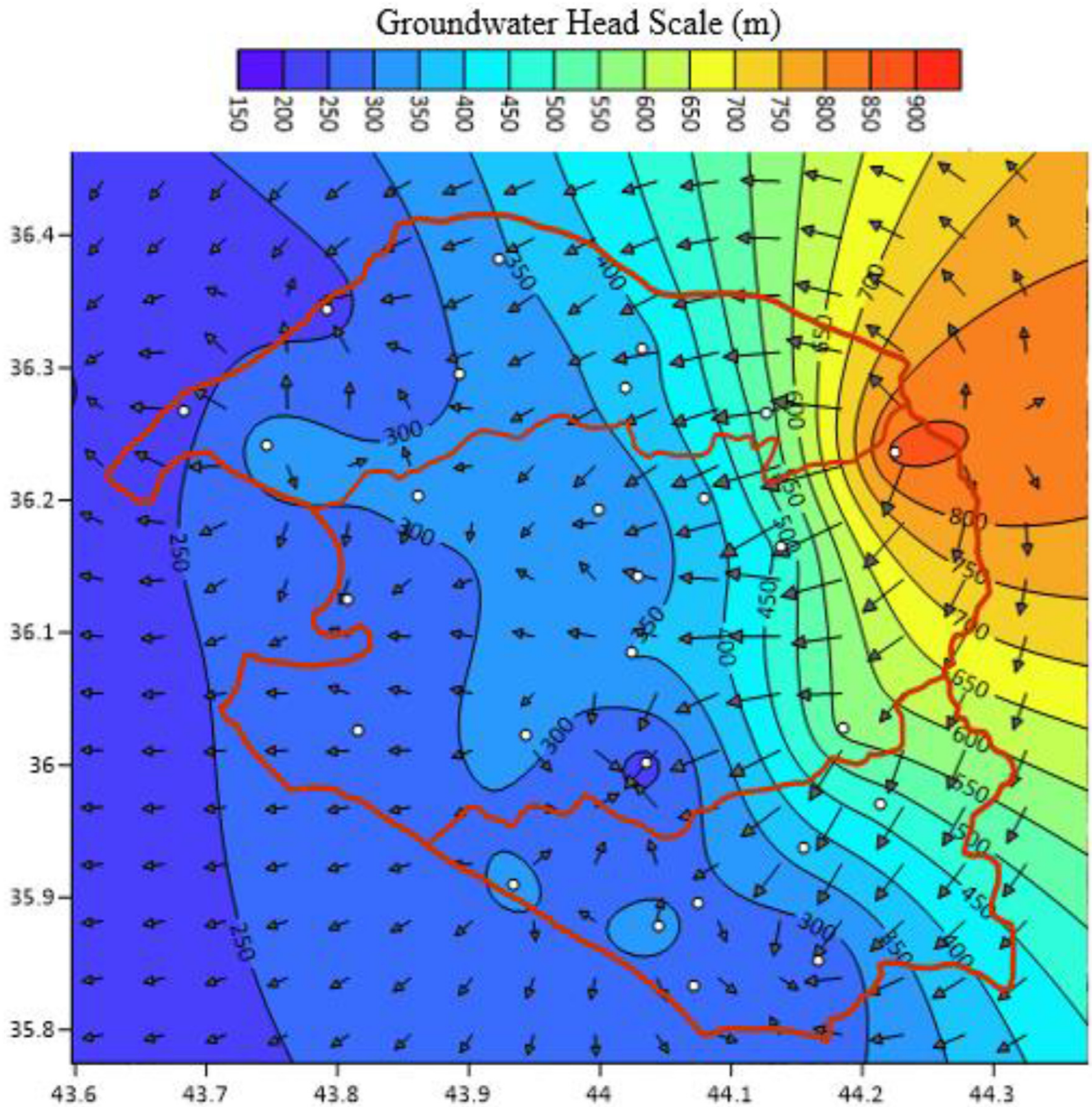

Fig. 8. The flow direction of groundwater over the study area.

seasonal variation of isotope composition. Because of this, the groundwater system's storage of $\delta^{18}O$ and $\delta^{2}H$ is often used to distinguish the origin of the groundwater. The parameters with the most dominant effect on the slope of (s = 6.59) are evaporation and seasonal variation since the sampling is carried out during summer and the recharge process is based on the precipitation during the previous winter and spring seasons. Meanwhile, the d-excess value indicates the source of the vapor in the Erbil basin.

Based on (Taylor et al., 1989) the study cited by (Tutbury, 2015) that analyzed isotopic contents of different water sources, the $\delta^{18}O$ Value $<$ −8.5‰ as reported in well no. 10, located in the Central Erbil sub-basin, was recharged with groundwater from a nearby aquifer. While, for $\delta^{18}O$ that ranged between (−7.5 to −8.5) ‰ originated as a mixture of meteoric water and groundwater. This was found in (well no. 5) at Bahirka, which is 13.8 km from the city center, and (well no. 12) at Mam-joghan village, located at east of Erbil, in the Central sub-basin.

The mean elevation of the recharge zones of the groundwater in the study area was estimated based on the relationship between oxygen-18 and the altitude of the rainwater. As can be seen in Fig. 7, the regression line of precipitation was ($\delta^{18}O$/100 m altitude = −0.22‰). The recharge height of the groundwater was estimated using the intersection of the well point with the atmospheric precipitation slope.

For the group of wells (no. 8, 9, 11 and 23), the recharge area ranged from 820 to 1060 m.asl, The mean elevation of the recharge zones of the groundwater in well groups (no. 1, 3, 4, 13, 15, and 19) ranged from 600 to 720 m.asl. Wells (no. 7, 16, 20, 22 and 27) seem to be infiltrated from a recharge zone with an elevation of about 500 m.asl. The final group of wells, (no. 6, 14, 18 and 21) were recharged at elevations ranging from 380 to 445 m.asl. Although these estimations correspond more or less to the natural topography in the study area, the elevation of the recharge zone of groundwater of well (no. 5, 10, 12 and 17) is higher than 1200 m.asl, which seems to be a little over-estimated.

The results of the recharge elevations indicate that most of the wells are recharged at elevations more than 500 m.asl. The starting elevation of Kasnazan district is approximately 570 m.asl. Therefore, the catchment areas above Kasnazan to the edge of the basin boundary at the Bakhcha hills near well (no. 12) will be the recharge zone inside the Erbil basin. More evidence for this finding can be explained by the groundwater flow direction that starts at well no. 12. The magnitudes of the estimated altitude effect mainly depend on the local climate and topography of the region. However, the altitudes of the groundwater recharge in wells are an estimation because this method may be subject to error and a precision is about ±50 m.

Conclusion

In conclusion, it can be stated that the use of the environmental isotope approach to investigate the groundwater at the Erbil basin can be seen to be a beneficial tool for resolving several issues that could not be resolved using conventional techniques. The isotopic composition of groundwater from various aquifer systems that pass through the Kapran, Central and Bashtapa sub-basins can be used to differentiate them.

The stable isotope content distributions changed with the water sample temperature in the groundwaters that emerged from the aquifer system. Due to recent quaternary sediments covering some locations in the aquifer, higher sample temperature conditions were caused by subsurface formation activities, such as the interaction of water and rocks. The results have demonstrated that enriched values of $\delta^{18}O$ indicate that these waters had undergone various levels of evaporation before recharge. Consequently, one source of recharge is the groundwater recharged by water evaporation from the little Zab river that permeates through the soil in some areas. While another type of recharge is the local precipitation in catchment areas higher than the Kasnazan district, especially the Bakhcha hills (910 m.asl). It is essential to determine the elevation of groundwater recharge based on the isotopic composition of precipitation. According to the altitudinal effect on $\delta^{18}O$ and $\delta^{2}H$ values of precipitation, which has gradients of −0.22 and −1.76 per 100 m.asl respectively, the elevation of the recharging zones has been discovered for various wells.

Declaration of competing interest

Two authors whose names are listed immediately after the current manuscript's title, certify the followings:

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors are in Iraq country, and they have NO affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in their manuscript.

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References

Ali, K.K., Al-Kubaisi, Q.Y., Al-Paruany, K.B., 2015. Isotopic study of water resources in a semi-arid region,western Iraq. J. Environ. Earth Sci. 74 (2), 1671–1686. https://doi.org/10.1007/s12665-015-4172-6.

Al-Naseri, S.K., Falih, A.H., Kumar, U.S., 2022. Moisture sources and spatio-temporal variation of isotopic signatures in Iraqi precipitation. J. Environ. Earth Sci. 81, 1–12.

Amroune, A., Mihoub, R., Enrico, G., Carlos, U., 2020. Groundwater flow dynamics and distribution of hydrochemical facies using GIS in Hodna Plain, M'Sila, Southeastern Algeria. Int. J. Sustain. Dev. Plann. 15 (6), 789–800. https://doi.org/10.18280/ijsdp.150601.

Cejudo, E., Acosta-Gonzalez, G., Leal-Bautista, R.M., Estrada-Medina, H., 2020. Water stable isotopes (δ2H and δ18O) in the Peninsula of Yucatan, Mexico. Tecnología y Ciencias del Agua, 13, pp. 1–35.

Clark, I.D., Fritz, P., 2013. Environmental Isotopes in Hydrogeology-Radioactive Tracers in Hydrogeology, pp. 1–343. https://doi.org/10.1201/9781482242911. Ottawa.

Clark, I.D., Fritz, P., Koop, T., 2015. Atmospheric Water-Fundamentals as the Basis for Understanding the Environment and Promoting Technology, 187, pp. 45–75. Vienna.

Demiroğlu, M., 2017. Identifying the groundwater basin boundaries using environmental isotopes: a case study. Journal of Applied Water Science 7 (3), 1161–1167. https://doi.org/10.1007/s13201-016-0516-y.

Dennis, K., 2014. Picarro Product Portfolio Update: the New Frontier in Cavity Ring-Down Spectroscopy. In: ASITA Conferance, pp. 1–41.

Dizayee, R., 2018. Effects of illegal wells on groundwater level in the central sub-basin, Erbil basin, Erbil, Kurdistan region-Iraq. (ASRJETS) American Scientific Research Journal for Engineering Technology and Sciences 39 (1), 244–249. http://asrjetsjournal.org/.

Hager, B., Foelsche, U., 2015. Stable isotope composition of precipitation in Austria. Austrian Journal of Earth Sciences 108 (2), 2–14. https://doi.org/10.17738/ajes.2015.0012.

Hamad, R., 2022. Erbil basin groundwater recharge potential zone determination using fuzzy-analytical hierarchy process(AHP) in north Iraq. Tikrit journal for agricultural sciences 22 (3), 175–190. https://doi.org/10.25130/tjas.22.3.20.

Hssaisoune, M., Bouchaou, L., Qurtobi, M., Marah, H., Beraaouz, M., El Messari, J., 2022. Isotopic and chemical tracing for residence time and recharge mechanisms of groundwater under semi-arid climate:case from rif mountains (northern Morocco). Geosci. J. 12 (2), 74. https://doi.org/10.3390/geosciences12020074.

IAEA, 2001. Tritium in the Atmosphere-In Environmental Isotopes in the Hydrological Cycle - Principles and Applications-Handbook, pp. 209–216.

Kattan, Z., 1994. Isotope field applications for groundwater studies in the middle east. Proceedings of the final co-ordination meeting of a regional technical co-operation project held in Ankara, Turkey 21–25, 127–150.

Liu, X., Song, X., Xia, J., Yu, J., Tang, C., Zhan, C., 2006. A study of surface water and groundwater using isotopes in Huaishahe basin in Beijing, China. IAHS-AISH Publ. 30 (2), 106–114.

Mawlood, D.K., 2003. Application of Isotope Hydrology Studies Considering the Specific Clamatic, Hydrological and Geological Conditions in Order to to Research Underground Water Resources in a Specific Area in the Near East. Ph.D. Thesis. TU Wein (technical university of Vienna, Austria. https://repositum.tuwien.at/handle/20.500.12708/186163?mode=full.

Mawlood, D.K., 2019. Sustainability of aquifer and groundwater condition in Erbil basin/Iraq. ZANCO Journal of Pure and Applied Sciences 31 (6), 51–60.

OIPC, 2022. Waterisotopes.org, Website for Stable Isotopes in Precipitation available at: https://wateriso.utah.edu/waterisotopes/index.html.

Patrick, H., 2021. Isotopic Water Analyzer Faster Measurement. modes- A new L2130-i-3105, Santa Clara, CA, 95054 - 408-962-3900.

Sissakian, V.K., Fouad, S.A., 2015. Geological Map of Iraq, Scale 1: 1000 000, 2012. In: Iraqi Bulletin of Geology and Mining, , fourth ed.11, pp. 9–17.

Taylor, C.B., Wilson, D.D., Brown, L.J., Stewart, M.K., Burden, R.J., Brailsford, G.W., 1989. Sources a n d flow of north canterbury plains groundwater-NewZealand. Sci. J. 106, 311–340.

Terwey, J.L., 1984. Isotopes in groundwater hydrology-Sudan. Challenges in African hydrology and water resources. Procedure harare symposium 144, 155–160.

Tutbury, R.O., 2015. An Isotopic and Anionic Study of the Hydrologic Connectivity between the Waimakariri River and the Avon River, Christchurch. MSc. thesis, University of Canterbury, NewZealand.

Zhou, P., Li, M., Lu, Y., 2017. Hydrochemistry and Isotope Hydrology for Groundwater Sustainability of the Coastal Multilayered Aquifer System. Hindawi, Geofluids, (Zhanjiang, China). https://doi.org/10.1155/2017/7080346. ID 7080346.