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Original Article

Hydrogeochemical Controls on Heavy Metal Enrichment in Drinking Water: A Case Study from Sulaimani Governorate, Kurdistan Region, Iraq

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ABSTRACT

The contamination of drinking water with heavy metals has emerged as a significant concern in this century. This research evaluates the risk of heavy metal contamination in drinking water throughout the Sulaimani Governorate. In the wet season, a total of 24 drinking water samples were collected from tap water, well water, and spring water. The elemental and isotopic composition was measured using inductively coupled plasma mass spectrometry (ICP-MS), Agilent 8900, together with the XD7500 UV-Vis Water Quality Spectrophotometer and the L213-i isotopic water analyzer. Concentrations of 30 elements (Ca, Mg, Na, K, S, As, Bi, Cd, Co, Cr, Cs, Cu, Li, Mn, Mo, Ni, Pb, Sb, Se, Sn, Te, Tl, V, W, and Zn) were quantified. The pH values ranged from 7.12 at Darbandikhan well water to 8.09 at Zargataikon tap water, TDS varied between 122 at Bainjan tap water and 503 mg/L at Bakrajo well water, and total hardness was between 10 at Dokana line 2 tap water and 38 mg/L at Bakrajo well water. The stable isotopes (^{18}O and ^{2}H) of drinking water samples imply a meteoric water origin. The average concentrations in μg/L of metals and metalloids in drinking water samples were ranked in decreasing order: Zn > Ba > Li > V > Mn > Mo > Cr > As > Se > Cu > Ni > Sb > Co > Pb > Sn > W > Tl > Cs > Te > Bi > Cd. Using the Heavy Metal Pollution Index (HPI), this research found that several drinking water sources in Sulaimani province were slightly contaminated with heavy metals according to Iraqi standards. The analysis suggests that anthropogenic activities, in addition to their natural geological background, may influence certain elements.

1. Introduction

The awareness regarding drinking water quality is progressively increasing in numerous countries worldwide (Aris et al., 2013). Water is absolutely essential for life; roughly 3% of the Earth's surface water is freshwater. An only 0.01% of freshwater is accessible for human use; nonetheless, it is evident that various factors have constrained water consumption for humans. About 2 billion individuals globally do not have access to safe drinking water (Zhang et al., 2024). The World Health Organization (WHO) report from 2015 indicated that approximately 71% of the global population had access to at least a basic drinking water service. By 2050, it's projected that roughly half of the world's population will reside in regions experiencing water stress (Alidadi et al., 2019).

Heavy metals exhibit toxicity, persistence, and bioaccumulation (Farahat and Linderholm, 2015),

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even at low concentrations (Gupta and Sandalio, 2011). They are major contaminants in aquatic environments due to their non-biodegradable characteristics and propensity for bioaccumulation (Marcovecchio and Botté, 2007). Understanding the regional geogenic and anthropogenic characteristics is essential for evaluating the quality of drinking water in the area under investigation (Virha et al., 2011; Teklearegay et al., 2025). The interactions of water with geological environments result in the formation of a diverse array of chemical compounds in groundwater, each present at different concentrations. The interactions of groundwater throughout the hydrological cycle influence its chemical composition (Kumar et al., 2017). This interaction may lead to a decline in groundwater quality as undesired elements leach into the ground (Safeeq and Fares, 2016). Different metals and metalloids naturally infiltrate water resources through leaching from the soil and the underlying rocks they interact with (Virha et al., 2011). The breakdown of rocks and minerals such as silicates, carbonates, and sulphates can significantly impact groundwater quality, with these processes occurring more readily in hot weather and acidic conditions. Some heavy metals, such as Mn, Cr, Se, Zn, Ni, Cu, and Fe, are required in trace quantities for our body's metabolism; nevertheless, having too much of these may be hazardous since they can become toxic at greater levels. At the same time, certain metals are toxic to the human body, such as As, Hg, Cd, and Pb. If their amount exceeds the necessary level and accumulates in the human or organism body, it may produce a variety of health issues, making this group categorized as carcinogenic (Nkono and Asubiojo, 1997; Nyambura et al., 2020). Heavy metals may also accumulate in the human body via a variety of mechanisms, including food chain transit and polluted water consumption (Chen et al., 2009; Osae et al., 2023). Monitoring the presence and behavior of heavy metal in water is, therefore. critical for guaranteeing both environmental sustainability and human health (Al-Hamdany et al., 2025). Numerous studies have been conducted to assess the geochemical quality and level of contamination of drinking water in Sulaimani. Here are two of these studies. Mahmmud et al. (2022) indicate that the dissolution of halite and gypsum influences the geochemistry of groundwater, and they also note a change in groundwater type from Ca–HCO_3 to Ca–Mg–HCO_3 as one moves from the recharge area to the axis of the basin. They indicate the groundwater exhibits high amounts of Ba, but levels of other heavy metals, including Mn, As, F, and Cr, are low. Ahmad and Esmail (2015) evaluate heavy metal pollution, which indicates a low contamination level. To evaluate water quality with precision, it is essential to utilize various indices and parameters. The index serves as an essential tool for assessing the level of contamination and its sources, including the Heavy Metals Pollution Index (HPI). Alongside the indices, various chemical parameters in drinking water can result in considerable environmental and health impacts, such as Ca, Na, Mg, PO_4, NO_3, SO_4, and total hardness (Napacho and Manyele, 2010; Farahat and Linderholm, 2015). In the Sulaimani Governorate, residents use surface water as tap water and groundwater from wells; moreover, those in rural areas outside the city get spring water. The aim of this study is to analyze drinking water samples from the Sulaimani Governorate to assess the extent of heavy metal contamination using selected indices and physicochemical parameters, as well as the origin of the water, and the key environmental or anthropogenic factors influencing its quality.

2. Study area

The study was conducted in the Kurdistan Region, located in northeastern Iraq, spanning latitudes 34°20' 47" to 36° 22' 05" N and longitudes 44° 25' 12" to 46° 24' 58" E (Fig. 1). The climate of northern Iraq is characterized by clear seasonal variations, mostly caused by changes in the type of air masses throughout the year and the level of insolation. The average annual temperature in northern Iraq is high, at approximately 20°C; January is the coldest month, but in July and August, temperatures in this region of Iraq typically rise above 30°C. Records indicate that it can reach 45°C (Ali, 2007). Sulaimani Governorate, within Iraqi Kurdistan Region, belongs to the Zagros Fold-Thrust Belt and is located in the northeastern part of the Arabian Plate. Because of its position as a triple junction between the Arabian and Eurasian plates, the area has a great deal of geological complexity. This area is characterized by intricate structural features, including faults, folding, and uplift, resulting from intense deformation that commenced in the Late Cretaceous period and persists to the present day. The stratigraphic sequence in the Sulaimani area is particularly intricate, featuring formations that span from the Paleozoic Era to the Quaternary Period (Jassim and Goff, 2006). The Sulaimani Governorate features a variety of hydrogeological significant aquifer systems (Mohammed et al., 2025b). Some of these are karstic-fissured aquifers including Cretaceous and Paleocene carbonate formations such as Pilaspi, Aqra-Bekhme, and Qamchuqa (Mustafa et al., 2023). Others include intergranular aquifers such as the Bai Hassan and Mukdadiya formations. There are also modest quantities of recent alluvial aquifers in various locations, and some areas have restricted aquifers (Stevanovic, 2003; Al-Jiburi and Al-Basrawi, 2012; Al-Zubedi, 2022).

3. Methodology

3.1 Water samples

In the wet season, twenty-four drinking water samples were collected from mid-October 2024 to early November 2024 for this study from various locations within Sulaimani Governorate (Fig. 1). Among the collected samples, 13 samples from tap water, 8 from well water, and 3 from spring water. The collected drinking water samples originated from several distinct geological and hydrological areas.

Physiochemical parameters of water samples - pH and TDS

The pH and total dissolved solids were measured in situ using a field measurement device, namely the TDS and EC meter hold and Multifunction pH Meter PCE-PHD 1, both of which were calibrated prior to the assessment of the physical parameters of the samples.

3.2 Multielement analysis (ICP-MS)

For trace and major element analysis, water samples were prepared in two dilutions. For trace element analysis, water samples were only acidified with 2 % (v/v) HNO3 (65 %, Trace SELECT, Fluka Germany). For major element analysis, water samples were diluted tenfold and acidified with 2 % (v/v) HNO3 (65 %, TraceSELECT, Fluka Germany). Water samples were analyzed for their multielement composition using a triple quadrupole inductively coupled plasma mass spectrometer (ICP-MS/MS, Agilent 8900) at the Ruđer Bošković Institute laboratory in Zagreb, Croatia. Typical instrument conditions and measurement parameters used throughout the work are listed in Table 1.

3.3 Stable Isotopes ($\delta^{18}O$ and $\delta^{2}H$)

In order to ascertain the origin of drinking water (whether from rain or groundwater) used in this research, a total of 12 samples were selected, ensuring representation of all samples, for stable isotope composition analysis. The analysis was conducted using Picarro L2130-i isotopic water analyzer at the Hydrogeology Laboratory within the Department of Earth Sciences and Petroleum at Sulaimani University. This analysis focused on determining the oxygen and hydrogen isotope ratios ($\delta^{18}O$ and $\delta^{2}H$) in each sample.

3.4 Anions analysis

Anion concentrations (SO_4^{2-}, Cl^-, HCO_3^-, and CO_3^{2-}) were determined in Hydro-pure Laboratory using a XD7500 UV-Vis Water Quality Spectrophotometer (Lovibond, Germany). The instrument functions using colorimetric and photometric detection in the visible and ultraviolet wavelength ranges 190 to 1100 nm were used.

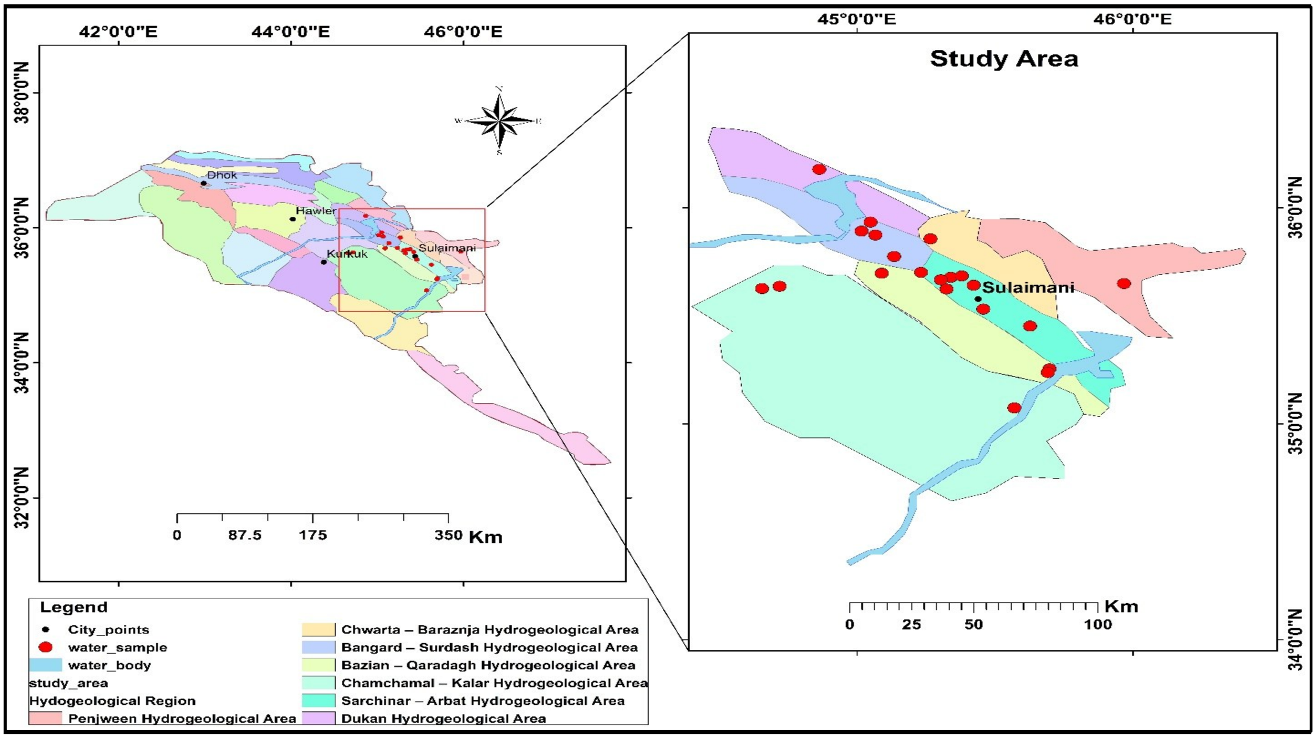

Figure. 1. Location map showing the distribution of the studied water samples within the study area (after Al-Zubedi, 2022).

Table 1. Instrumental conditions of used mass spectrometer and data acquisition parameters for determination of selected elements.

ICP-QQQ	8900 Agilent, USA
RF power	1550 W
Plasma gas flow rate	15.0 L min^{-1}
Auxiliary gas flow rate	0.90 L min^{-1}
Sample gas flow rate	1.01 L min^{-1}
Torch	Fassel type, 1.5 mm i.d.
Nebulizer	MicroMist (Nebulizer Sample Particle Size Tolerance - 40 µm)
Sample cone	Ni
Skimmer cone	Ni
Acquisition mode	Spectrum
No. Scans	50
Calibration	External

All samples were analyzed for a total concentration of 27 elements which include (As, Ba, Bi, Ca, Cd, Co, Cr, Cs, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, Pb, S, Sb, Se, Sn, Te, Tl, V, W and Zn). The measurement of the blank sample alongside certified reference material for water was done simultaneously for quality control of the analytical procedure (SLRS-4, NRC, Ottawa, ON, Canada). Good agreement between the analyzed and certified concentrations within their analytical uncertainties for all elements was obtained (<10%).

3.5 Statistical analysis

Using statistical approaches and water pollution indices, the study looked at and examined the sources and concentrations of heavy metals. Indices of water pollution and statistical analysis techniques help to identify and evaluate water quality data. Statistical analysis may helps identify the cause and mechanism of water contamination. In this study, the principal component analysis (PCA) elucidated the relationships among the examined heavy metals and chemical contaminants, while cluster analysis was used to categorize water samples based on their geographic variations in heavy metal and chemical characteristics. ANOVA facilitated the assessment of variance significance across several sample locations (Ali et al., 2017; Argun, 2025). The statistical assessments were conducted using IBM SPSS Statistics 27.

Table 2. Calculation of HPI on sample 3 from the studied drinking water samples in this research.

Heavy metals	Si (µg/L)	Li (µg/L)	Monitor Value(µg/L)	Wi	Qi	Wi Qi
As	10	0	0.67	0.10	6.70	0.67
Ba	700	0	58.545	0.00	8.36	0.01
Fe	300	0	0	0.00	0.00	0.00
Bi	100	0	0.004	0.01	0.00	0.00
Cd	3	0	0.001	0.33	0.03	0.01
Co	70	0	0.016	0.01	0.02	0.00
Cr	50	0	0.08	0.02	0.16	0.00
Cs	1000	0	0.002	0.00	0.00	0.00
Cu	2000	100	0.224	0.00	5.25	0.00
Li	100	0	9.515	0.01	9.52	0.10
Mn	400	0	0.032	0.00	0.01	0.00
Mo	70	0	1.34	0.01	1.91	0.03
Ni	70	0	0.169	0.01	0.24	0.00
Pb	10	0	0	0.10	0.00	0.00
Sb	20	0	0.073	0.05	0.37	0.02
Se	40	0	0.407	0.03	1.02	0.03
Sn	2000	0	0.009	0.00	0.00	0.00
Te	10	0	0	0.10	0.00	0.00
Tl	2	0	0.003	0.50	0.15	0.08
V	50	0	1.681	0.02	3.36	0.07
W	100	0	0.009	0.01	0.01	0.00
Zn	3000	500	0	0.00	0.00	0.00
			∑(Wi)	1.33	∑(Wi*Qi)	1.01
					HPI=∑(Wi*Qi)/∑(Wi)	0.76

3.6 Heavy metal pollution index

The Heavy Metal Pollution Index (HPI) reflects the overall quality of drinking water related to present heavy metals concentrations (Prasanna et al., 2012; Sheykhi and Moore, 2012). This index is computed in accordance with Eq. 1 and 2 as follows:

$$HPI = \frac{\sum_{i=1}^{n} W_i Q_i}{\sum_{i1}^{n} w_i} \qquad (1)$$

where:

- Wi is the unit weight assigned to the *i*-th parameter (reflecting its relative importance),
- Qi is the sub-index of the *i*-th parameter,
- *n* is the total number of heavy metals considered.

Furthermore, Wi and Qi represent the unit weightage and sub-index of the *i* parameter. Equation 1 shows that *n* is the total number of parameters to be examined.

$$Q_i = \sum_{i=1}^{n} \frac{Mi - L_i}{S_i - L_i} * 100 \qquad (2)$$

Mi and Li represents the monitored and ideal values of the *i* parameter, respectively, whereas Si represents the standard value of the *i* parameter in parts per billion (ppb), taken from the WHO guidelines for drinking water quality (WHO, 2011), as stated in equation (2).

4. Results and discussion

4.1 Physiochemical parameters of water samples; pH, TDS and T.H

Drinking water samples were studied and evaluated to ascertain their quality, and then compared to World Health Organization (WHO) standards and other criteria. According to Detay (1997), the primary objectives of researching the physiochemical properties of groundwater are to ascertain the geographical origin of the water and the extent of the contamination involved. The pH value of the studied water samples did not differ significantly between different water types, ranging from 7.1 to 8.1, with an average of 8.0. The highest pH value (8.1) was detected at the site of the Zargataikon area (tap water sample) (Table 3). The observed pH range falls within the expected/optimal range for drinking water (WHO, 2011).

Total dissolved solids (TDS), often known as salinity, are the solids that remain after a water sample evaporates to dryness (Drever, 1997). TDS is calculated by multiplying the EC by a factor (0.64) (Albu et al., 2012). In the analyzed water samples, the TDS values were between 122 and 503 mg/L, which according to Altoviski (1962) and Gorrell (1958) falls into the freshwater category (0-1000) (Table 3). The total hardness (TH) values of the studied water samples ranged from 10 to 38 mg/L, with an average of 18 (Table 3). The water samples are classified as soft water according to Boyd (2000).

4.2 Distribution of major cations and anions in drinking water samples

The concentration of Ca^{2+} in water samples ranged from 2.6 to 9.0 mg/L and was higher in well water compared to tap water and spring water (Table 4). Specifically, the concentration of Ca^{2+} in well water ranged from 5.0 to 9.0 mg/L. The source of calcium in the studied area is primarily geological, originating from units such as chalky limestone, crystalline limestone, and dolomitic limestone found within Jurassic formations, Qamchuqa, Balambo, Kometan, Sinjar, Pilaspi, limestone and gypsum of the Fatha Formation (Al-Manmi, 2008; Dartash, 2012). The content of Mg^{2+} in the samples ranged from 0.5 to 4.6 mg/L (Table 4).

The magnesium content in the study samples is much higher in well water than in other sample types. The concentration of Mg^{2+} in well water varies from 2 to 4.6 mg/L. The source of magnesium in the studied region is also considered primarily geological, notably from Jurassic formations such as Sarki and Sehkaniyan, particularly in the Rania area (Al-Manmi, 2008), as well as Qamchuqa, Balambo, Kometan, Pilaspi, the Fatha Formation, and metamorphic and igneous rocks in the Penjwen area.

The Na+ concentration of water samples ranges from 0.14-7.4 mg/L (Table 4). Similarly to Ca and Mg, the Na content in the study samples was much higher in well water than in other sample types. The range of K^{+} concentrations in water samples was from 0.03 to 0.41mg/L (Table 4). When compared to the other sample types, the potassium content was highest in the tap water. The range of S^{+} concentrations in water samples was from 0.36 to 3.9 mg/L (Table 4). When compared to other sample types, the sulfur content was highest in the well water samples.

The quantities of hydrogen carbonate (HCO3) - in water samples ranged from 210 to 620 mg/L, with an average of 370 mg/L (Table 4), whereas the content of carbon dioxide (CO3) 2- in all samples was zero. The concentration of (CO3) 2- is zero due to the pH value being below 8.1 for all water samples. Namely, at pH below 8.1, all (CO3)2- is transformed to (HCO3)-. The concentrations of sulfate ions $(SO_4)^{2-}$ in water samples are listed in Table 4, ranging from 25.0 to 296 mg/L, with an average of 75.4 mg/L. The most probable sources of sulphate are gypsum layers, like those in the Fatha Formation (Dartash, 2012), gypsum that forms in caves and cracks in the study area, and human activities. Namely, activities and sewage leaks are known to provide additional sources of sulphate to local water bodies (Zhang et al., 2020). In the research region, the concentrations of chloride in water samples ranged from 9.2 to 84 mg/L, with an average of 23 mg/L (Table 4). Similarly as for all other anions, geological formations are considered the main sources of chloride, with additional contributions from fertilizers and human activities (Kouacou et al., 2024).

Table 3. Physical parameters (pH, TDS and TH) of drinking water samples in Sulaimani Governorate, Kurdistan Region, Iraq.

water sample location	pH	TDS	TH	Longitude	Latitude
Kalar tap water	7.23	205	16.2	45° 34' 12.00"	35° 4' 22.80"
Bainjan well water	7.74	203	12.1	45° 5' 21.78"	35° 41' 46.32"
Bainjan Tap water	7.69	122	13.7	45° 5' 21.78"	35° 41' 46.32"
Sarchnar spring	7.16	212	12.6	45° 20' 24.30"	35° 40' 38.23"
Dokan line1 tap water	7.39	150	9.96	45° 0' 58.68"	35° 53' 27.51"
Tasluja spring water	7.6	221	24.3	45° 13' 53.87"	35° 41' 59.94"
Rapurin tap water	7.75	162	12.0	45° 18' 13.55"	35° 39' 57.37"
Chamchamal tap water	7.45	142	19.2	44° 39' 22.01"	35° 37' 29.44"
Chamechamal well water	7.42	499	28.6	44° 43' 11.43"	35° 38' 7.68"
Qamchuqa well water	7.14	477	26.3	45° 2' 56.75"	35° 55' 58.29"
Piramagrun well water	7.37	190	14.2	45° 8' 2.64"	35° 46' 24.75"
Karezawshk tap water	7.89	141	15.6	45° 25' 20.29"	35° 38' 26.57"
Arbat tap water	7.75	235	9.79	45° 37' 35.75"	35° 27' 5.59"
Gapillon well water	7.43	257	18.8	45° 15' 57.36"	35° 51' 18.35"
Piramagrun tap water	7.6	130	12.8	45° 8' 2.64"	35° 46' 24.75"
Khabat tap water	7.49	159	16.1	45° 27' 27.41"	35° 31' 47.07"
Zargataikon tap water	8.09	143	16.4	45° 22' 45.94"	35° 41' 0.93"
Dokana line 2 tap water	7.32	150	9.90	45° 3' 58.94"	35° 52' 23.13"
Rania spring	7.32	214	17.2	44° 51' 48.24"	36° 10' 36.00"
Penjwen well water	7.81	225	24.5	45° 58' 1.51"	35° 38' 53.81"
Bakrajo well water	7.32	503	38.2	45° 19' 26.19"	35° 37' 23.01"
Bakrajo tap water	7.55	211	13.4	45° 19' 26.19"	35° 37' 23.01"
Darbandikhan well water	7.12	270	23.1	45° 41' 28.85"	35° 14' 11.88"
Derbandikhan tap water	7.48	124	15.9	45° 41' 49.16"	35° 15' 11.18"
Min	7.12	122	10.0		
Max	8.09	503	38.2		
Average	7.50	223	18		

4.3 Water classification

Water may be characterized by a chemical examination of its predominant ions. Figure 2 presents a Piper diagram for potable water samples. According to the Piper diagram, the well water samples show high level of calcium, between 55% and 80%, magnesium levels below 45%, and the average amount of sodium and potassium below 25%, reflecting the influence of carbonate sedimentary rocks.

Nonetheless, the well water samples from Penjwen, Chamchamal, and Qamchuqa diverge from this categorization (Fig. 2). The water samples from the Penjwen and Chamchamal wells exhibit similar concentrations of calcium (Ca) and magnesium (Mg) with low levels of sodium plus potassium (Na+ K), while the Qamchuqa well water sample exhibited high levels of Na+ K (59%) and low concentrations of Mg and Ca (25% each) (Fig. 2). The well water samples can be classified as bicarbonate type, as they are rich in bicarbonate ion, exceeding 80%, with minimal amounts of SO_4^{2-} and Cl^-.

Table 4. Minimum, maximum, range and average of hydrochemical parameters of water samples from Sulaimani Governorate, Kurdistan Region, Iraq.

Variables	Min	Max	Range	Average
Ca^{2+} mg/L	2.6	9	2.6-9.0	4.4
Mg^{2+} mg/L	0.5	4.6	0.5-4.6	1.6
Na^{+} mg/L	0.14	7.4	0.14-7.4	1.07
K^{+} mg/L	0.035	0.4	0.035-0.41	0.11
S mg/L	0.36	3.9	0.36-3.9	1.3
SO_4^{2-} mg/L	25	296	25-296	75.4
Cl^{-} mg/L	9.2	84.0	9.2-84.0	23
HCO_3^{-} mg/L	210	620	210-620	369.5
CO_3^{-} mg/L	0	0	0	0
pH	7.0	8.09	7-8.09	7.5
TDS mg/L	122.0	503.0	122-503	223
TH mg/L	10.0	38.18	10-38.18	18

Exceptions are the Darbandikhan, Bakrajo, and Qamchuqa well water samples that show bicarbonate levels ranging from 55% to 70% and SO_4^{2-} content between 25% and 35%, along with minimal Cl. Thus, all well water samples, based on overall ionic dispersion (diamond-shaped region), are of the Ca-Mg-bicarbonate type, except for the Qamchuqa well water sample, which is a mixed type (Fig. 2).

The spring water samples, categorized by cation types, mostly include calcium, exhibiting concentrations between 70% and 88%, while magnesium levels fluctuate from 10% to 30%. Sodium and potassium levels are minimal, attributable to the geological region, which is largely composed of carbonate rocks. Also, the spring water samples, grouped by anion type, are mainly bicarbonate type, with more than 65% bicarbonate and very low levels of SO_4^{2-} and Cl^-. All spring water samples, based on overall ionic dispersion (diamond-shaped region), are also of the Ca-Mg-bicarbonate type.

The tap water samples, grouped by cation type, predominantly include calcium, with concentrations ranging from 53% to 90%, whereas magnesium levels range from 10% to 38%. Sodium and potassium levels are low. Tap water samples grouped by anion type largely include bicarbonate (over 68%), with modest amounts of SO_4^{2-} and Cl^-. All tap water samples, based on overall ionic dispersion (diamond-shaped area), are Ca-Mg-bicarbonate.

Most water samples exhibit Ca-Mg-HCO_3^- hydrochemical facies. The hydrochemical facies is defined by the presence of weak acid anions (HCO_3^- and CO_3^{2-}). as well as Ca and Mg ions in abundance. The water samples are freshwater, impacted mostly by carbonate rock dissolution and, to a lesser extent, by evaporite rock and human activity.

4.4 Heavy metal concentrations

Obtained element concentration in water samples are shown in Table 5, along with basic statistical parameters (minimum, maximum, average and standard deviation), In the studied water samples the average concentrations of heavy metals and metalloids were found in the following order: Zn>Ba >Fe> Li >V> Mn >Mo >Cr >As >Se> Cu >Ni> Sb> Co> Pb> Sn> W> Tl >Cs> Te >Bi >Cd.

The concentration of heavy metals in drinking water samples in the Sulaimani governorate adheres to the IQS (2001) and WHO (2022) recommendations; all of the samples are considered acceptable for consumption as all measured elements were below the thresholds established by these standards (Table 6).

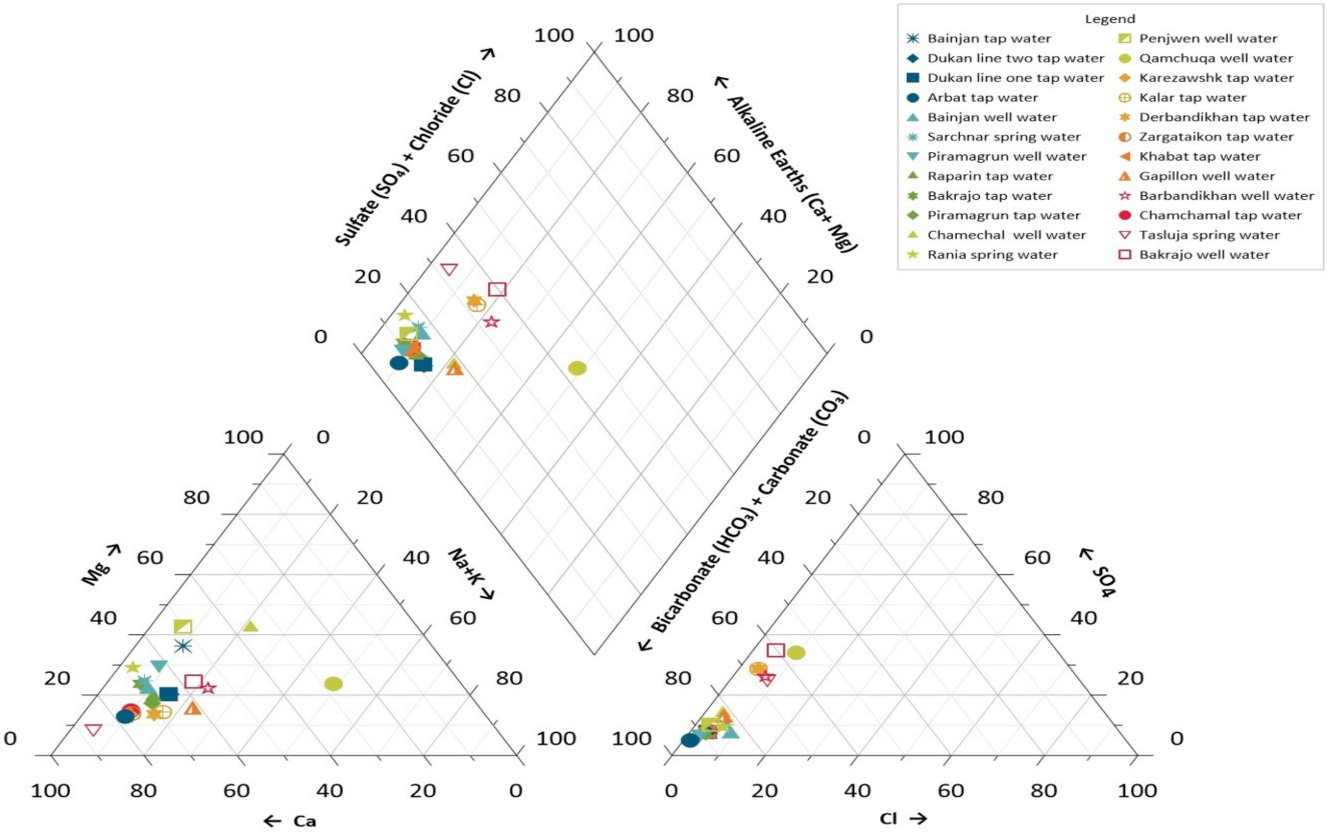

Figure. 2. Piper diagram for drinking water samples analysis in Sulaimani Governorate, Kurdistan Region, Iraq.

4.5 Statistical analyses of the elemental concentrate-ons of studied water samples

To analyze the origin of the predominant cations and anions in the studied drinking water samples, and to determine the extent of similarity among these samples different statistical methods were used. ANOVA is a statistical approach that determines if there are significant differences between the means of three or more independent groups. The approach divides the overall variance in a dataset into components that arise from several sources, especially the differences between groups and the differences within each group (Montgomery, 2017).

The elemental composition in the sample-based one-way ANOVA analysis is uniform across the majority of samples, except for the concentration of Mg, Na, S, HCO3-, Cl-, SO42-, As, Li, Mo, Sb, Te, V, Sc and Tl Significant differences were observed among the sampling sites ($\rho < 0.05$). A statistically significant difference in magnesium concentration occurs between well water samples with each sample of spring and tap water; however, no significant difference is seen between tap water and spring water. Each of sodium and sulfur elements are differ in concentration between tap water and well water samples however, no significant difference is seen between spring water sample compared with tap and well water samples. The quantity of HCO_3^- varies between tap water and well water samples, as well as between well water and spring water samples; however, no substantial variation is seen between spring water samples and tap water samples. The concentrations of Cl^- and SO_4^{2-} anions vary between tap water and well water samples; however, no significant variation is seen when comparing the spring water sample to the tap and well water samples. the concentration of the heavy metal of As varies between the tap water sample and both the spring and well water samples. Moreover, each of Li, Te and V are differ between tap water and well water samples. Sc differs between tap water and well water samples, as well as between well water and spring water samples.

Mo, Sb and Tl does not represent the concentration differing between well and tap water; rather, it indicates the difference between spring water and each sample of drinking water sourced from either wells or taps.

Cluster analysis was used for purpose of assessing water quality data and identifying whether samples can be categorized into distinct populations (hydrochemical groups) that hold significance in both geological and statistical contexts (Güler et al., 2002). Figure 3a illustrates the degree of similarity that exists between the samples that were investigated using Q-mode cluster analysis, while using R-mode cluster analysis, Figure 3b illustrates the degree to which the elemental compositions in the region under investigation are comparable to one another.

The Q-mode cluster analysis revealed similarities among the analysis's samples based on their primary elemental compositions (Fig. 3a). Furthermore, two principal groups may be identified using a minimum distance value of 5 to assess the degree of correlation among the samples.

Group 1: this is the main group, including the samples 2, 3, 4, 5, 7, 8 ,9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 and 22. The linkage distance between this group is a very short linkage distance that suggests strong similarity means common origin and common geochemical composition.

Group 2: samples 1, 6, 10, 21, 23 and 24 is part of this group. Additionally, as they have a common origin and have a greater S, SO_4-, Na, and Cl- content than group 1, the quantity of heavy metals Ba, Fe, Li, Mo, and V in this drinking water sample also exceeds that of other samples collected in the Sulaimani governorate.

Al and Ti are advantageous reference points in complex geochemical research since they are found in rocks and do not migrate significantly in most regions. These elements are typically derived from silicate minerals, with little effect from human activity (Reimann and De Caritat, 2005). The goal is to ascertain whether mineral weathering or anthropogenic inputs are the source of the heavy metals and metalloids found in drinking water samples in the Sulaimani governorate.

The chemical composition of heavy metals of studies drinking water samples can be categorized into four major groups when taking the similarity distance value at 22 levels as follows:

Group 1: comprises the two primary groupings. The first group comprises Mo, Sb, and Tl, which are closely associated with the subsequent primary group of elements K, Se, SO42-, S, Cl-, Na, Co and Cs. The combination of major ions K, SO_4^{2-}, S, Cl^-, and Na with Mo, Sb, Tl, Se, Co, and Cs, potentially attributable to the geochemical process and industrial activity influenced by the chemical composition of the analyzed sample in the study area, and the ions in this cluster indicate the interaction between water and evaporite rocks (Appelo and Postma, 2005). The existence of trace metals such as Mo, Sb, Tl, Se, Co, and Cs signifies industrial pollution and redox-sensitive conduct (Kabata-Pendias, 2000).

Group 2: has two subgroups. The first subgroup comprises Sn, W and Te, which exhibit a favorable association with the subsequent subgroup, including As, Mn, Ti, Cd, Cu, Zn, Pb and Ni. The grouping of those trace metals and metalloids shows how pollution affects the chemistry of drinking water, as the separate clusters of As, Cu, and Zn, apart from that group, along with the distinct clusters lacking both lithogenic elements of Al and Ti, suggest extra human influences, like those from farming or industry (Guda et al., 2024).

Group 3: comprise the two main clusters. The first cluster includes Al and Bi, which are closely linked to the next main cluster of Mg, Sc, HCO_3^-, Li, V, Fe, Ba, Ca, and Cr. The presence of Al with Li, V, Bi, Ba, Cr, Fe and Sc indicate the silicate weathering or clay mineral dissolution under slightly pH condition (Guda et al., 2024), while the presence of Ca, Mg and HCO_3^- indicate the carbonate rock water interaction (Tiwari and Singh, 2014).

Table 5. Elemental composition (in µg /L) and statistical parameters in the analyzed drinking water samples from Sulaimani Governorate, Kurdistan Region, Iraq.

Location	**Sample No.**	**Ca**	**Mg**	**Na**	**K**	**S**	**HCO3-**	**Cl$^-$**	**SO4-**	**Al**	**Ti**	**Sc**
Kalar tap water	1	4837	1006	1024	162	1569	326300	20500	140000	113.37	0.03	0.01
Bainjan well water	2	3123	1037	407	42	555	299700	31400	28000	0.62	bdl	0.00
Bainjan tap water	3	2585	1760	441	55	416	340000	15000	31000	3.35	0.01	0.00
Sarchnar spring water	4	3134	1152	317	47	918	210000	16300	25400	2.11	0.00	bdl
Dokan line1tap water	5	2627	827	489	123	548	340400	15000	29400	2.93	0.03	bdl
Tasluja spring water	6	8431	784	455	35	2087	271600	32400	100000	2.73	0.01	bdl
Rapurin tap water	7	3271	932	475	111	694	339000	14400	30000	2.22	bdl	bdl
Chamchamal tap water	8	5816	1147	608	139	630	341500	15200	30800	4.45	0.00	0.00
Chamchamal well water	9	3906	4596	2301	52	1965	620300	30800	106000	0.91	0.03	0.02
Qamchuqa well water	10	4348	3768	7396	311	3927	485900	84000	296000	0.18	0.01	0.01
Piramagrun well water	11	3210	1513	353	90	653	420200	13200	30000	1.41	0.06	0.00
Karezawshk tap water	12	4833	868	510	117	595	342200	15000	31000	7.65	0.00	bdl
Arbat tap water	13	3079	511	338	43	363	560200	9200	30000	0.92	0.01	bdl
Gapillon well water	14	5278	1358	1517	418	1492	435300	24000	70000	0.52	bdl	0.01
Piramagruntap tap water	15	3616	905	548	132	651	338800	15100	30500	9.32	0.00	bdl
Khabat tap water	16	5033	852	500	119	639	339200	14800	30000	4.97	bdl	bdl
Zargataikon tap water	17	5022	928	552	135	610	341800	13800	30200	7.35	0.20	bdl
Dokana line 2 tap water	18	2614	821	508	127	604	342000	14600	30000	9.32	0.04	bdl
Rania spring water	19	4022	1731	137	44	953	283000	21200	31500	0.81	0.04	bdl
Penjwen well water	20	4093	3490	512	54	1105	543000	20400	64000	0.68	0.01	0.04
Bakrajo well water	21	8980	3838	2870	50	3790	379200	30800	220000	0.28	0.02	0.03
Bakrajo tap water	22	3411	1175	318	50	1018	344000	14000	28000	7.81	0.02	bdl
Barbandikhan well water	23	5576	2242	2245	58	3407	419400	44500	164000	0.40	0.01	0.03
Derbandikhan tap water	24	4841	921	890	168	1170	324000	21200	139000	0.53	0.03	0.00
Min		2585	511	137	35	363	210000	9200	25400	0.18	0.00	0.00
Max		8980	4596	7396	418	3927	620300	84000	296000	113.37	0.20	0.04
Average		4404	1590	1071	112	1265	374458	22783	72700	7.70	0.03	0.01

Bdl: below detection limit

Table 5 Continued...

Location	Sample No.	As	Ba	Bi	Cd	Co	Cr	Cs	Cu	Fe	Li	Zn
Kalar tap water	1	0.67	58.6	0.004	0.001	0.016	0.08	0.002	0.22	bdl	9.52	bdl
Bainjan well water	2	0.27	38.5	0.003	0	0.01	2.77	0.001	bdl	0.28	3.44	bdl
Bainjan Tap water	3	0.71	23.3	0.002	0.001	0.007	3.77	0.004	0.04	bdl	2.75	bdl
Sarchnar spring water	4	0.27	84.1	0.002	0	0.009	0.43	0.002	0.02	1.24	2.54	0.08
Dokan line1tap water	5	1.96	26.8	0.002	0	0.014	0.04	0.002	0.38	0.38	2.26	0.08
Tasluja spring water	6	0.22	36.6	0.002	0.002	0.055	2.40	0.001	1.22	0.01	1.83	149
Rapurin tap water	7	1.28	42.5	0.002	0	0.008	0.11	0.003	0.35	0.21	2.35	0.42
Chamchamal tap water	8	1.58	29.8	0.001	0.001	0.009	0.35	0.002	0.33	0.06	2.92	122
Chamchamal well water	9	0.31	109	0.001	0	0.047	1.84	0.003	0.03	39.8	14.32	bdl
Qamchuqa well water	10	0.14	57.3	0.001	0	0.187	0.31	0.031	0.19	bdl	5.48	bdl
Piramagrun well water	11	0.13	30.1	0.001	0	0.015	1.43	0.003	bdl	bdl	2.57	bdl
Karezawshk tap water	12	0.99	31.0	0.001	0.002	0.007	0.04	0.003	0.22	bdl	2.42	44.3
Arbat tap water	13	0.14	231	0.001	0	0.004	0.43	0.002	0.21	bdl	2.22	0.60
Gapillon well water	14	0.17	43.8	0.001	0.001	0.021	0.04	0.014	0.12	bdl	7.14	bdl
Piramagruntap tap water	15	1.78	27.9	0.001	0	0.011	0.06	0.007	0.26	bdl	2.40	bdl
Khabat tap water	16	1.52	31.8	0	0.001	0.009	0.14	0.007	1.21	bdl	2.20	182
Zargataikon tap water	17	1.64	32.6	0.001	0.004	0.007	0.06	0.006	1.50	bdl	2.12	107
Dokana line 2 tap water	18	1.83	28.1	0.001	0	0.009	0.03	0.008	0.72	bdl	2.37	bdl
Rania spring water	19	0.24	29.4	0	0.004	0.006	0.31	0.002	bdl	bdl	2.20	bdl
Penjwen well water	20	0.34	5.33	0.001	0	0.019	0.89	0.002	bdl	bdl	1.89	12.7
Bakrajo well water	21	0.24	92.0	0.001	0.001	0.016	1.18	0.011	0.19	bdl	10.73	bdl
Bakrajo tap water	22	0.28	85.7	0	0.003	0.074	0.52	0.002	0.82	bdl	2.07	147
Barbandikhan well water	23	0.43	157	0	0	0.032	1.77	0.005	0.11	bdl	5.86	0.49
Derbandikhan tap water	24	0.78	42.1	0	0.001	0.012	0.07	0.002	0.38	bdl	4.98	0.67
Min		0.13	5.33	0.00	0.00	0.00	0.03	0.00	0.02	0.01	1.83	0.08
Max		1.96	231	0.00	0.00	0.19	3.77	0.03	1.50	39.8	3.44	182
Average		0.75	57.2	0.00	0.00	0.03	0.79	0.01	0.43	5.99	4.11	58.9

Bdl: below detection limit

Table 5 Continued…

Location	sample No.	Mn	Mo	Ni	Pb	Sb	Se	Sn	Te	Tl	V	W
Kalar tap water	1	0.03	1.34	0.17	bdl	0.07	0.41	0.009	0	0.003	1.68	0.009
Bainjan well water	2	bdl	0.29	bdl	bdl	0.02	0.27	0.01	0	0.002	4.64	0.004
Bainjan Tap water	3	0.35	0.59	0.05	0.001	0.03	0.41	0.007	0	0.004	2.36	0.018
Sarchnar spring water	4	1.13	0.47	bdl	0.001	0.02	0.58	0.005	0	0.006	1.40	0.002
Dokan line1 tap water	5	4.23	0.53	0.20	bdl	0.09	0.15	0.06	0.009	0.007	0.67	0.005
Tasluja spring water	6	0.01	0.09	0.25	0.113	0.02	0.76	0.007	0	0.002	3.14	0.003
Rapurin tap water	7	2.06	0.51	bdl	bdl	0.07	0.22	0.002	0.006	0.003	0.79	0.003
Chamchamal tap water	8	0.71	0.56	0.36	bdl	0.08	0.30	0.005	0.009	0.004	0.96	0.006
Chamchamal well water	9	0.21	1.39	0.23	0.054	0.02	0.32	0.015	0.002	0.002	7.43	0.007
Qamchuqa well water	10	bdl	0.41	0.30	bdl	0.07	1.37	0.02	0	0.013	2.76	0.003
Piramagrun well water	11	0.00	0.19	bdl	0.002	0.01	0.29	0.009	0	0.001	2.30	0.002
Karezawshk tap water	12	1.98	0.56	0.13	0.006	0.08	0.23	0.023	0.007	0.004	0.85	0.006
Arbat tap water	13	0.00	0.35	bdl	bdl	0.03	1.15	0.012	0	0.001	1.63	0.003
Gapillon well water	14	0.01	0.67	bdl	bdl	0.03	4.37	0.006	0	0.007	0.52	0.004
Piramagruntap tap water	15	1.45	0.51	bdl	bdl	0.08	0.17	0.003	0.016	0.002	0.70	0.006
Khabat tap water	16	7.76	0.60	0.28	0.009	0.17	0.16	0.002	0	0.004	0.81	0.007
Zargataikon tap water	17	2.03	0.54	0.99	0.076	0.09	0.17	0.005	0.004	0.001	0.80	0.006
Dokana line 2	18	2.30	0.52	bdl	bdl	0.08	0.10	0.004	0.013	0.002	0.67	0.007
Rania spring water	19	0.02	9.99	0.02	0.01	1.34	1.13	0.024	0	0.038	2.07	0.006
Penjwen well water	20	0.03	0.25	1.05	bdl	0.01	0.23	0.007	0	0	2.67	0.033
Bakrajo well water	21	0.03	0.53	bdl	bdl	0.06	0.50	0.002	0	0.009	6.48	0.003
Bakrajo tap water	22	0.48	0.46	bdl	0.002	0.04	0.62	0.139	0.02	0.009	1.42	0.037
Barbandikhan well water	23	0.00	0.24	bdl	bdl	0.03	0.24	0.003	0	0	5.10	0.003
Derbandikhan tap water	24	0.34	1.14	bdl	bdl	0.07	0.27	0.002	0.002	0.006	0.95	0.004
Min		0.00	0.09	0.02	0.00	0.01	0.10	0.00	0.00	0.00	0.52	0.00
Max		bdl	0.29	bdl	0.11	1.34	4.37	0.14	0.02	0.04	7.43	0.04
Average		1.14	0.95	0.34	0.03	0.11	0.60	0.02	0.00	0.01	2.20	0.01

Bdl: below detection limit.

Table 6. Comparing of analyzed drinking water samples in Sulaimani Governorate, Kurdistan Region, Iraq with (WHO, 2022) and (IQS, 2001) standards.

Heavy metals	Min (µg/L)	Max (µg/L)	Average (µg/L)	Iraqi Standard 2001 (IQS, 2001) (µg/L)	WHO (2022) (µg /L)
Zn	0.078	182	58.9	3000	3000
Ba	5.33	231	56.8	N. D	700
Fe	0.01	39.8	5.99	300	300
Li	1.83	14.3	4.26	N. D	N. G
V	0.520	7.43	2.17	N. D	0.1 (provisional)
Mn	0.001	7.76	1.11	100	80 (provisional)
Mo	0.085	9.99	1.01	N. D	70
Cr	0.030	3.77	0.766	50	50 (Total)
As	0.125	1.96	0.744	10	10
Se	0.096	4.37	0.592	10	40
Cu	0.020	1.50	0.414	1000	2000
Ni	0.019	1.05	0.322	20	70
Sb	0.013	1.34	0.108	N. D	20
Co	0.004	0.187	0.026	N. D	N. G
Pb	0.001	0.113	0.025	10	10
Sn	0.002	0.139	0.016	N. D	N. G
W	0.002	0.037	0.008	N. D	N. G
Tl	<0.001	0.038	0.005	N. D	2
Cs	0.001	0.031	0.005	N. D	N. G
Te	<0.001	0.020	0.004	N. D	N. G
Bi	<0.001	0.005	0.001	N. D	N. G
Cd	<0.001	0.006	0.001	3	3

N. D: Not Determined, N. G: Not Guideline, Provisional: presents standards established with a degree of ambiguity.

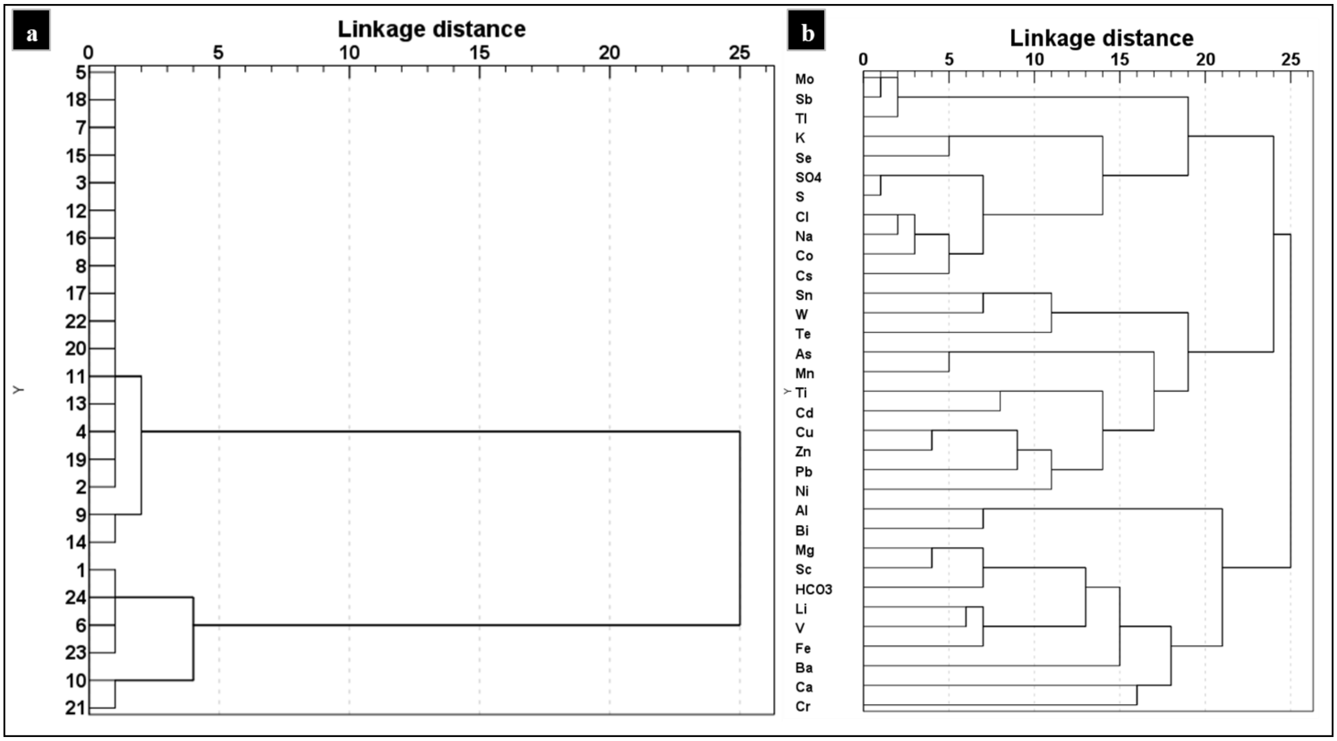

Figure. 3. (a) (Q-mode) of the studied drinking water samples Cluster analyses (b) (R-mode) of the studied heavy metals analysis of drinking water samples in Sulaimani Governorate, Kurdistan Region, Iraq.

Principal component analysis (PCA) was used to find the predominant hydrogeochemical variables contributing to the majority of the dataset variability. The importance of the identified main component components was assessed based on the computed eigenvalues greater than unity (Fiket et al., 2018; Issa and Alshatteri, 2021). Likewise, PCA facilitates cluster analysis as previously noted. The water samples in the research region are contaminated by natural resources and impacted by industrial contamination. The first four principal components (PCA) were responsible for explaining 57.5% of the overall variability among the variables. The first component (PC1) provided 24.6% of the total variance, while the second component (PC2), third component (PC3) and fourth component (PC4) each contributed 11.9%, 10.8% and 10.2% of the total variance, respectively (Fig. 4). The PCA factor loadings for the first four principal components are shown in Table 7.

HCO_3^-, Cl^-, SO_4^{2-}, Mg, Na, S, Sc, Co, Cs, Li, and V showed the most significant positive loading on PC1, whereas Ti, As, Cd, Cu, Mn, Te, and Zn displayed the highest negative loading on PC1. The positive loading of PC1 indicates the influence of both carbonate and silicate weathering (HCO_3^-, Mg, Na, and Li), while the presence of Cl^-, SO_4^{2-}, Na, and S in the positive loading side indicates the evaporate rock dissolution. The Sc, Cs, Co, and V closely associated with Li indicate silicate weathering. The negative loading on PC1 which includes the metals and metalloids Cu, As, Zn, Mn, Te, and Pb, constitutes a distinct group, as seen in Figure 4c, indicates an anthropogenic influence on the water sample's chemistry (Rajmohan et al., 2023). In the second component, PC2, the most notable positive loadings include Cd, Cs, and Tl, whereas the highest negative loadings of PC2 are HCO_3^-, Sc, Ba, Bi, Cr, Fe, Li and V. The positive loading of PC2 indicates anthropogenic pollution due to the present the toxic and redox sensitive elements of Cd, Cs, and Tl at the positive loading side of PC2, while the negative loading of PC2 indicate the carbonate water interaction (HCO_3^-, Ba) and reflect geogenic influence (Li, V, Bi, Cr and Fe) (Mohammed et al., 2025a). The component PC3, the Cu, Ni, and Zn, composed the highest positive PC3 loading, while the Mo, Sb, Se, and

Tl composed the negative PC3 loading. The PC3 component indicates that both geogenic and anthropogenic processes have affected the drinking water samples (Reimann and De Caritat, 2005). In the PC4, the notable positive loads encompass Cd and Pb. The notable negative PC4 loadings are Al, Na, K, As, Bi, Cs, Mn, and Se. The positive loading of PC4 strongly suggests anthropogenic pollution (Alshehri et al., 2023), whereas the presence of Al as a reference element alongside Na, K, As, Bi, Cs, Mn, and Se in the negative loading of PC4 indicates silicate rock or clay weathering (Guda et al., 2024).

Table 7. PCA Factor loading for elemental concentrations in studied drinking water samples in Sulaimani Governorate, Kurdistan Region, Iraq.

	Components			
	1	2	3	4
HCO3	0.57	-0.24	0.14	0.04
Cl	0.82	0.34	0.10	-0.12
SO4	0.86	0.26	0.15	-0.09
Ca	0.35	0.28	0.31	0.33
Mg	0.83	-0.05	0.02	0.28
Na	0.84	0.36	0.16	-0.25
K	0.23	0.49	0.10	-0.65
S	0.88	0.25	0.13	0.06
Al	-0.06	-0.07	0.02	-0.14
Ti	-0.22	0.28	0.30	0.34
Sc	0.66	-0.27	0.10	0.26
As	0.70	-0.30	-0.34	-0.15
Ba	-0.46	-0.06	0.10	0.18
Bi	-0.23	-0.36	-0.18	-0.28
Cd	0.49	0.57	0.47	-0.16
Co	-0.21	0.08	0.39	0.68
Cr	-0.47	-0.21	0.37	-0.29
Cs	-0.21	0.10	-0.01	0.60
Cu	0.73	-0.20	0.44	-0.05
Fe	-0.37	-0.11	0.47	-0.10
Li	-0.67	-0.05	0.25	0.03
Mn	0.64	-0.21	-0.18	-0.09
Mo	0.01	0.92	-0.01	-0.31
Ni	0.33	-0.19	0.42	-0.14
Pb	0.15	-0.12	0.75	-0.38
Sb	0.13	0.92	-0.05	-0.30
Se	-0.27	0.36	-0.04	0.35
Sn	0.31	0.22	0.29	0.57
Te	0.57	-0.09	-0.09	0.43
Tl	0.02	0.96	-0.01	0.00
V	-0.72	-0.07	0.48	-0.14
W	0.27	0.02	0.33	0.36
Zn	0.67	-0.11	0.55	0.02
Eigenvalues	4.53	3.59	2.66	2.22
Total variance %	20.57	16.31	12.07	10.09
Cumulative % variance	20.57	36.88	48.95	59.04

4.6 Isotopic composition of water samples for the studied area

In the research region, water samples were taken between mid-October 2024 and early November 2024 for the analysis of their isotopic composition (δ18O and δ2H) to ascertain the original source of the water samples. The water samples from the research area have stable isotope values, with δ18O ranging from -6.74 ‰ to -3.97 ‰ and an average of -5.45 ‰, and δ2H ranging from -34.18 ‰ to -20.86‰ with an average of -27.22 ‰ (Table 8). Water isotope composition, including δ18O and δ2H can be used to ascertain the source of water, its storage characteristics; hydrodynamics, interactions between surface and groundwater, water migration including transit times, and groundwater contamination (Gat et al., 2001).

For that purpose, the δ2H and δ18O values of the different water samples are displayed on the δ2H - δ18O (Global Meteoric Water Line; Figure 5). The local meteoric water line (LMWL) used in this research was previously established by Salih (2018) in the Sulaimani city region based on rainwater samples collected between October 2015 and April 2016. All water samples were found situated between the global meteoric water line (GMWL) and the local meteoric water line (LMWL). This demonstrates that the water from all these water samples originates from precipitation. Moreover, the δ18O and δ2H values of the groundwater are closely aligned with the LMWL line, indicating little evaporation in the region (Chizhova et al., 2022). The samples have a slope that is slightly different from the Global Meteoric Water Line (GMWL). This is because of local climate factors like temperature, humidity, and altitude (Pradhan et al., 2022).

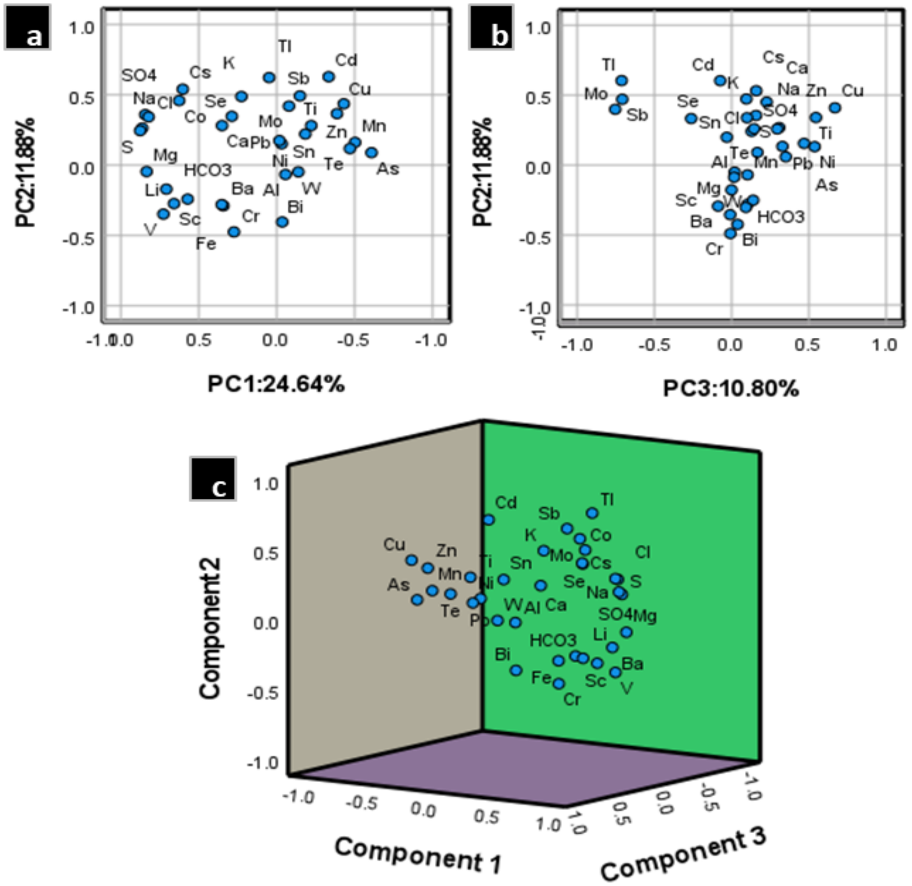

Figure. 4. (a) PCA loadings 2D plots: PC1 vs.PC2, (b) PCA loadings 2D plots: PC3 vs.PC2, (c) Principal component analysis (PCA) loading 3D plots: PC1, PC2 and PC3 for elemental composition in drinking water samples in Sulaimani Governorate, Kurdistan Reg

Table 8. Isotopic compositions (δ ^{18}O and δ^{2}H) for drinking water samples in Sulaimani Governorate, Kurdistan region, Iraq.

Location	δ ^{18}O ‰	δ^{2}H ‰
Darbandikhan well water	-4.567	-21.783
Bainjan well water	-5.388	-25.52
Qamchuqa well water	-4.159	-20.868
Arbat tap water	-6.173	-30.879
Bakrajo well water	-5.415	-26.79
Dukan line 1 tap water	-5.477	-26.911
Sarchnar springe water	-6.394	-31.799
Rania springe water	-6.74	-33.895
Piramagrun well water	-5.331	-26.6
Gapillon well water	-5.787	-28.677
Penjwen well water	-6.535	-34.188
Chamchamal well water	-4.963	-24.951
Max	-4.159	-20.868
Min	-6.74	-34.188
Average	-5.577	-27.738

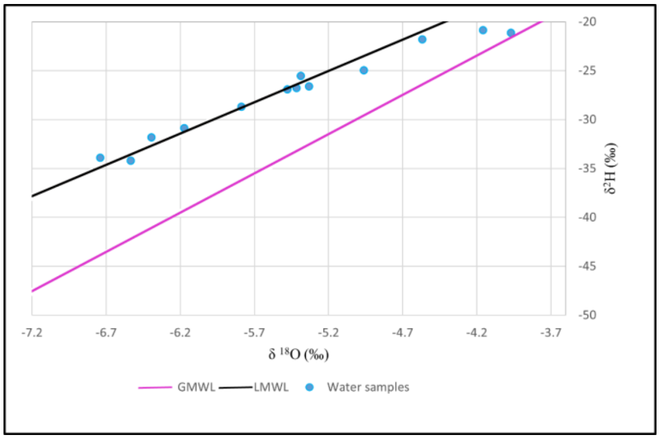

Figure. 5. The δ^{2}H versus δ^{18}O relationship of the drinking water samples in Sulaimani Governorate, Kurdistan region, Iraq, and compared with GMWL (the diagram after Salih,2018).

4.7 Contamination assessment based on HPI

This research used pollution indices like HPI to evaluate drinking water samples in Sulaimani Governorate, Kurdistan Region, Iraq, for human consumption. Heavy metal contamination indices in water samples are the most popular water quality assessment method because they show how individual heavy metals affect water quality (Ameen et al., 2019; Chaudharı et al., 2024). HPI values for water quality typically have a critical contamination signal of 100. When the HPI is over 100, the water is polluted; below 100, heavy metal contamination is low (Prasad and Bose, 2001).

All of the examined drinking water samples were below the threshold for a contamination index value of 100 and not polluted critically with respect to the heavy metals used in the present study. Nevertheless, as stated by IQS (2001), HPI results were classified as very pure (<0.3), pure (0.3–1), slightly affected (1–2), moderately affected (2–4), strongly affected (2–4), or seriously affected (4–6) (Table 10). In this case, eight locations (Table 10) are slightly affected by heavy metal pollution. The highest HPI value was recorded at Dokan line 1, followed by Dokan line 2 and Rania Spring water. In the Dokan line, 1 and 2 may be associated with anthropogenic contamination rather than geogenic sources, because their source is the Dukan Dam basin, which has a wide surface area and may be contaminated by branches that run into it from other locations; conversely, in the Rania Spring, heavy metal pollution mostly originates from geogenic sources with little contribution from industrial sources. The lowest HPI values were recorded in Piramagrun well water, followed by Arbat tap water and Penjwen well water (Table 9).

Table 9. Heavy metal pollution (HPI) for drinking water samples in Sulaimani Governorate, Kurdistan region, Iraq.

Location	Sample No.	HPI	
		Value	Critical pollution category
Kalar tap water	1	0.76	Pure
Bainjan well water	2	0.52	Pure
Bainjan Tap water	3	0.87	Pure
Sarchnar spring water	4	0.45	Pure
Dukan line1	5	1.70	Slightly Affected
Tasluja spring water	6	0.54	Pure
Rapurin tap water	7	1.11	Slightly Affected
Chamchamal tap water	8	1.40	Slightly Affected
Chamchamal well water	9	0.80	Pure
Qamchuqa well water	10	0.59	Pure
Piramagrun well water	11	0.28	Very Pure
Karezawshk tap water	12	0.94	Pure
Arbat tap water	13	0.31	Pure
Gapillon well water	14	0.58	Pure
Piramagruntap tap water	15	1.47	Slightly Affected
Khabat tap water	16	1.35	Slightly Affected
Zargataikon tap water	17	1.45	Slightly Affected
Dukan line 2	18	1.51	Slightly Affected
Rania spring water	19	1.50	Slightly Affected
Penjwen well water	20	0.42	Pure
Bakrajo well water	21	0.74	Pure
Bakrajo tap water	22	0.56	Pure
Barbandikhan well water	23	0.62	Pure
Derbandikhan tap water	24	0.84	Pure
Min		0.28	
Max		1.70	
Range		0.28 - 1.70	

Table 10. Iraqi guideline (IQS, 2001) for heavy metals.

Class	Property/Characteristics	HPI
1	Very Pure	< 0.3
2	Pure	0.3 – 1
3	Slightly Affected	1 – 2
4	Moderately Affected	2 – 4
5	Strongly Affected	4 – 6
6	Seriously Affected	> 6

4.8 Drinking water sample quality evaluation

Based on the analytical results, the drinking water sample from the Sulaimani Governorate in the Kurdistan region of Iraq meets the Iraqi standard, and the WHO confirms that the water samples are safe for consumption. The quality of drinking water was evaluated by estimating the physiochemical parameters (colour, odour, test, pH, TDS), major ions and heavy metals, and biological properties, which were determined by the Iraqi Standard, the WHO, and other standards. Based on colour, odour and taste, all water samples are described as colourless, odourless, and tasteless.

The optimal range for TDS is 115-503 mg/L, which is below the safety threshold established by the WHO in 2011 and the IQS in 2001, both of which permit a limit of 1000 mg/L. The water samples are categorized as freshwater, as cited by Altoviski (1962) and Gorrell (1958). The classification of drinking water samples based on total hardness categorizes them as soft water (Boyd, 2000). is within the safe limits (1000 mg/L) established for drinking water by the IQS (2001) and (WHO, 2011). The pH value ranges from 7 to 8.09 in the water samples and is within the safe limits (6.5–8.5) prescribed for drinking by Iraqi Standards (IQS, 2001) and the (WHO, 2011) Table 11. All the drinking water samples are safe for people to drink, except for sample number 18, which has a sulphate (SO_4) level of 296 mg/l that is higher than what is allowed by (WHO, 2011) and (IQS, 2001).

Analysis of heavy metal concentrations (As, Ba, Fe, Bi, Cd, Co, Cr, Cs, Cu, Li, Mn, Mo, Ni, Pb, Sb, Se, Sn, Te, Tl, V, W, and Zn) (Table 6) indicates that all sampled tap water, well water, and spring water exhibit very low levels; all heavy metal values conform to WHO (2002) and IQS (2001) standards, with certain trace elements in some samples falling below detection limits. This finding suggests that the heavy metals in the drinking water samples from the research region provide no health hazard risk. The concentration of heavy metals varies from wet to dry season due to precipitation dilution (Jiang et al., 2018). As a result, the research proposes collecting enough data during the dry season to permit further seasonal monitoring.

Table 11. Comparing range of analyzed drinking water samples from Sulaimani Governorate, Kurdistan region, Iraq, with (WHO, 2011) and (IQS, 2001) standards.

Parameter	This study	WHO (2011)	IQS (2001)
Ca^{+2} (mg /L)	2.59-8.90	75	50
Mg+2 (mg L)	0.60-1.15	150	50
Na+ (mg /L)	0.14-7.40	200	200
K+ (mg /L)	0.035-0.418	N. G	N. G
Cl^- (mg /L)	9.2-84.0	250	250
HCO_3^- (mg /L)	210-620	N. G	N. G
SO_4^{2-} (mg /L)	25.4-296	250	250
T.H. (mg/L)	10.0-38.2	1000	500
TDS (mg/L)	115-503	1000	1000
pH	7.0-8.1	6.5-8.5	6.5-8.5

N.G: No Guideline

5. Conclusions

All of the studied drinking water samples from Sulaimani Governorate based on the physicochemical parameters reveal that they meet standard sensory quality criteria: colorless, odorless, and tasteless. Total Dissolved Solids (TDS) values range from 115 to 503 mg/L, indicating that the water is of freshwater quality and much lower than the maximum allowable level of 1000 mg/L. The pH levels of the samples indicate no imminent danger of corrosivity or alkalinity concerns; they are within the recommended range for drinkable water. All samples are classified as soft water based on total hardness measurements, which is often associated with reduced scaling potential and higher consumer acceptance. Hydrochemical facies investigation indicates that the Ca-Mg-HCO_3 water type is predominant due to natural geochemical processes, particularly carbonate rock dissolution. Secondary contributions from evaporitic lithologies and potential anthropogenic causes are also readily apparent. Spatial variability analysis using one-way ANOVA reveals significant variations ($\rho < 0.05$) in the concentrations of some elements (Mg, Na, S, As, Li, Mo, Sb, Te, V, and Tl) across sampling sites. This suggests site-specific hydrogeochemical heterogeneity and possibly localized geochemical or anthropogenic influences.

The statistics reveal that, both chemically and physically, the groundwater in the research region is of acceptable quality for human consumption.

Principal Component Analysis (PCA) and cluster analysis, along with other multivariate statistical tests, indicate that both natural and anthropogenic factors influence the chemical composition of drinking water sources in Sulaimani Governorate. The PCA results effectively distinguish between components originating from natural processes, such as mineral weathering, and those resulting from human-induced pollution, thereby clarifying the sources of these components. Cluster analysis substantiates these conclusions by categorizing the sampling locations according to local environmental conditions and the extent of industrial and urban activity affecting them. The average concentrations of heavy metals in the water samples are ranked in descending order as follows: Zn, Ba, Fe, Li, V, Mn, Mo, Cr, As, Se, Cu, Ni, Sb, Co, Pb, Sn, W, Tl, Cs, Te, Bi, Cd. The heavy metal pollution Index (HPI) reveals that the majority of sites exhibit a low level of contamination, specifically within the range of 1 to 2. All measured concentrations adhere to national and international drinking water standards, as many elements are present at very low levels or below detection limits. The study of isotopic composition indicates that all investigated water samples have a meteoric origin of recharge, confirming that precipitation is the primary input to the local aquifer systems. Natural hydrogeological processes, particularly carbonate and evaporite dissolution, primarily influence the drinking water in Sulaimani Governorate, while anthropogenic activities exert a secondary effect. The overall water quality remains within acceptable limits for human consumption and does not present significant health risks, despite minor geochemical variability and slight pollution indicators.

Conflict of interest.

The authors declare that they are not associated with or do organization with any entity that has financial interests.

CRediT authorship contribution statement.

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