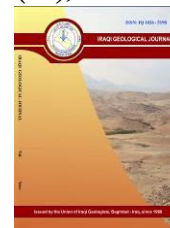




Iraqi Geological Journal

Journal homepage: <https://www.igj-iraq.org>



Hydrogeochemistry, Water Quality, Heavy Metals, Reactions and Mechanisms Controlling Groundwater in Aqra Area, Kurdistan, Iraq

Omar S. Aqrabi^{1,*}  and Aahed Y. Al-Mallah¹ 

¹ Department of Geology and Petroleum, College of Science, University of Mosul, Mosul, Iraq

* Correspondence: omar.aqrabi@uomosul.edu.iq

Abstract

Received:
10 January 2026
Accepted:
13 July 2026
Published:
31 August 2026

Twenty one of groundwater samples were analyzed to find out the content of the main cations (Ca^{2+} , Mg^{2+} , Na^{+} , and K^{+}), and anions (HCO_3^{-} , SO_4^{2-} , Cl^{-} and NO_3^{-}); as well as to determine the Physicochemical characteristics pH, EC, TH, and TDS. The pH values indicate that the water is intermediate to slightly alkaline and range from soft to very hard. According to Piper classification, the water wells in the study area are of a mixed type; also, five hydrochemical facies were distinguished, but most of the well's water is of calcium, and magnesium bicarbonate constituted (76.19%) of all samples. The area's water is excellent for human consumption, except for two wells located within the poor field, according to the water quality index, which ranges between 13.5 and 59.0. Wilcox's classification indicated that most samples are excellent for irrigation. Regarding heavy metals, the contamination factor indicates that the water is generally potable; however, three wells are moderately contaminated with iron, and one well is very highly contaminated. Regarding the contamination index degree, all wells exhibit a low level of contamination except for; one well within a moderate degree contamination with heavy metals. Gibbs Diagram indicates the rock weathering as the primary mechanism that governs the groundwater chemistry in the study area.

Keywords: Hydrogeochemistry; WQI; Heavy Metals; Gibbs Diagram; Contamination factor

1. Introduction

Water pollution has become a focus of modern studies in worldwide due to the importance of water to human life. Groundwater pollution and its suitability for drinking and agriculture are influenced by many factors, including exposure of groundwater to rocks and different geological layers, and pollution from materials added to the environment by human activities. Therefore, these additives contribute to deteriorating water quality, and they are used industrial processes, and in agricultural materials such as pesticides and chemical fertilizers (Weiner, 2000).

The study of water quality includes several hydrogeochemical factors, in addition to contamination with heavy metals. Therefore, it is important to study the physicochemical properties of water, which include (pH, EC, TDS, and TH), as well as the concentrations of positive, and negative ions and heavy elements in groundwater.

Hydrochemical assessment is an important method for determining water quality (Britto et al., 2018). Water quality is strongly influenced by natural factors, including chemical and physical

processes such as rock weathering, rainfall climate, and human activities (Hadgu et al., 2014). Therefore, it is necessary to develop water quality monitoring programs, which are considered one of the most effective ways to assess the environmental status of water resources. In the current study, the water quality index (WQI) has been used.

Geochemical processes are responsible for the spatial and seasonal changes in the chemistry of groundwater, so groundwater evolves chemically through interactions with minerals of the aquifer or through internal mixing of different groundwater along underground flow paths (Nganje et al., 2010).

The presence of heavy metals in the groundwater is so dangerous and can lead to death. Metals such as arsenic, cadmium, chromium, copper, lead, mercury, nickel, and zinc are commonly found in polluted sites and aquatic systems. Heavy metals can cause diseases affecting the bones, brain, kidneys, and muscles, and may lead to various disorders such as anemia, kidney disease, neurological disorders, and even death (Sharma, 2014).

The current study is significant and may be the first of its kind in Aqra and the surrounding areas. Therefore, the main objective is to study the geochemistry and quality of the groundwater that is important for humans, soil, and crops, as well as to know the region's water content of heavy elements and the extent of its pollution relying on hydrogeochemical models, which help identify the various factors that control the development of groundwater during its presence in the aquifer (Hussein et al., 2021).

2. The Study Area

The study area is positioned in the Kurdistan region, northern part of Iraq, at latitudes $36^{\circ}30''$ to $37^{\circ}01''$ and longitudes of $43^{\circ}36''$ to $44^{\circ}18''$ (Fig. 1), represented by mountainous heights in the north part of it and a large sedimentary basin extending to the south that includes a considerable number of wells used for drinking, agriculture, and irrigation purposes. The area is characterized by an average rainfall 736.07 mm from 2000 to 2020, and an average temperature 20.7°C .

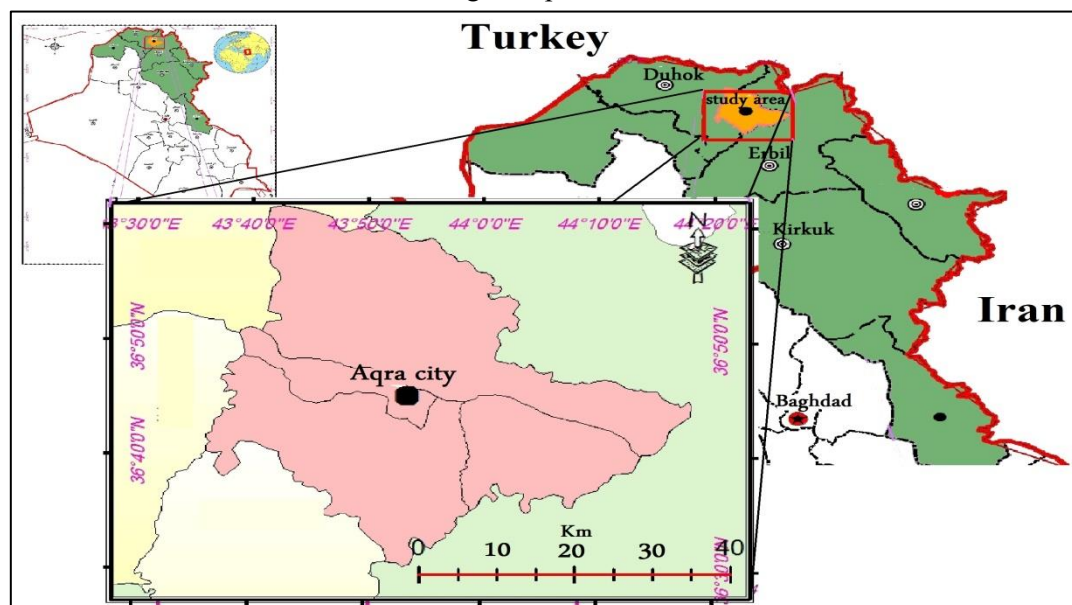


Fig.1. Location map of the study area

In terms of stratigraphy and geomorphology, the vast majority of the land in the study area are of a mountainous nature, characterized by complexity and steep slope, occupying about 56% of the district's total area. Most of the mountainous areas are concentrated in the northern and northeastern sides of Aqra District, where limestone and dolomite of the Pila Spi, Aqra, and Qamchuqa formations are predominant, along with bituminous materials within Aqrah and Shiranish formations (Jassim and Goff,

2006). The rocks of the Fatha Formation consist of anhydrite, gypsum, limestone, and marl, and the Injana Formation consists of fine-layered sandstone, red and green clay rocks and recent sediments that form Bai Hassan. These are spread across large valleys between the high folds. After this the land begins to decline in the south to form undulating plains that occupy the southern and southwestern regions representing about 33% of the total area, while the eastern sides are hills and plateaus that occupy about 11% of the total area (Britto et al., 2018), in which the Bai Hassan Formation rocks are spread consisting of large-sized rocks and coarse gravel representing estuaries.

3. Materials and Methods

To represent the entire study area, the sites for taking samples must be carefully selected (Fig.2). Accordingly, the sites for samples were selected using the ArcMap GIS program, and 21 groundwater wells were selected, which are distributed over the entire Aqra District on the various formations in the area, including those located within residential neighborhoods and agricultural lands, where the water of these wells is used for drinking, various domestic purposes, agriculture, and irrigation. The depths of the selected wells range between 50 and 300 m. Table 1 shows the coordinates, depths, and elevations of the wells.

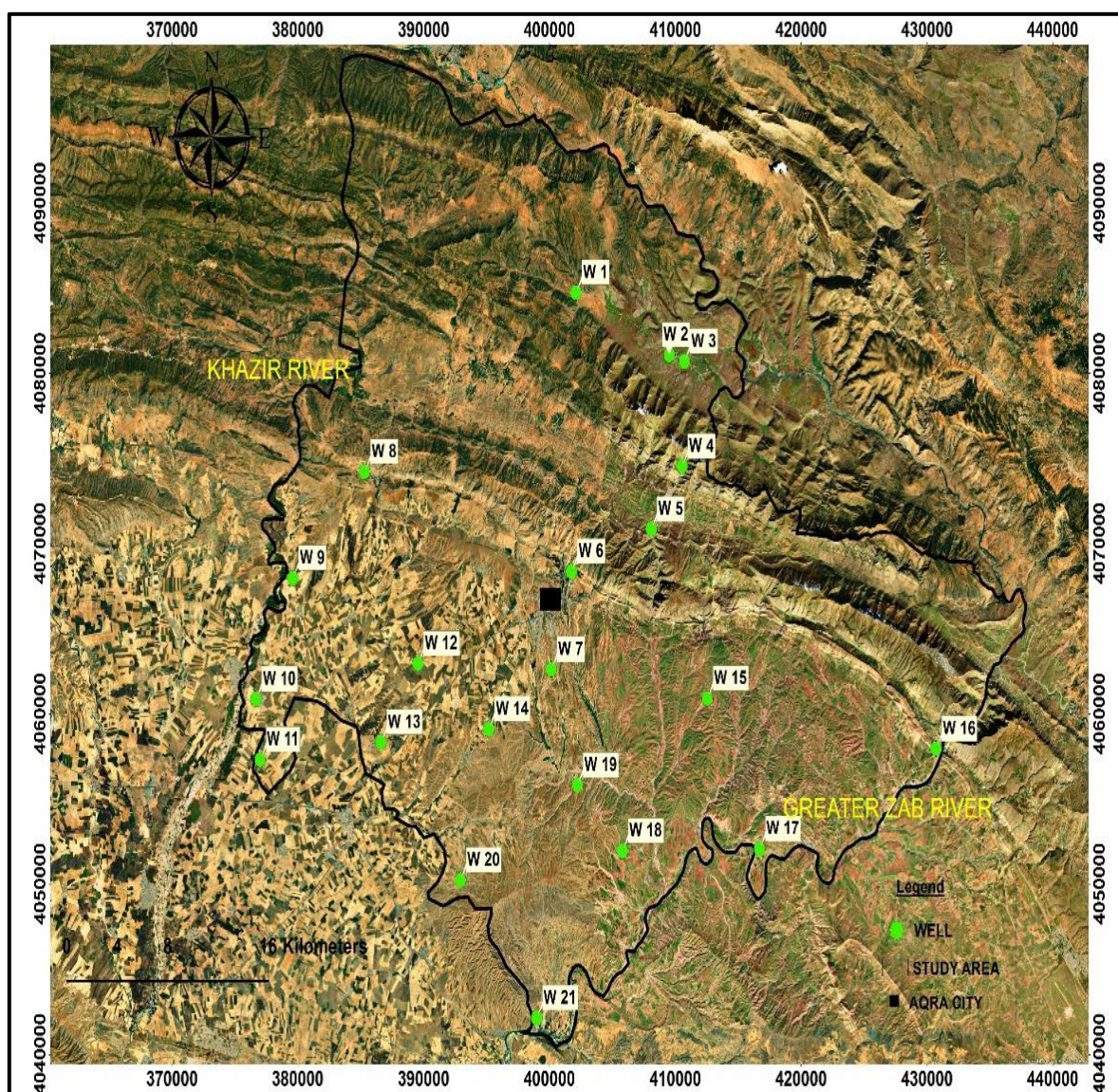


Fig. 2. The locations of the selected samples

Table 1. The coordinates, depths and elevations of the wells above sea level

Well No.	Longitude	Latitude	Elevation (m)	Depth (m)	Geological formation	Drilling (year)
W 1	407107	4084759	646	276	Pila Sni	2016
W 2	409516	4081113	543	160	Shiranish	2004
W 3	410716	4080721	526	215	Fatha	2011
W 4	410534	4074564	970	50	Aqra	2003
W 5	408087	4070871	645	120	Fatha-Pila Sni	2010
W 6	401760	4068385	720	140	Pila Sni	2012
W 7	400139	4062621	577	300	Recent-Bai Hassan	2013
W 8	385310	4074246	808	119	Aqra-Shiranish	2008
W 9	379606	4067997	444	240	Recent-Bai Hassan	2011
W 10	376678	4060880	405	200	Recent-Bai Hassan	2011
W 11	377010	4057336	398	135	Recent-Bai Hassan	1989
W 12	389548	4062979	560	240	Recent-Bai Hassan	2017
W 13	386614	4058346	495	180	Recent-Bai Hassan	2000
W 14	395188	4059127	569	280	Recent-Bai Hassan	2013
W 15	412538	4060927	509	110	Recent-Bai Hassan	2008
W 16	430721	4057965	440	106	Recent-Bai Hassan	2010
W 17	416697	4052087	373	165	Recent-Bai Hassan	2008
W 18	405794	4051969	462	250	Recent-Bai Hassan	2008
W 19	402216	4055833	488	184	Recent-Bai Hassan	2000
W 20	392909	4050243	631	200	Recent-Bai Hassan	2016
W 21	398991	4042155	358	210	Recent-Bai Hassan	2010

Water samples collected from these wells were analyzed to quantify major cations (Ca^{2+} , Mg^{2+} , Na^+ , and K^+), and major anions (Cl^- , SO_4^{2-} , NO_3^- , and HCO_3^-), along with measuring the physicochemical indices (pH, EC, TH, and TDS). The concentrations of heavy metals (Cd, Pb, Co, Zn, Cu, Fe, Mn, Cr, and Ni) in the water conducted using the Atomic Absorption Spectrophotometer.

The Water Quality Index (WQI) is used to determine the water suitability for drinking. It can be calculated through the following equations (Ameen, 2019).

$$W_i = K/S_i = 1/S_i \dots\dots\dots (1)$$

Where: (W_i) unit weight; (K) constant of proportionality; (S_i) water quality standards.

$$Q_i = (V_i/S_i) * 100 \dots\dots\dots (2)$$

Where: (Q_i) water quality rating, (V_i) average of the data observed, (S_i) water quality standards.

$$Q_{pH} = [(V_{pH} - 7.0) / 1.5] * 100 \dots\dots\dots (3)$$

Where: Q_{pH} is the quality rating for pH, V_{pH} is the value of pH observed

$$WQI = [\sum (Q_i \cdot W_i) / \sum W_i] \dots\dots\dots (4)$$

The Water Quality Index (WQI) indicates the suitability of water for drinking; the higher value is the higher unsuitability of water for human consumption, as shown in Table 2.

Table 2. Types of water based on WQI values (Horton, 1965; Ameen, 2019)

WQI	Type of Water	Possible use
0-25	Excellent	Drinking, irrigation, and industrial
26-50	Good	Drinking, irrigation, and industrial
51-75	Poor	Irrigation and industrial
76-100	Very Poor	Irrigation
>100	Unsuitable	Proper treatment required before use

A contamination factor (CF) was used, a simple and effective tool for monitoring and assessing the extent of water pollution by heavy metals. It can be calculated by the equation below (Bhutiani et al., 2017; Alfaifi et al., 2021) as suggested by Hakanson (1980).

$$CF_i = CA_i/CN_i \dots\dots\dots (5)$$

Where; Cfi: Contamination factor, CAi: Analytical Concentration, CNi: Permissible Concentration

Depending on the contamination factor (CF) values, the water is classified according to Table 3 as below.

Table 3. Classification of water polluted by heavy metals in relation to the pollution factor (Hakanson, 1980)

Contamination factor	Contamination level
< 1	Low Contamination factor
1-3	Moderate Contamination factor
3-6	Considerable Contamination factor
> 6	Very high Contamination factor

The contamination factor (CF) quantifies contamination of the sample by individual elements; therefore, the contamination degree index (CD) (Singh et al., 2014) can be used, which represents the total pollution factors present in the sample to provide a unified description of the pollution. It can be calculated from the following equation.

$$CD = \sum_{i=1}^n CF_i \dots\dots\dots (6)$$

Where: CD: Contamination degree index, CF: Contamination factor

Depending on the CD values, the water is classified as in Table 4 (Singh et al., 2014).

Table 4. Classification of water contaminated with heavy metals based on the degree of pollution index. (Hakanson, 1980)

Contamination degree index	Contamination Degree
< 8	Low Degree of Contamination
8-16	Moderate Degree of Contamination
16-32	Considerable Degree of Contamination
> 32	Very high Degree of Contamination

As for the heavy elements and the sensitivity limits of the device; an atomic absorption spectrophotometer (Shimadzu AA-7000) was used to measure the concentrations of heavy elements in water; both the graphite furnace and flame methods were applied (Table 5).

Table 5. Detection limits of the instrument used for analyzing heavy metals in the water samples

Elements	Flame (ppm)	Graphite Furnace (ppm)
Cd	< 0.01	< 0.00001
Pb	0.01~ 0.09	0.00001~0.00009
Co	0.01~ 0.09	0.0001~0.0009
Zn	< 0.01	0.00001~0.00009
Cu	< 0.01	0.00001~0.00009
Fe	0.01~ 0.09	0.00001~0.00009
Mn	0.01~ 0.09	0.00001~0.00009
Cr	0.01~ 0.09	0.00001~0.00009
Ni	0.01~ 0.09	0.0001~0.0009

4. Results and Discussion

4.1. Major Ions and Hydrochemical Parameters

The major ions and hydrochemical parametare results (Table 6) showed an increase in the pH value of the sample W18 to reach 8.3 in the study area, but generally, it ranged between 7.0 and 8.3 and reached an average of 7.5, it is located within standard limits for drinking water. The high pH value of the mentioned well is due to sodium bicarbonate water type $Na^+HCO_3^-$ as indicated by the Piper

classification. In general the electrical conductivity (EC) of groundwater in the study area range from 258.7 to 1787 $\mu\text{S}/\text{cm}$, with an average of 485.9 $\mu\text{S}/\text{cm}$, the highest value recorded in the well W5 that was drilled on the Fatha Formation caused by the increase in the well's content of dissolved solids although this percentage is within the standard limits of the World Health Organization (WHO) (Cotruvo, 2017). The TDS values in the water of the wells in the study area ranged from 165.6 to 1143.7 ppm, with an average of 311.01 ppm, and the highest value was recorded in well W5, which exceeds the WHO specifications. The water hardness ranged from 74.8 to 876 ppm, with an average of 262.5 ppm. The highest value was recorded at well W5, exceeding the World Health Organization's permissible limit of 500 ppm. In general, there is a decrease in the hydrochemical parameters as we move away from the large folds in the north of the area to the south towards the groundwater flow. Fig. 3 shows the spatial distributions of these variables in the study area.

Table 6. Concentrations of cations, anions, accuracy, hydrochemical parameters, and WQI for the groundwater samples.

Well	Unit	Cations				Sum. Cations	Anions				Sum Anions	E %	A %	pH	EC	TDS	TH	$\sum Q_i$	WQI
		Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺		Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	HC O ₃ ⁻									
W 1	ppm	62.10	19.50	1.10	0.40	83.1	14.00	9.20	0.80	240.00	264.0								
	epm	3.11	1.60	0.05	0.01	4.8	0.40	0.20	0.00	3.90	4.5	2.5	97.5	7.5	419.6	268.5	235	2.1	13.970
	epm %	65.12	33.66	1.00	0.22	100.0	8.80	4.20	0.30	86.70	100.0								
	ppm	75.20	29.30	1.70	0.60	106.8	12.00	24.10	1.60	297.00	334.7								
W 2	ppm	3.76	2.41	0.07	0.02	6.3	0.30	0.50	0.00	4.90	5.7	4.3	95.7	7.2	466.5	298.6	308	2.6	17.551
	epm	60.06	38.52	1.18	0.25	100.0	6.00	8.70	0.40	84.80	100.0								
	epm %	73.06	22.52	1.58	0.00	97.7	12.00	16.90	1.00	275.00	304.9								
	ppm	73.60	22.30	1.50	0.30	97.7	12.00	16.90	1.00	275.00	304.9								
W 3	ppm	3.68	1.84	0.07	0.01	5.6	0.34	0.40	0.00	4.50	5.2	3.4	96.6	7.3	435.8	278.9	275	2.3	15.218
	epm	65.85	32.84	1.17	0.14	100.0	6.60	6.70	0.30	86.40	100.0								
	epm %	84.79	40.07	2.18	0.25	130.3	12.00	60.00	4.20	332.00	408.2								
	ppm	84.40	40.50	2.10	0.90	130.3	12.00	60.00	4.20	332.00	408.2								
W 4	ppm	4.24	3.33	0.09	0.07	7.7	0.30	1.30	0.10	5.40	7.1	4.3	95.7	7.2	613.5	392.7	378	4.7	31.629
	epm	54.79	43.07	1.18	0.96	100.0	4.80	17.60	1.00	76.60	100.0								
	epm %	201.6	90.70	91.00	2.10	385.4	190.0	480.8	3.10	310.00	983.9								
	ppm	201.6	90.70	91.00	2.10	385.4	190.0	480.8	3.10	310.00	983.9								
W 5	ppm	10.08	7.47	3.96	0.05	21.6	5.40	10.00	0.00	5.10	20.6	2.3	97.7	7.0	1787	1143.7	876	8.1	54.236
	epm	46.76	34.63	18.36	0.25	100.0	26.40	48.70	0.20	24.70	100.0								
	epm %	73.60	42.30	12.30	0.40	132.9	24.00	87.90	16.00	272.10	400.0								
	ppm	73.60	42.30	12.30	0.40	132.9	24.00	87.90	16.00	272.10	400.0								
W 6	ppm	3.68	3.48	0.53	0.12	7.8	0.70	1.80	0.30	4.50	7.2	3.9	96.1	7.2	617.5	395.2	357	6.3	42.116
	epm	47.08	44.54	6.44	1.54	100.0	9.50	25.30	3.60	61.60	100.0								
	epm %	51.20	14.40	10.50	0.60	76.7	13.60	4.90	0.20	197.20	226.5								
	ppm	51.20	14.40	10.50	0.60	76.7	13.60	4.90	0.20	197.20	226.5								
W 7	ppm	2.56	1.19	0.46	0.02	4.2	0.40	0.10	0.20	3.20	3.9	3.9	96.1	7.3	346.5	221.8	187.2	2.3	15.278
	epm	60.71	28.10	10.83	0.36	100.0	10.00	2.60	4.50	82.90	100.0								
	epm %	104.0	43.16	2.20	0.00	166.1	16.00	22.90	113.00	392.00	543.9								
	ppm	104.0	43.16	2.20	0.00	166.1	16.00	22.90	113.00	392.00	543.9								
W 8	ppm	5.20	3.61	0.70	0.05	9.6	0.50	0.50	1.80	6.40	9.2	2.1	97.9	7.0	793.9	508.1	440	8.9	59.098
	epm	54.34	37.76	7.36	0.54	100.0	5.00	5.20	19.80	70.00	100.0								
	epm %	76.30	14.99	0.90	0.50	101.2	18.00	16.90	23.20	235.60	293.7								
	ppm	76.30	14.99	0.90	0.50	101.2	18.00	16.90	23.20	235.60	293.7								
W 9	ppm	3.82	1.19	0.43	0.01	5.5	0.50	0.40	0.40	3.90	5.1	3.3	96.7	7.8	443.0	283.5	250.4	3.4	22.680
	epm	69.98	21.89	7.90	0.24	100.0	10.10	6.90	7.30	75.70	100.0								
	epm %	48.00	17.82	0.80	0.60	74.2	8.00	0.70	7.90	193.00	226.7								
	ppm	48.00	17.82	0.80	0.60	74.2	8.00	0.70	7.90	193.00	226.7								
W 10	ppm	2.40	1.40	0.30	0.00	4.2	0.20	0.40	0.10	3.20	3.9	3.9	96.1	7.6	342.4	219.1	191.2	2.2	14.973
	epm	2.40	1.40	0.30	0.00	4.2	0.20	0.40	0.10	3.20	3.9	3.9	96.1	7.6	342.4	219.1	191.2	2.2	14.973

Well	Unit	Cations				Sum. Cations	Anions				Sum Anions	E %	A %	pH	EC	TD S	TH	$\sum Q_i$ w _i	WQ I
		Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺		Cl ⁻	SO ₄ ²⁻	NO ₃ ⁻	HC O ₃ ⁻									
		0	3	6	02														
	epm	57.09	34.07	8.48	0.37	100.0	5.90	9.50	3.30	81.30	100.0								
	%	52.80	13.20	3.50	0.50	70.0	8.80	12.20	9.40	179.20	209.6								
W 11	ppm	2.64	1.09	0.15	0.01	3.9	0.30	0.30	0.20	2.90	3.6	4.0	96.0	7.8	333.8	213.7	186.0	2.3	15.277
	epm	67.84	27.92	3.91	0.33	100.0	7.00	7.10	4.20	81.70	100.0								
	%	46.60	12.90	3.10	0.30	62.9	8.80	5.50	11.50	170.20	196.0								
W 12	ppm	2.33	1.06	0.13	0.01	3.5	0.30	0.10	0.20	2.80	3.3	2.8	97.2	7.9	285.4	182.7	169.2	2.1	14.116
	epm	65.93	30.04	3.81	0.22	100.0	7.50	3.40	5.60	83.50	100.0								
	%	45.80	13.90	3.10	0.30	63.1	9.60	1.50	13.10	174.90	199.1								
W 13	ppm	2.29	1.14	0.13	0.01	3.6	0.30	0.00	0.20	2.90	3.4	2.8	97.2	7.9	291.7	186.7	171.2	2.2	14.586
	epm	64.03	31.99	3.77	0.22	100.0	8.10	0.90	6.20	84.70	100.0								
	%	54.90	12.60	3.40	0.30	71.2	12.60	4.40	14.90	182.00	213.9								
W 14	ppm	2.75	1.04	0.15	0.01	3.9	0.40	0.10	0.20	3.00	3.7	3.4	96.6	7.5	309.8	198.3	188.8	2.3	15.458
	epm	69.71	26.34	3.75	0.20	100.0	9.80	2.50	6.50	81.20	100.0								
	%	23.20	17.10	30.10	1.20	71.6	11.40	5.50	13.70	180.20	210.8								
W 15	ppm	1.16	1.41	1.31	0.03	3.9	0.30	0.10	0.20	3.00	3.6	3.9	96.1	7.8	314.8	201.5	128.0	2.5	16.709
	epm	29.69	36.02	33.50	0.79	100.0	9.00	3.20	6.10	81.70	100.0								
	%	58.40	44.80	17.00	0.80	121.0	32.00	42.40	13.20	298.00	385.6								
W 16	ppm	2.92	3.69	0.74	0.02	7.4	0.90	0.90	0.20	4.90	6.9	3.3	96.7	7.3	597.4	382.3	329.6	3.2	21.594
	epm	39.64	50.05	10.03	0.28	100.0	13.30	12.80	3.10	70.80	100.0								
	%	45.90	30.30	13.40	1.00	90.6	13.40	3.30	10.30	265.00	292.0								
W 17	ppm	2.30	0.98	0.58	0.03	5.4	0.40	0.10	0.20	4.30	5.0	4.2	95.8	7.3	414.5	265.3	238.8	2.7	18.093
	epm	42.52	46.21	10.79	0.48	100.0	7.70	1.40	3.30	87.60	100.0								
	%	17.60	7.50	55.30	0.90	81.3	20.00	36.50	10.80	132.00	199.3								
W 18	ppm	0.88	0.62	2.40	0.02	3.9	0.60	0.80	0.20	2.20	3.7	3.4	96.6	8.3	342.6	219.3	74.8	2.2	14.587
	epm	22.42	15.73	61.26	0.59	100.0	15.60	20.70	4.70	59.00	100.0								
	%	36.50	19.20	22.50	0.90	79.1	10.00	14.60	9.90	205.00	239.5								
W 19	ppm	1.83	1.58	0.98	0.02	4.4	0.30	0.30	0.20	3.40	4.1	3.5	96.5	7.7	369.1	236.2	170.0	2.4	16.080
	epm	41.42	35.86	22.20	0.52	100.0	7.00	7.40	3.90	81.80	100.0								
	%	40.30	9.70	3.80	0.30	54.1	8.80	4.40	14.90	135.00	163.1								
W 20	ppm	2.02	0.80	0.17	0.01	3.0	0.30	0.10	0.20	2.20	2.8	3.3	96.7	7.7	258.7	165.6	140.4	2.0	13.530
	epm	67.48	26.73	5.53	0.26	100.0	9.00	3.30	8.60	79.10	100.0								
	%	63.70	14.50	11.80	1.00	91.0	18.00	34.30	33.50	169.60	255.4								
W 21	ppm	3.19	1.19	0.51	0.03	4.9	0.50	0.70	0.50	2.80	4.5	3.9	96.1	7.5	421.0	269.5	218.8	3.8	25.475
	epm	64.77	24.27	10.43	0.52	100.0	11.30	15.70	11.90	61.10	100.0								
MI N	ppm	17.6	7.5	1.1	0.3		8.00	1.50	0.80	132.00				7.0	258.7	165.6	74.8		
MA X	ppm	201.6	90.7	91.0	4.7		190.00	480.80	113.00	392.00				8.3	1787	1143.7	876		
Mean	ppm	63.6	25.3	15.31	1.06		22.52	43.14	16.04	230.25				7.5	485.9	313.01	262.5		
WH O, 2017	ppm	75	100	200	12		250	250	50	350				6.5-8.5	<1000-2000	1000	500		

When comparing the hardness values presented in Table 6 with Todd (1980) classification in Table 7, it becomes evident that well W18 falls within the freshwater type, and the wells W 15, and 20 are classified within the intermediate field, while the wells W 1, 3, 7, 9, 10, 11, 12, 13, 14, 17, 19, and 21 are located within the hard field, and the W 2, 4, 5, 6, 8, and 16 are categorized as very hard water. Furthermore, this hardness is of a temporary type, which is caused by the prevalence of limestone and dolomite rocks consisting of the Aqra and Peris folds, which supply the water with bicarbonate, calcium, and magnesium. Except that, the hardness in well W5 is of the permanent type resulting from sulfate ions associated with calcium as indicated by the Piper classification.

Table 7. Water Classification Based on Hardness Levels (Todd, 1980)

Hardness (mg/l)	Water quality
0 – 75	Fresh
75 – 150	Medium
150 – 300	Hard
> 300	Very hard

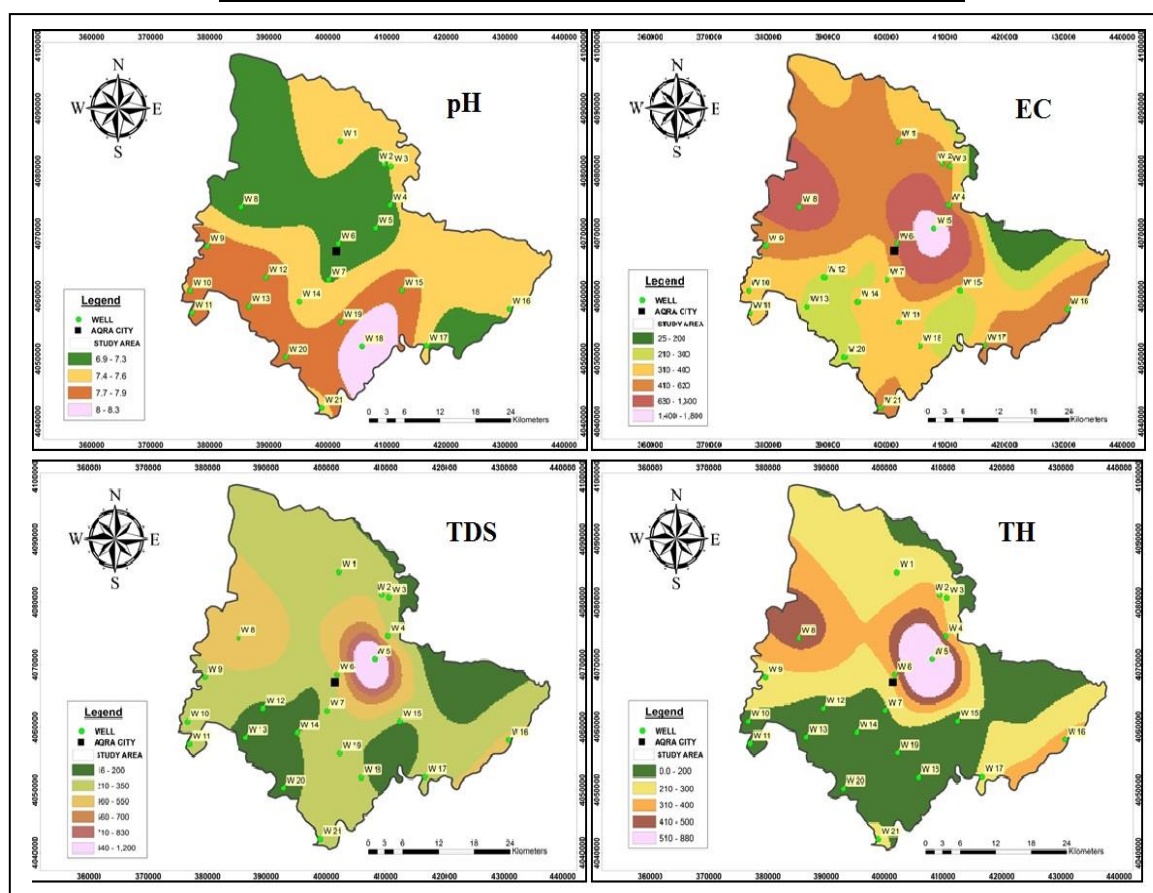


Fig. 3. Spatial distribution of the hydrochemical parameters in the studied area

As for the cations, the concentration of calcium ions in the wells of the study area ranged between 17.6 and 201.6 ppm, with an average of 63.6 ppm. The standards of WHO recommend that the proportion of calcium should not exceed 75 ppm. Accordingly, the wells W2, W4, W5, W8, and W9 recorded an excess of calcium above the limits of WHO specifications that mentioned in Table 5 (Cotruvo, 2017).

Magnesium ion values ranged between 7.5 and 90.7 ppm, with an average of 25.3 ppm; these values generally fall within the standard specifications for drinking water. From Fig. 4, it can be seen that the contents of calcium and magnesium ions decrease toward the south, away from the source of dolomite in Aqra and Peris folds (Pila Spi and Bakhme-Aqra formations), which corresponds to the direction of groundwater flow, except that the highest percentage of calcium was recorded in the well W5 drilled on the Fatha Formation. The dispersal of carbonate rocks in the study area for Aqra, Bakhme, Pila Spi, Qamchuqa, and Fatha formations make them the main sources of these two ions in the groundwater.

The concentration of sodium ions in the water of the study area ranged between 1.1 and 91 ppm with an average of 15.31 ppm, where the international specifications of the WHO recommend a percentage not exceeding 200 ppm. Fig. 4 shows an increase in the concentration of sodium in the south and southeast of the study area, which is toward the direction of the groundwater flow, and the highest percentage was recorded in well W5 reached 91 ppm, which is believed to be due to the dissolution of evaporite rocks from the Fatha Formation, as well as the W18 recorded a rate of 55.3 ppm and the water is of sodium bicarbonate type according to Piper classification.

The potassium ion values range between 0.3 and 4.7 ppm, with an average of 1.06 ppm. It also can be noted that this percentage decreases towards the groundwater flow south of the study area (Fig. 4).

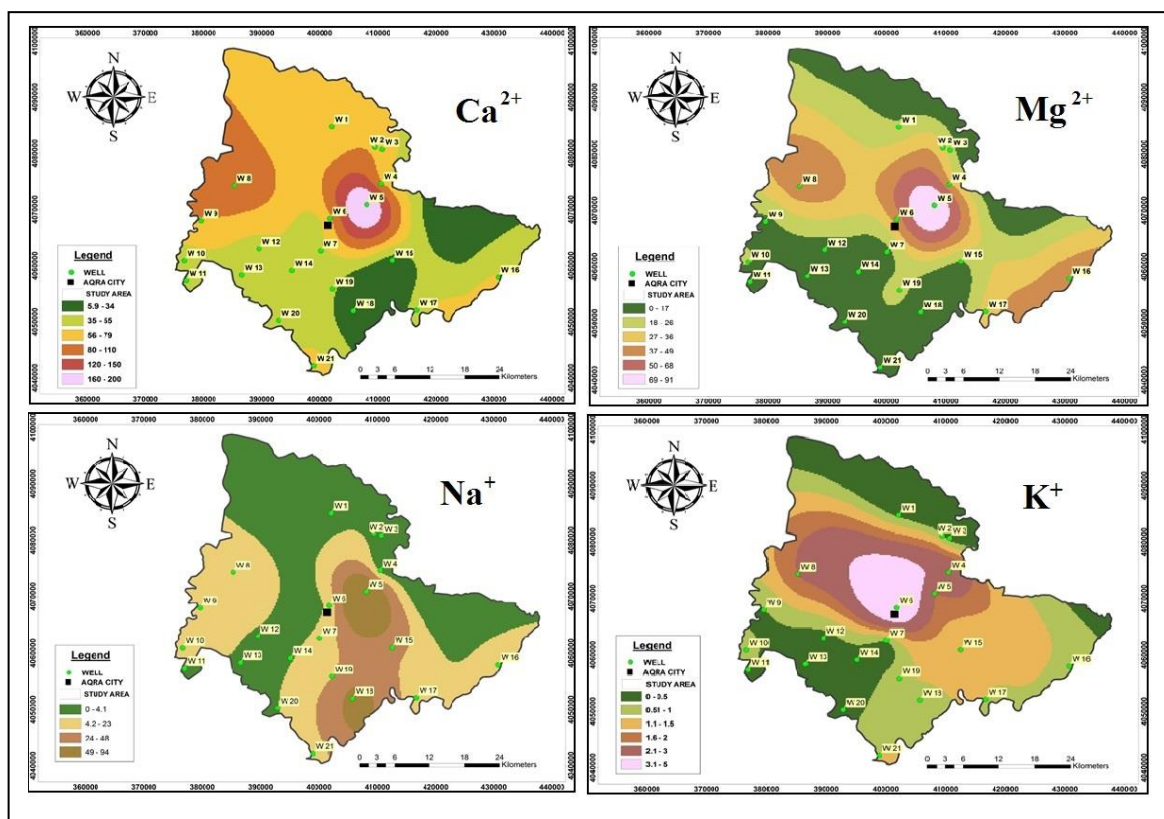


Fig. 4. Spatial distribution of the cations in the studied area

The concentration of bicarbonate ranged from 132 to 392 ppm, with an average of 230.24 ppm, it generally did not exceed the WHO guideline value of 350 ppm, except for well W8, which recorded the highest concentration of bicarbonate 392 ppm, it can be noted from Fig. 5 that wells close to carbonate rock sources have a higher percentage of bicarbonate, which is a result of the large spread of limestone and dolomitic rocks in the Aqrah and Peris folds, these percentages begin to decline towards the movement of groundwater south and southeast of the study area.

The concentration of chloride ranged between 8 and 190 ppm, with an average of 22.52 ppm. This percentage falls within the limits of international standards of the WHO. Fig. 5 shows that the highest percentage of chloride was observed in the W5 well, which was drilled in the Fatha Formation.

Sulfate ions ranged from 1.5 to 480.8 ppm with an average of 43.14 ppm. The international specifications of the WHO guideline for sulfate in drinking water is 250 ppm. Fig 5 shows that the highest sulfate concentration was recorded in well W5, which was drilled within the Fatha Formation, and this is related to the presence of gypsum and anhydrite within the formation. In contrast, most other wells in the study area recorded relatively low sulfate concentrations.

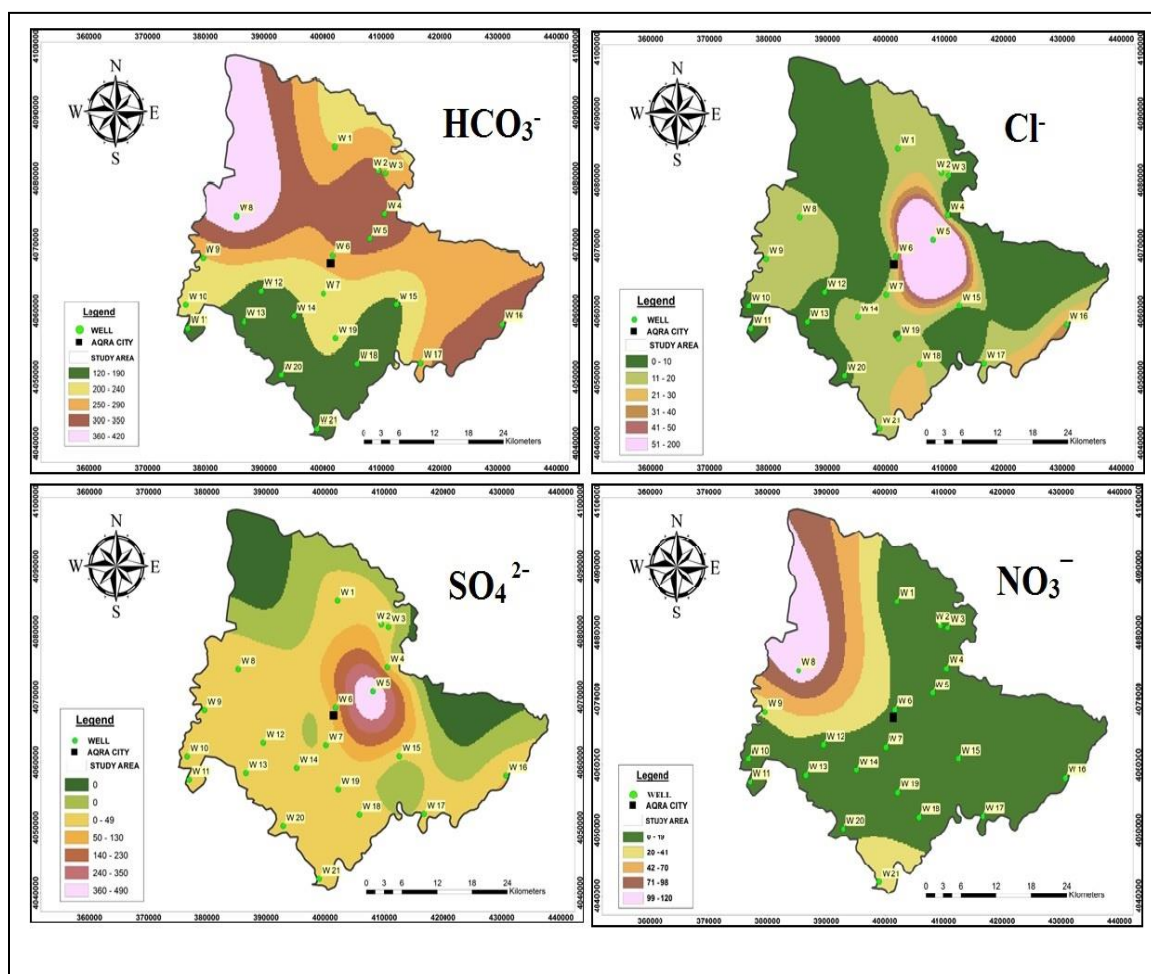


Fig. 5. Spatial distribution of the anions in the studied area

Using the Piper classification, it was found that the prevalent cation is calcium, followed by magnesium, sodium, then potassium, $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$, and the anions are bicarbonate, followed by sulfates, chlorides, and then nitrates $\text{HCO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{NO}_3^-$.

The water samples from wells 1, 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 16, 17, 20, and 21 are classified as normal earth-alkaline water with dominant bicarbonate, samples of wells 15, and 19 correspond to earth alkaline water with increased alkali content with prevailing bicarbonate, and sample W5 is identified as normal earth alkaline water with dominant sulfate or chloride, The water sample W18 is located within the alkaline water category with prevailing bicarbonate concentration, as shown in Fig. 6

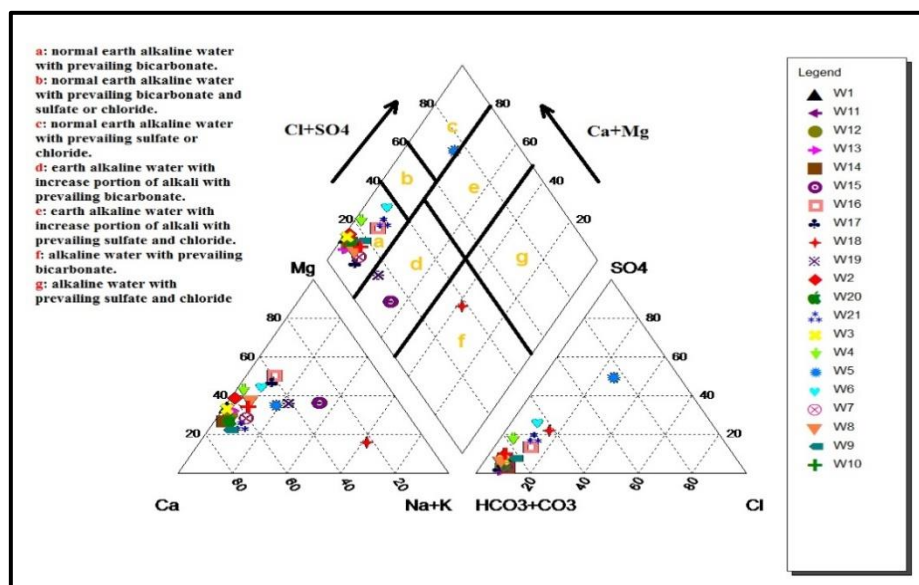


Fig. 6. Classification of water samples according to the Piper (1944) diagram

The ionic composition of water is used to classify it into ionic types based on the predominant anion and cation expressed in meq/l. The dominant dissolved ion must constitute more than 50% of the total dissolved ions for water to be classified. Moreover if no cation or anion prevalent (constituting more than 50%) water will be classified as mixed type and the most common cations or anions are used in descending order of abundance to describe the type of water (Ravikumar et al., 2015; U.S. Geological Survey, 2019). Accordingly, through Piper classification within the Aqua Chem program (Fig. 6), it was found that all the water from the wells of the study area are represent mixed type, and five hydrochemical facies were distinguished. However, most of the wells water are calcium and magnesium bicarbonate type, where it constituted 76.19% of all samples. W15 contains magnesium and sodium bicarbonate representing a percentage of 4.76%. W16 and W17 contain magnesium and calcium bicarbonate, representing of 9.5%, and W18 of sodium and calcium bicarbonate, which represents a percentage of 4.76%, and W5 has water type of calcium and magnesium sulfate represent 4.76% of all wells, as shown in Table 8.

The diversity in the groundwater facies in the study area indicates that it passes through various rock formations, so it derives calcium, magnesium, and bicarbonate from the rock formations (Aqra, Qamchuqa, and Pila Spi), while sulfate, sodium, and chloride are derived from the Fatah Formation, so this diversity appears in the water.

Table 8. The hydrochemical facies of the water samples in the study area

Well No.	Chemistry of water	Type of water	Percentage of studied water sample
W(1,2,3,4,7,8,9,10,11,12, 13,14 ,20,21)	Ca-Mg-HCO ₃	Ca-Mg-HCO ₃	66.6 %
W5	Ca-Mg-SO ₄ -Cl-HCO ₃	Ca-Mg-SO ₄	4.76 %
W6	Ca-Mg-HCO ₃ -SO ₄	Ca-Mg-HCO ₃	4.76 %
W15	Mg-Na-Ca-HCO ₃	Mg-Na-HCO ₃	4.76 %
W16 , W17	Mg-Ca-HCO ₃	Mg-Ca-HCO ₃	9.5 %
W18	Na-Ca-HCO ₃ -SO ₄	Na-Ca-HCO ₃	4.76 %
W19	Ca-Mg-Na-HCO ₃	Ca-Mg-HCO ₃	4.76 %

4.1.1. Suitability of the water for drinking

To estimate the suitability of water for drinking, the water quality index (WQI) was used, by representing the results of the analysis using equations 1, 2, 3, and 4. After comparing the obtained results for the WQI values in the study area which are shown in Table 5, and the limits of water quality index (Table 2), it was found that the wells 1, 2, 3, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, and 21 are excellent for human consumption as low values of WQI were calculated for most samples, and the wells W4, W6 are located within the good field, except for the two wells W5 and W8 which are located within the poor field, where they showed high values due to the excess levels of nitrates, sulfates, calcium, and others above the permissible limits.

4.1.2. Groundwater uses for irrigation

Wilcox Diagram (1955) was used (Fig. 7); the scheme is divided into five fields, and the water is classified based on electrical conductivity and sodium percentage. All the studied samples were excellent for irrigation, except for wells W5 and W8, which are located within the good irrigation water.

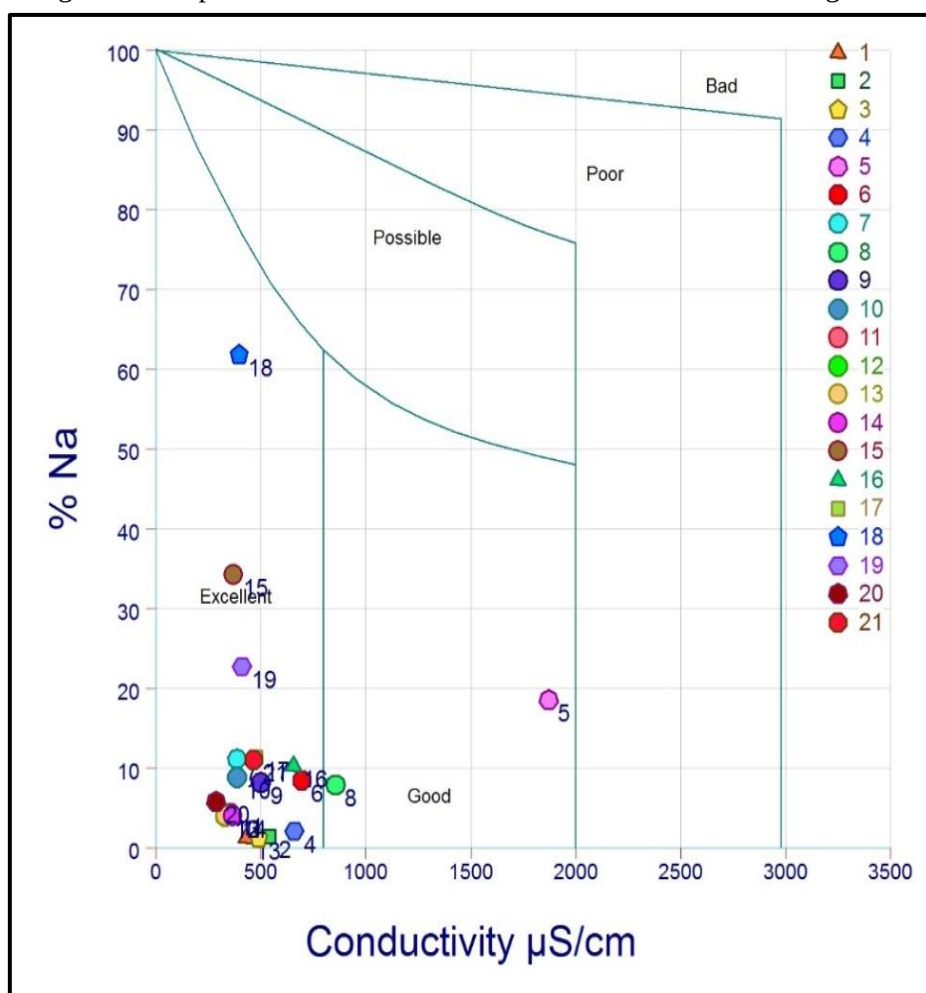


Fig. 7. A representation of the samples on the Wilcox (1955) diagram

4.2. Heavy Metals Assessment

The current study measured the concentrations of several heavy metals in groundwater, including Cd, Pb, Co, Zn, Cu, Fe, Mn, Cr, and Ni. The measured values, along with the permissible global limits, are presented in Table 9 in ppm.

Table 9. Heavy metal concentrations in the water wells of the study area

W	metal /	Cd	Pb	Co	Zn	Cu	Fe	Mn	Cr	Ni
	WHO, 2017 /	0.003	0.01	0.005	3.0	2.0	0.3	0.1	0.05	0.07
W1		0.00000	0.00015	0.00014	0.4325	0.4033	0.0831	0.0662	0.0000	0.0089
W2		0.00000	0.00000	0.00037	0.1011	0.4073	0.1325	0.0662	0.0000	0.0237
W3		0.00000	0.00052	0.00102	0.1892	0.4043	0.6717	0.0808	0.0247	0.0000
W4		0.00000	0.00000	0.00008	0.1038	0.4093	0.1536	0.0727	0.0205	0.0296
W5		0.00000	0.00000	0.00077	0.2388	0.4073	1.8901	0.0824	0.0247	0.0325
W6		0.00000	0.00082	0.00116	0.1065	0.4003	0.1043	0.0759	0.0163	0.0089
W7		0.00000	0.00139	0.00087	0.1020	0.3963	0.8456	0.0889	0.0000	0.0000
W8		0.00000	0.00124	0.00009	0.1241	0.4013	0.7187	0.0824	0.0122	0.0000
W9		0.00000	0.00000	0.00005	0.1088	0.4202	0.0526	0.0905	0.0000	0.0000
W10		0.00000	0.00000	0.00004	0.1016	0.3934	0.0620	0.0800	0.0000	0.0000
W11		0.00000	0.00106	0.00019	0.1002	0.4132	0.0408	0.0751	0.0000	0.0000
W12		0.00000	0.00209	0.00016	0.2505	0.4103	0.2899	0.0662	0.0000	0.0177
W13		0.00000	0.00000	0.00022	0.1002	0.4182	0.0291	0.0889	0.0040	0.0000
W14		0.00000	0.00000	0.00010	0.0989	0.4132	0.0361	0.0857	0.0000	0.0000
W15		0.00000	0.00000	0.00018	0.2654	0.3874	0.0749	0.0873	0.0000	0.0000
W16		0.00000	0.00000	0.00000	0.0998	0.4043	0.1313	0.0694	0.0081	0.0148
W17		0.00000	0.00000	0.00016	0.1079	0.4232	0.0667	0.0889	0.0332	0.0000
W18		0.00000	0.00000	0.00004	0.1056	0.3894	0.0667	0.0840	0.0000	0.0000
W19		0.00000	0.00055	0.00008	0.1034	0.3953	0.0631	0.0824	0.0000	0.0000
W20		0.00000	0.00033	0.00000	0.2239	0.4152	0.1278	0.0662	0.0000	0.0000
W21		0.00000	0.00727	0.00123	0.1011	0.3973	0.0479	0.0808	0.0000	0.0000
mean		0.0000	0.0007	0.0003	0.1507	0.4052	0.2709	0.0791	0.0068	0.0065

The contamination factor (CF) was used, a simple and effective tool for monitoring and assessing the extent of water pollution by heavy metals. The contamination factor (CF) quantifies contamination of the sample by individual elements, therefore, the contamination degree index (CD) (Singh et al., 2014) can be used, which represents the total pollution factors present in the sample to provide a unified description of the pollution.

After representing the results of analyses of heavy metals in water using equations 5 and 6, the results were as shown in Table 10. When compared with Tables 3 and 4, it was clear that most wells are considered safe based on the contamination factor (CF). However, samples from W3, W7, and W8 are located within moderate pollution with iron, and W5 is located within the very high pollution field with iron. As for the contamination degree index (CD), all wells are located within a field of low pollution, except for W5, which is located within the field of medium pollution with heavy metals.

Table 10. Represents the analysis of the water in the study area with the equations of water pollution with heavy metals

WELL	CONTAMINATION FACTOR (Cf)									Degree of
	Cd	Pb	Co	Zn	Cu	Fe	Mn	Cr	Ni	Contamination (CD)
W1	0.0000	0.0030	0.0280	0.1442	0.4033	0.2770	0.6620	0.0000	0.0890	1.6065
W2	0.0000	0.0000	0.0740	0.0337	0.4073	0.4417	0.6620	0.0000	0.2370	1.8557
W3	0.0000	0.0104	0.2040	0.0631	0.4043	2.2390	0.8080	0.4940	0.0000	4.2228
W4	0.0000	0.0000	0.0160	0.0346	0.4093	0.5120	0.7270	0.4100	0.2960	2.4049
W5	0.0000	0.0000	0.1540	0.0796	0.4073	6.3003	0.8240	0.4940	0.3250	8.5842
W6	0.0000	0.0164	0.2320	0.0355	0.4003	0.3477	0.7590	0.3260	0.0890	2.2059
W7	0.0000	0.0278	0.1740	0.0340	0.3963	2.8187	0.8890	0.0000	0.0000	4.3398
W8	0.0000	0.0248	0.0180	0.0414	0.4013	2.3957	0.8240	0.2440	0.0000	3.9491
W9	0.0000	0.0000	0.0100	0.0363	0.4202	0.1753	0.9050	0.0000	0.0000	1.5468
W10	0.0000	0.0000	0.0080	0.0339	0.3934	0.2067	0.8000	0.0000	0.0000	1.4419
W11	0.0000	0.0212	0.0380	0.0334	0.4132	0.1360	0.7510	0.0000	0.0000	1.3928
W12	0.0000	0.0418	0.0320	0.0835	0.4103	0.9663	0.6620	0.0000	0.1770	2.3729
W13	0.0000	0.0000	0.0440	0.0334	0.4182	0.0970	0.8890	0.0800	0.0000	1.5616
W14	0.0000	0.0000	0.0200	0.0330	0.4132	0.1203	0.8570	0.0000	0.0000	1.4435
W15	0.0000	0.0000	0.0360	0.0885	0.3874	0.2497	0.8730	0.0000	0.0000	1.6345
W16	0.0000	0.0000	0.0000	0.0333	0.4043	0.4377	0.6940	0.1620	0.1480	1.8792
W17	0.0000	0.0000	0.0320	0.0360	0.4232	0.2223	0.8890	0.6640	0.0000	2.2665
W18	0.0000	0.0000	0.0080	0.0352	0.3894	0.2223	0.8400	0.0000	0.0000	1.4949
W19	0.0000	0.0110	0.0160	0.0345	0.3953	0.2103	0.8240	0.0000	0.0000	1.4911
W20	0.0000	0.0066	0.0000	0.0746	0.4152	0.4260	0.6620	0.0000	0.0000	1.5844
W21	0.0000	0.1454	0.2460	0.0337	0.3973	0.1597	0.8080	0.0000	0.0000	1.7901

4.3. Reactions and Mechanisms Controlling the Groundwater Chemistry

Some mathematical ratios are used to describe the ions present in water. These ratios help explain the interactions between the rocks and water, besides using them to determine the changes in the properties of groundwater due to chemical processes that occur along the flow path.

The Ca/Mg ratio can be used to identify the type of rocks that supply water with ions; a ratio of more than 1 indicates that the dissolving of calcite rocks contributes to the addition of Ca^{2+} and Mg^{2+} ions to the water, and whenever it is less than 1, this indicates the contribution of dolomite rocks to the addition of these ions (Rifat et al., 2021). In the study area, most of the samples recorded a ratio greater than 1, which indicates a greater contribution of calcite rocks to the addition of these ions to the water, except for the W15, W16, and W17, where they recorded values less than 1, which are closer to the dolomitic Bakhma Formation, as shown in Table 11.

The Cation Exchange Value (CEV) is a measure of the number of cations that can be retained on the surfaces of soil particles, where negative charges on the surfaces of soil particles bind to positively charged atoms or molecules (cations) but allow them to exchange with other positively charged particles in the surrounding soil water (Nusantara et al., 2020). The cation exchange value (CEV) can be determined using the $\text{Cl}-(\text{Na}+\text{K})/\text{Cl}$ ratio, which showed positive values in 62% of all well water samples from the study area. This indicates an ion exchange process between Na^{+} and K^{+} ions in the water and Ca^{2+} and Mg^{2+} ions in the rocks or soil. Conversely, 38% of the samples showed negative

values, indicating a reverse exchange process between Ca^{2+} and Mg^{2+} ions in the water and Na^+ and K^+ ions in the rocks or soil (Nwankwoala and Udom, 2011; Saha et al., 2019) (Table 12).

The weathering of carbonate rocks and silicate minerals is the main source of Ca^{2+} , Mg^{2+} , and HCO_3^- ions in water of inland origin. Therefore, the source of these ions can be determined from $\text{Mg}/(\text{Ca}+\text{Mg})$ ratio. If it is less than 0.5, it indicates weathering of calcite and dolomite rocks; if it is greater than 0.5, it indicates weathering of dolomite and calcite precipitation. In the study area, this ratio recorded a rate of 0.38, which indicates that the source of calcium and magnesium ions is from the weathering of calcite and dolomite minerals in the study area (Saha et al., 2019) (Table 11).

Depending on the ratio $\text{HCO}_3^-/\sum \text{Anion}$, if it is greater than 1, it indicates the dominance of carbonate and silicate rock dissolution, while if it is less than 0.8, it indicates the dominance of gypsum rock dissolution. In the study area, this ratio recorded values greater than 0.8, which indicates the dominance of the carbonate and silicate rocks dissolution, while the sample W5 engraved on the Fatha Formation recorded a ratio of 0.25, which indicates the dominance of gypsum rock dissolution within the formation (Saha et al., 2019) (Table 11).

The dissolution of salt rocks adds nearly equivalent concentrations of sodium and chloride ions to the water, so the ratio between them will be close to 1. After representing the values of sodium and chlorine in the water samples of the study area with a linear relationship (Fig. 8), it was found that most of the samples are located close to the 1:1 line, which indicates that the source of sodium and chlorine is from the dissolution of salt rocks of Fatha Formation. However, some points are located far from the 1:1 line, which indicates that other processes contribute to the addition of sodium and chlorine to the water, therefore when the ratio of Na/Cl is greater than 1, this indicates that silicate rock weathering or ion exchange processes in clay minerals act as sources of adding sodium ions to the water (Sajil and James, 2016), and this was observed in several water samples in the study area especially W18, with water type of sodium bicarbonate. Furthermore, when this ratio is less than 1, it indicates that the dissolution of salt rocks is the source of sodium ions in the water (Table 11).

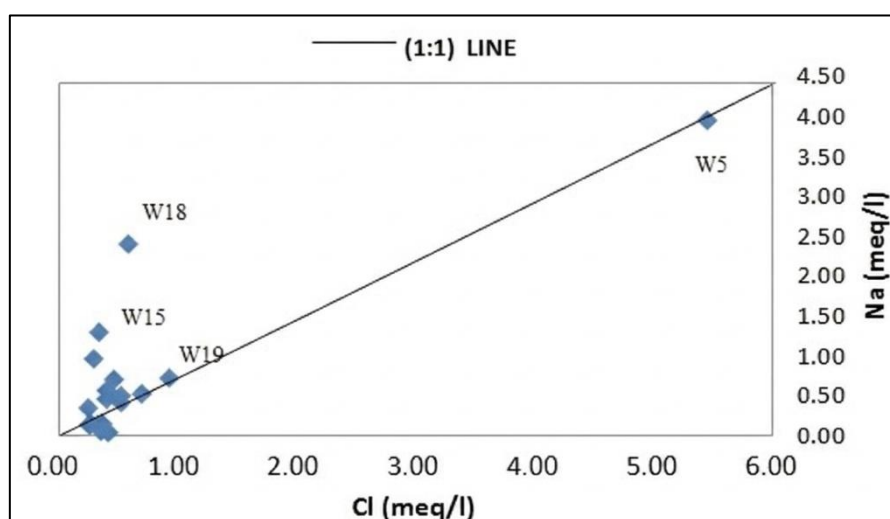


Fig. 8. Illustrates the relationship between (Na) and (Cl) for the wells in the study area

The sources of Ca and Mg ions can be identified by representing the relationship between the sums of $\text{Ca} + \text{Mg}$ and $\text{SO}_4 + \text{HCO}_3^-$. When the points (representing the samples) are close to or cluster around the 1:1 line this indicates that the dissolution of calcite, dolomite, and gypsum is the dominant geochemical process. After representing the samples from the study area using this relationship, the data points cluster around the 1:1 line, indicating that the dissolution of calcite, dolomite, and gypsum is responsible for the addition of calcium and magnesium ions in the water (Nganje et al., 2010), as shown in Fig. 9.

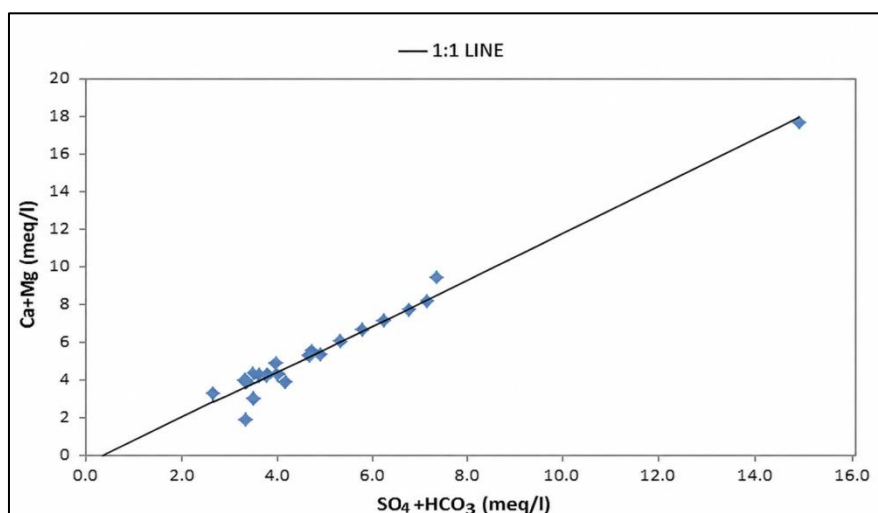


Fig. 9. The relationship between Ca + Mg and $\text{SO}_4 + \text{HCO}_3$

Table 11. Geochemical ratios used to explain the chemistry of the water in the study area

Well	Ca/Mg	Mg/(Ca+Mg)	HCO_3/Σ Anion	Na/Cl	Well	Ca/Mg	Mg/(Ca+Mg)	HCO_3/Σ Anion	Na/Cl
W1	1.93	0.34	0.87	0.12	W12	2.19	0.31	0.83	0.54
W2	1.56	0.39	0.85	0.22	W13	2.00	0.33	0.85	0.49
W3	2.01	0.33	0.86	0.19	W14	2.65	0.27	0.81	0.41
W4	1.27	0.44	0.77	0.27	W15	0.82	0.55	0.82	4.02
W5	1.35	0.43	0.25	0.73	W16	0.79	0.56	0.71	0.81
W6	1.06	0.49	0.62	0.78	W17	0.92	0.52	0.88	1.52
W7	2.16	0.32	0.83	1.17	W18	1.43	0.41	0.59	4.21
W8	1.44	0.41	0.70	1.54	W19	1.15	0.46	0.82	3.42
W9	3.20	0.24	0.76	0.84	W20	2.52	0.28	0.79	0.66
W10	1.68	0.37	0.81	1.56	W21	2.67	0.27	0.61	1.00
W11	2.43	0.29	0.82	0.61	mean	1.77	0.38	0.75	1.19

In order to determine the predominant geochemical process in the study area, the Gibbs Diagram was used, which is an important tool for studying the geochemical processes. Gibbs identified three natural mechanisms that control water chemistry: rock weathering, precipitation, evaporation, and crystallization.

The Gibbs Diagram is obtained when the ratio $\text{Na}/(\text{Na}+\text{Ca})$ on the X-axis is plotted against the TDS values on the Y-axis, and the same is for $\text{Cl}/(\text{Cl}+\text{HCO}_3)$ vs. TDS. Therefore, when rock weathering is the predominant process, water is produced in which Ca^{2+} and HCO_3^- ions predominate, with moderate TDS values, and the water sample points are located in the middle part of the diagram. In the second process, the low salinity of NaCl-type water is due to precipitation processes, therefore, the sample points plot in the lower right corner of the chart arm. The third mechanism controlling water chemistry is the evaporation-crystallization process, which is important in arid regions where evaporation exceeds precipitation; under these conditions, the sample points plot in the upper part of the diagram. (Rout et al., 2012).

After plotting the water samples on the Gibbs Diagram, it was found that they lied in the rock weathering field, which is the predominant mechanism controlling groundwater chemistry in the study area (Fig. 10).

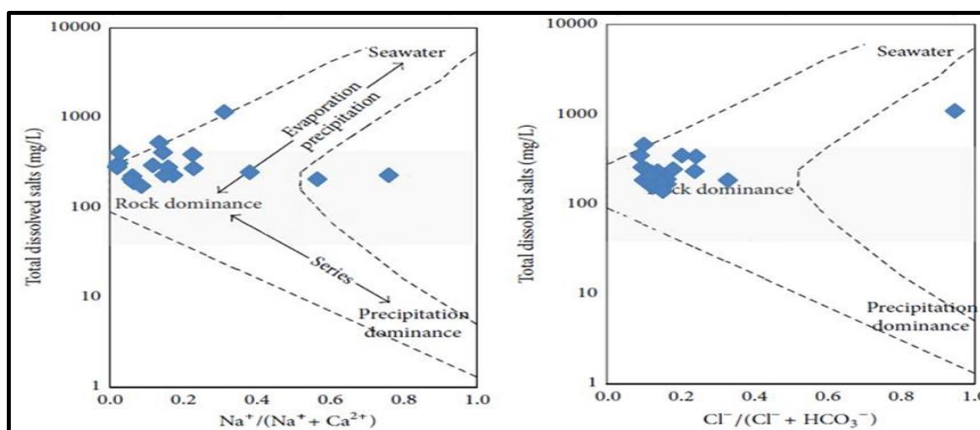


Fig. 10. Representation of the groundwater samples in the study area by the Gibbs (1970) diagram

4.4. The Origin of the Groundwater

Geochemical ratios are usually used to find out the origin of groundwater by linking the ions through mathematical relationships (Hussein et al., 2021). In this study, several ratios were applied to explain the origin of the groundwater in the study area.

- Cl/HCO₃ ratio: This ratio ranges from 1 to 5 in fresh water, and 20 to 50 in seawater (Rout et al., 2012). These values in the study area range from 0.063 to 1.068, with an average of 0.159, which refers to the inland origin of the groundwater.
- Mg/Ca ratio: Since marine water contains more magnesium than calcium, this ratio is close to 3.7 for the marine origin water (Nganje et al., 2010; Hussein et al., 2021). This ratio in the study area ranged between 0.31 and 1.26, which refers to the inland origin of the groundwater.
- Cl-(Na+K)/Cl Cation Exchange Value (CEV): Low and near-zero values of this relationship (whether positive or negative) refer to low-salinity inland water, whereas in marine waters the ratio ranges between 1.2 and 1.3 (Rout et al., 2012; Hussein et al., 2021). In the study area, values range from -3.11 and 0.04, which indicates the inland origin of the groundwater (Table 12).

Table 12. Geochemical ratios and CEV values for groundwater in the study area

Well	Cl/HCO ₃	Mg/Ca	CEV	Well	Cl/HCO ₃	Mg/Ca	CEV
W1	0.10	0.52	0.85	W12	0.09	0.46	0.43
W2	0.07	0.64	0.74	W13	0.10	0.50	0.48
W3	0.08	0.50	0.79	W14	0.12	0.38	0.57
W4	0.06	0.79	0.52	W15	0.11	1.21	-3.11
W5	1.07	0.74	0.26	W16	0.19	1.26	0.17
W6	0.15	0.95	0.04	W17	0.09	1.09	-0.59
W7	0.12	0.46	-0.21	W18	0.26	0.70	-3.25
W8	0.07	0.69	-0.65	W19	0.09	0.87	-2.50
W9	0.13	0.31	0.14	W20	0.11	0.40	0.31
W10	0.07	0.60	-0.63	W21	0.18	0.37	-0.05
W11	0.09	0.41	0.34	mean	0.16	0.66	-0.25

4.5. Statistical Analysis

The correlations between cations, anions, and selected physicochemical parameters were evaluated to identify the common geochemical behavior between these elements in the study area, the data were statistically analyzed using SPSS software, as follows.

The bicarbonate recorded a significant inverse correlation with the pH ($r = -0.825$), indicating that an increase in bicarbonate increases the acidity of the water's alkaline when it combines with calcium, magnesium, and other ions.

Strong significant correlations were observed between TDS and each of Ca^{2+} , Mg^{2+} , Cl^- , SO_4^{2-} , and a moderate correlation with Na^+ and HCO_3^- ; therefore, these ions are responsible for the increase in total dissolved solids in the water.

A significant positive correlation ($r = 0.975$) was observed between TDS and TH, indicating that water hardness is primarily controlled by the total dissolved solids.

A significant positive correlation between Ca^{2+} and Mg^{2+} ($r = 0.877$) indicates that they originate from the same source, which may be due to the dissolution of carbonate rocks that are widespread in the area.

A significant positive correlation was recorded between Ca^{2+} and SO_4^{2-} and Ca^{+2} , and Cl^- and SO_4^{2-} and Cl^- , where these ions are associated in the Fatha Formation rocks of gypsum, anhydrite, and salt deposits. High concentrations of all these ions are observed in well W5, which is drilled within the Fatha Formation.

Sodium and chloride show a significant positive correlation ($r = 0.832$), as they are generally associated due to their common geochemical origin and similar formation processes (Table 13).

No significant relationship was observed with nitrate ions (NO_3^-), especially that well W8 shows a high nitrate concentration, which refers to the organic source of nitrate, independent of the other major ions, especially in this well.

Table 13. Correlation coefficient matrix for the main components of the water wells in the study area

	pH	TDS	TH	Ca^{++}	Mg^{++}	Na^+	K^+	Cl^-	SO_4^{2-}	NO_3^-	HCO_3^- & CO_3
pH	1										
TDS	-0.589	1									
TH	-0.716	0.975	1								
Ca^{++}	-0.675	0.943	0.974	1							
Mg^{++}	-0.717	0.946	0.963	0.877	1						
Na^+	-0.026	0.736	0.572	0.517	0.599	1					
K^+	-0.462	0.466	0.491	0.390	0.579	0.251	1				
Cl^-	-0.374	0.936	0.865	0.849	0.825	0.832	0.276	1			
SO_4^{2-}	-0.402	0.947	0.887	0.867	0.850	0.811	0.391	0.986	1		
NO_3^-	-0.235	0.123	0.138	0.155	0.109	-0.022	0.195	-0.100	-0.113	1	
HCO_3^- & CO_3	-0.825	0.600	0.713	0.648	0.743	0.085	0.503	0.308	0.341	0.382	1

The SPSS program was also used to perform a statistical analysis (cluster analysis) of the wells and separate them into groups with similar properties, as shown in Fig. 11, from which we note the following:

At the first similarity level a, two independent groups were distinguished.

The first group includes the W5, which has high content of sulfur and sulfur-quality water of calcium sulfate.

The second group includes the rest of the wells, which are characterized by their high content of bicarbonate and water of bicarbonate quality, mostly calcium bicarbonate.

As for level b, four distinct groups emerged.

The first group includes wells 1, 2, 3, 4, 6, 9, 16, and 17 characterized by a carbonate nature and having a higher TDS.

The second group includes wells 7, 10, 11, 12, 13, 14, 15, 18, 19, 20, and 21, which are also characterized by a carbonate nature and contain a lower TDS than the first group.

The third group: W8 contains bicarbonate water and has a high nitrate content.

The fourth group includes W5, which is unique in that its water is of a sulfurous nature from calcium sulfate.

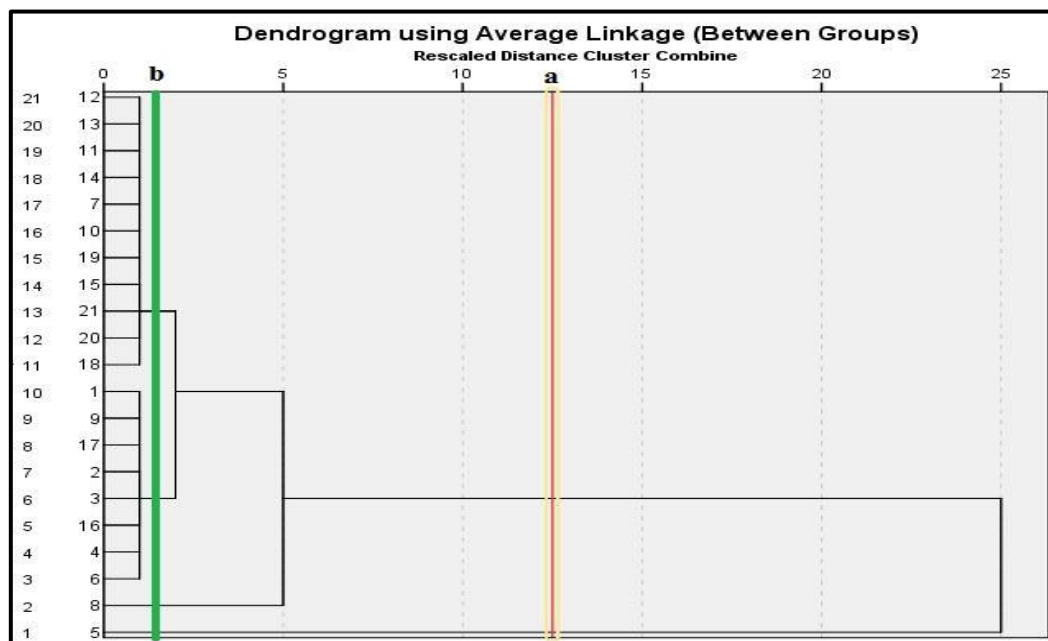


Fig. 11. Cluster analysis using SPSS program shows the correlation between the studied wells

5. Conclusions

From studying the components of groundwater, it was found that the water is neutral to low basic and ranges from soft to very hard, but most of the samples are located within the field of temporary hardness resulting from the dissolution of carbonate rocks spread in the area, except for one well W5, drilled on the Fatha Formation, the water of which is permanently hard. The water is of a mixed type, and five hydrochemical facies were distinguished, but most of the samples are of the calcium and magnesium bicarbonate type, which constituted (76.19%) of all samples.

The Water Quality Index (WQI), shows that most of the water wells are excellent for human consumption, while the water of wells W4, and W6 are located within the good field, however, W5, and W8 are located within the poor field, where the well W5 showed slightly high values of sulfate, calcium, chloride, and sodium, and well W8 recorded an increase in nitrate ion.

Wilcox classification indicated that most of the samples are excellent water for irrigation, and the wells W5 and W8 fall within the good field due to the higher electrical conductivity of these wells than the others. In general, the water content of heavy metals is low, as indicated by the contamination factor (CF), except for the wells W3, W7, and W8 that fall within the field of medium pollution with iron, and the well W5 falls within the field of very high pollution with iron. As for the contamination degree index (CD), all wells fall within the low-pollution field, except for W5, which falls within the medium-pollution field for heavy metals. The groundwater in the area is of inland origin, and there is no pollution by ancient marine water bodies. The Gibbs Diagram indicates the rock weathering is a dominant mechanism that controls the chemistry of the groundwater in the study area.

Authors contributions: CRediT

Omar S. Aqrabi: Conceptualization, Data curation, Methodology, Formal analysis, Writing - original draft, Software.

Aahed Y. Al-Mallah: Supervision, Writing – review and editing, Validation.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding sources

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sector.

Data Availability

Data will be made available on request.

References

- Alfaifi, H., El-Sorogy, A.S., Qaysi, S., Kahal, A., Almadani, S., Alshehri, F., Zaidi, F.K., 2021. Evaluation of heavy metal contamination and groundwater quality along the Red Sea coast, southern Saudi Arabia. *Marine Pollution Bulletin*, 163, 111975. <https://doi.org/10.1016/j.marpolbul.2021.111975>
- Ameen, H.A., 2019. Spring water quality assessment using water quality index in villages of Barwari Bala, Duhok, Kurdistan Region, Iraq. *Applied Water Science*, 9(8), 1–12. <https://doi.org/10.1007/s13201-019-1080-z>
- Bhutiani, R., Kulkarni, D.B., Khanna, D.R., Gautam, A., 2017. Geochemical distribution and environmental risk assessment of heavy metals in groundwater of an industrial area and its surroundings, Haridwar, India. *Energy, Ecology and Environment*, 2(2), 155–167. <https://doi.org/10.1007/s40974-016-0019-6>
- Britto, F.B., Vasco, A.N.D., Aguiar Netto, A.D.O., Garcia, C.A.B., Moraes, G.F.O., Silva, M.G.D., 2018. Surface water quality assessment of the main tributaries in the lower São Francisco River, Sergipe. *RBRH*, 23, 6–23. <https://doi.org/10.1590/2318-0331.231820170061>
- Cotruvo, J.A., 2017. WHO guidelines for drinking water quality: first addendum to the fourth edition. *Journal - American Water Works Association*, 109(7), 44–51. <https://doi.org/10.5942/jawwa.2017.109.0087>
- Gibbs, R.J., 1970. Mechanisms controlling world water chemistry. *Science*, 170(3962), 1088–1090.
- Hadgu, L.T., Nyadawa, M.O., Mwangi, J.K., Kibetu, P.M., Mehari, B.B., 2014. Application of water quality model qual2k to model the dispersion of pollutants in river ndarugu, Kenya. *Computational Water, Energy, and Environmental Engineering*, 3(04), 162. <https://doi.org/10.4236/cweee.2014.34017>
- Hakanson, L., 1980. An ecological risk index for aquatic pollution control. A sedimentological approach. *Water Research*, 14(8), 975–1001. [https://doi.org/10.1016/0043-1354\(80\)90143-8](https://doi.org/10.1016/0043-1354(80)90143-8)
- Horton, R.K., 1965. An index number system for rating water quality. *Journal of Water Pollution Control Federation*, 37(3), 300–306.
- Hussein, H., Abd El-Raouf, A., Almadani, S., Abdelrahman, K., Ibrahim, E., Osman, O.M., 2021. Application of geochemical modeling using NETPATH and water quality index for assessing the groundwater geochemistry in the south Wadi El-Farigh area, Egypt. *Journal of King Saud University-Science*, 33(2), 101284. <https://doi.org/10.1016/j.jksus.2020.101284>
- Jassim, S.Z., Goff, J.C., 2006. *Geology of Iraq*. Dolin, Prague and Moravian Museum, Brno, Czech Republic.
- Nganje, T.N., Adamu, C.I., Ugbaja, A.N., Amah, A.E., 2010. Evaluation of hydrogeochemical characteristics of groundwater in parts of the lower Benue Trough, Nigeria. *Chinese Journal of Geochemistry*, 29(4), 398–406. <https://doi.org/10.1007/s11631-010-0472-4>
- Nusantara, R.W., Sudarmadji, S., Djohan, T.S., Haryono, E., 2020. Impact of land-use change on soil carbon dynamics in tropical peatland, West Kalimantan-Indonesia. *Indonesian Journal of Geography*, 52(1), 61–68. <https://doi.org/10.22146/ijg.48451>
- Nwankwoala, H.O., Udom, G.J., 2011. Hydrochemical facies and ionic ratios of groundwater in Port Harcourt, Southern Nigeria. *Research Journal of Chemical Sciences*, 1(3), 87–101.
- Piper, A.M., 1944. A graphic procedure in the geochemical interpretation of water analyses. *Transactions, American Geophysical Union*, 25(6), 914–923. <https://doi.org/10.1029/TR025i006p00914>

- Ravikumar, P., Somashekar, R.K., Prakash, K.L., 2015. A comparative study on usage of Durov and Piper diagrams to interpret hydrochemical processes in groundwater from SRLIS river basin, Karnataka, India. *Elixir Earth Science*, 80, 31073–31077.
- Rifat, M.A.H., Howlader, S., Alam, M.A., Islam, M.N., Afrin, A., Ali, F., Ganguli, S., 2021. Hydrogeochemical characteristics, quality assessment and health impact analysis of groundwater for drinking in the University of Chittagong, Bangladesh. *Malaysian Journal of Chemistry*, 23(1), 74–102. <https://doi.org/10.55373/mjchem.v23i1.880>
- Rout, S., Kumar, A., Sarkar, P.K., Mishra, M.K., Ravi, P.M., 2012. Groundwater geochemistry study of estuarine aquifer, Western India: Mumbai using chemometric and conventional techniques. *Indian Journal of Advances in Chemical Science*, 1, 1–9.
- Saha, S., Reza, A.S., Roy, M.K., 2019. Hydrochemical evaluation of groundwater quality of the Tista flood plain, Rangpur, Bangladesh. *Applied Water Science*, 9(8), 1–12. <https://doi.org/10.1007/s13201-019-1085-7>
- Sajil Kumar, P.J., James, E.J., 2016. Identification of hydrogeochemical processes in the Coimbatore district, Tamil Nadu, India. *Hydrological Sciences Journal*, 61(4), 719–731. <https://doi.org/10.1080/02626667.2015.1022551>
- Sharma, S.K., 2014. Heavy Metals in Water: Presence, Removal and Safety. Royal Society of Chemistry. <https://doi.org/10.1039/9781782620174>
- Singh, P.K., Verma, P., Tiwari, A.K., Sharma, S., Purty, P., 2014. Review of various contamination index approaches to evaluate groundwater quality with geographic information system (GIS). *International Journal of ChemTech Research*, 7(4), 1920–1929.
- Todd, D.K., 1980. Ground Water Hydrology (2nd ed.). New York
- U.S. Geological Survey, 2019. Dictionary of water terms. U.S. Geological Survey web page, accessed December 2019. <https://www.usgs.gov/special-topic/water-science-school/science/dictionary-water-terms>
- Weiner, E.R., 2000. Applications of Environmental Chemistry: A Practical Guide for Environmental Professionals. CRC Press, Lewis Publishers, Florida.
- Wilcox, L.V., 1955. Classification and Use of Irrigation Waters. US Department of Agriculture.