Chapter 7

Hydrogeology and Groundwater Geochemistry of the Clastic Aquifer and Its Assessment for Irrigation, Southwest Kuwait

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Additional information is available at the end of the chapter

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Abstract

Al-Atraf field, is located southwest of Kuwait City, the groundwater is produced from the Kuwait Group aquifer. The objectives are to identify aquifer type and its characteristics. The major geochemical processes operating in the aquifer have to be revealed. In addition, to evaluate the groundwater quality and its suitability of drinking and agriculture usage, an investigation was carried out by estimating physiochemical parameters like pH, EC, TDS, TH, Na^+, K^+ Ca^{2+}, Mg^{2+}, Cl^-, HCO_3^-, SO_4^{2-}, total alkalinity, and SiO_2. Irrigation parameters like SAR, %Na, RSC, potential salinity, magnesium ratio, Kelly's ratio, permeability index, and chloro-alkaline index have been determined. The aquifer is confined and occupied by brackish groundwater mainly of NaCl type. Gibb's plot suggests that the chemical weathering of rock primarily controls the chemistry of the study area. WATEVAL program revealed that the main geochemical processes are silicate weathering, dissolution, precipitation, and reverse ion exchange. WATEQ4F indicates that the groundwater is oversaturated with respect to calcite and dolomite and undersaturated with respect to gypsum and anhydrite. The high total hardness and TDS identify the unsuitability of groundwater for drinking, while irrigation parameters indicate that this water cannot be used on soil without special management for salinity control and salt tolerance plants.

Keywords: Kuwait Group aquifer, saturation index, geochemical processes, Gibb's ratio, irrigation parameters

1. Introduction

The State of Kuwait is located at the northwestern side of the Arabian Gulf and occupies an area of about 18,000 km^2. Kuwait is bordered on the north and west by Iraq and on the south by the Kingdom of Saudi Arabia. The climate is extremely hot and dry in summer and mild-to-cold in winter. The rainfall is scarce and limited to the period from October to May. The highest ever temperature recorded in Kuwait was 54°C on July 2016. The average annual precipitation recorded during the period 2001–2016 is 114.5 mm. It lies within an arid-semiarid zone lacking renewable surface water. The natural water resources are the brackish groundwater located in the Kuwait Group and the Dammam Formation aquifers, which have been utilized since 1953 on a small scale and for limited purpose, but with increasing population and growth of demands, the production of groundwater embarked on a wide scale project to provide consumers with it through a separate pipe network. This groundwater is used for blending with distilled water for fresh water production, irrigation and landscaping plus household purposes, livestock watering, and construction works. The present total output installed capacity of groundwater wells is around 145 MIGD, meanwhile the maximum consumption hit 114.6 MIGD. However, the demand for water in Kuwait is met from three sectors: desalination, brackish groundwater, and tertiary treated waste water.

The Al-Atraf field is one of the brackish groundwater fields and is located southwest of Kuwait between 29° 18⁻ to 29° 24⁻ north latitudes and 47° 31⁻ to 47° 38⁻ east longitudes. The area under study is about 87.75 km^2 and includes 83 water wells, producing groundwater from the Kuwait Group aquifer, where the nominal production capacity is 30 MIGPD. The salinity of the aquifer ranges from 3504 to 6366 mg/l, with an average value of 4441 mg/l.

1.1. Topography

The topography of Kuwait is generally flat, with a gentle rise from sea level at the coast to an elevation of about 270 m in the southwest corner of the country (**Figure 1**). Local relief is low except in the Jal-Az-Zor escarpment, the Ahmadi Ridge, the Wara Hill, and the Wadi Al-Batin [1]. The Jal-Az-Zor escarpment, about 60 km in length and 145 m in height above MSL, borders the northwestern shore of Kuwait Bay. It trends from Al-Atraf southwest to Bahra northeast. The Ahmadi Ridge parallels to the coastline south of Kuwait City and rises to a height of 137 m above MSL. The east and west slopes of the ridge are very gentle. Another elevation is the Wara Hill, located southeastern Kuwait and has a local relief of about 31 m. The Wadi Al-Batin is a major and shallow depression marking the western boundary of the country for a distance of 75 km with an average width of 6–8 km. The central part of Kuwait and the Neutral Zone are featureless with few wadis and little vegetation. Furthermore, small and shallow depressions exist throughout the northern, western, and central areas. The northern and the western parts of the country have a dense drainage pattern of small and shallow wadi systems, draining northeast toward the Iraq border and toward the shallow depressions near Al-Rawdhatain [2].

1.2. General stratigraphy

The surface of Kuwait is formed by sedimentary rocks and sediments ranging from Middle Eocene to Recent. The Dammam Formation represents the oldest exposed sedimentary rocks. The Recent deposits of fine-grained beach sands cover the southern coast of Kuwait and the Neutral Zone. The Cenozoic (Tertiary-Quaternary) sediments can be divided into two groups:

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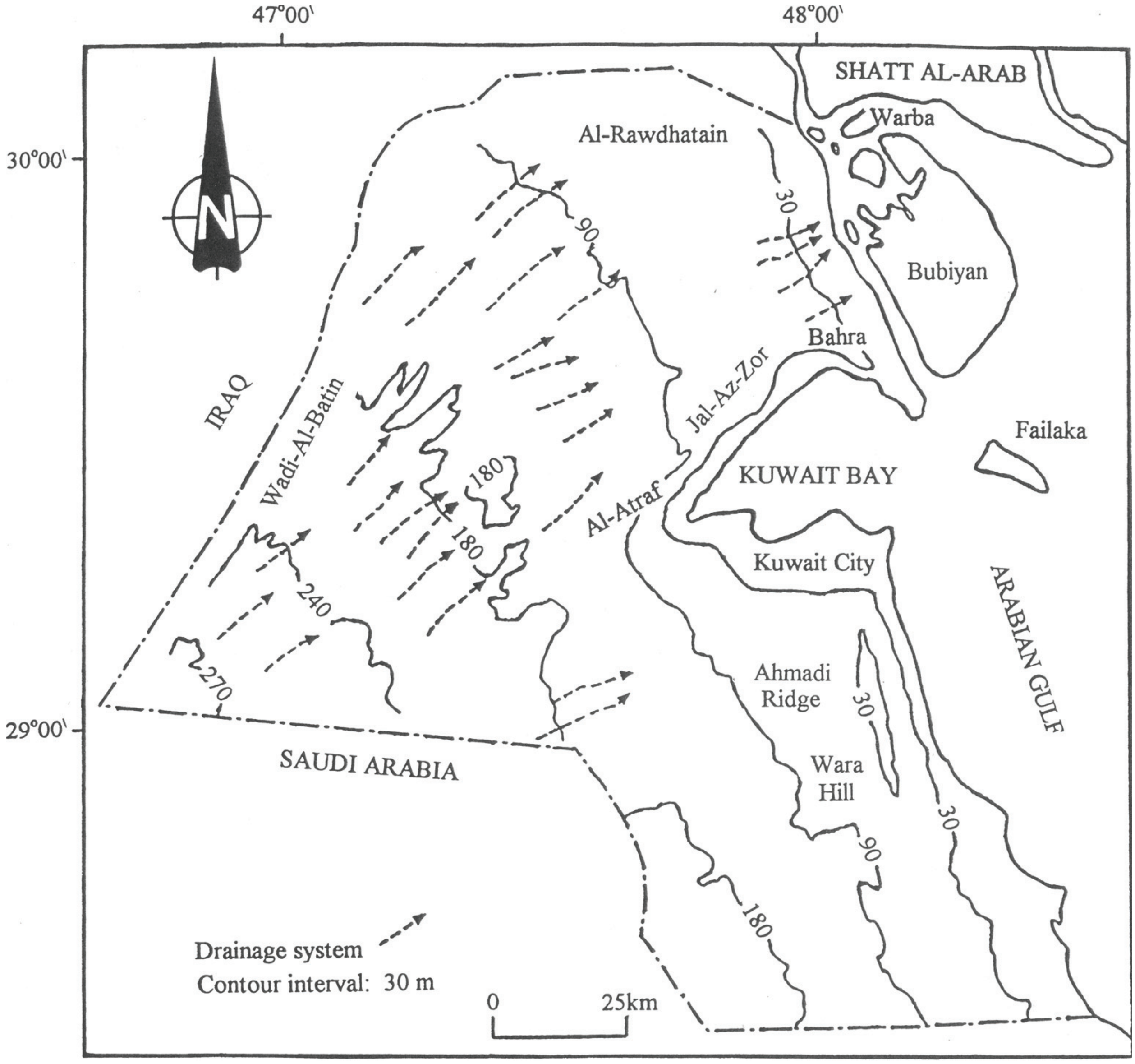

Figure 1. The topographic and the dominant northeast drainage patterns of Kuwait.

the Kuwait Group and the Hasa Group. The Mesozoic (Late Cretaceous) sediments are characterized by carbonate rocks [3]. A generalized lithostratigraphic subdivisions of Tertiary-Quaternary sediments in Kuwait with the groundwater conditions [4] is summarized and discussed below.

1.3. The Kuwait Group

The Kuwait Group consists of sand, gravel, sandstone, clay, silt, calcareous and gypseous cemented sandstones, and marl covering the entire surface of Kuwait and extending down to the top of the underlying Dammam Formation. The thickness of the Kuwait Group increases from 150 m in the southwest to about 400 m in the northeast. The Kuwait Group is relatively dry in the extreme southwest and is almost saturated with water along the coast of the Arabian Gulf. In the north of Kuwait, the Kuwait Group can be divided into three formations based on the presence of an intermediate evaporite development. These divisions are Dibdibba, Lower Fars, and Ghar Formations, arranged from top to bottom. The undivided Kuwait Group extends under all of Kuwait with an extension eastwards beneath the Arabian Gulf. The Dibdibba Formation was named after the type locality Al-Dibdibba Plain, which extends from Basra to the northern part of Kuwait. The Dibdibba Formation is overlain by unconsolidated Recent and sub-Recent sediments of varying lithologies. The Lower Fars Formation ranges in thickness from 61 m in the west to more than 100 m in the eastern area into the offshore and it is absent in the south. It consists of fine to coarse-grained conglomeratic sandstone, variegated shale, and thin, fossiliferous limestone. The outcrop thickness of the Ghar Formation is only 33 m but it increases in subsurface and ranges from 195 to 250 m of marine to terrestrial, coarse-grained, unconsolidated sandstone with a few thin, sandy limestone, clay and anhydrite layers. At the base of the formation, above the eroded top of the Dammam Formation, is a brown, marly, coarse-grained sandstone with white, crystalline limestone resting unconformably over the Dammam Formation, and in gradational contact with the Lower Fars Formation.

2. Hydrogeology

The northeastern part of Arabian Peninsula is characterized by four major systems of aquifers. These are (1) The Paleozoic-Triassic System, (2) The Cretaceous System, (3) The Eocene System, and (4) The Neogene-Quaternary System. The last two aquifers contain usable water, while the other deeper aquifers have connate water. Thus, the principle aquifer system in Kuwait consists of the Kuwait Group and the Dammam Formation of the Hasa Group. Many hydrological and hydrochemical evidences indicate local hydraulic connection between the Kuwait Group and the Dammam Formation aquifers in which both aquifers are considered as one complex system forming the main potential aquifers in Kuwait. Basically, the saturated part of the Kuwait Group and the Dammam Formation aquifers are replenished by infiltration on the outcrop area of Hasa Group at the eastern-northeastern part of Saudi Arabia and groundwater is discharged in Shatt Al-Arab and the Arabian Gulf [5]. Potentiometric level maps of the Kuwait Group and the Dammam Formation aquifers indicate a direction of groundwater movement from southwest to northeast direction. Due to the variations of clay percentage and cementation degree, the Kuwait Group is divided into two aquifers separated by an aquitard formation of clay and sand. Accordingly, the Kuwait Group appears to be semi-confined aquifer with a free water surface in the uppermost horizons. The saturated thickness of the Kuwait Group aquifer gradually increases toward northeast direction, as related to the structure of the Dammam Formation, where the groundwater in the aquifer becomes very saline.

The Kuwait Group aquifer is hydraulically connected with the underlying Dammam Formation aquifer under natural hydrological conditions; the flow occurs in a dynamic equilibrium state, in SW-NE direction, to be discharged finally by seepage into Kuwait Bay and the Arabian Gulf [6]. The Kuwait Group aquifer gains part of its water by leakage from the Dammam Formation aquifer. The other sources of aquifer replenishment are the infiltration through the well-developed wadies and depression system, and lateral flow coming from Saudi Arabia. It is generally estimated that the hydraulic conductivity in the aquifer conjunctively decreases with depth by the increase of cementation degree. The hydraulic conductivity is relatively high in the upper saturated zones of the aquifer.

3. Objectives of the study

The main objectives of this piece of research are to identify the aquifer type and its characteristics, to reveal the geochemistry of the study area in order to recognize the prevailing and the major geochemical processes that control the quality of the groundwater. Moreover, to evaluate the suitability of groundwater for drinking and irrigation, physiochemical and irrigation parameters have been determined.

4. Methodology

Seventy-one groundwater samples have been collected and analyzed to determine physical parameters like pH, EC, TDS, total hardness (TH), total alkalinity, and SiO_2. In addition, the chemical parameters of the major cations and anions such as Ca^{2+}, Mg^{2+}, Na^+, K^+, HCO_3^-, SO_4^{2-}, and Cl^- expressed in mg/l were analyzed and converted to equivalent per million (e.p.m), and % e.p.m. [7]. Ion balance equation was applied to validate the accuracy of the chemical analyses where $\pm 5\%$ is acceptable [8]. The reaction error of all groundwater samples was less than the accepted limit of $\pm 10\%$ [9].

A speciation model has been used to determine the degree of saturation of groundwater with respect to some minerals using WATEQ4F program [10]. A mass-balance modeling WATEVAL computer program [11] is used to reveal the major geochemical reactions that control the geochemistry of the study area, along with the application of Gibb's ratio to assess the functional sources of dissolved chemical constituents, and to recognize the main processes governing the groundwater chemistry of the study area [12]. Hydrochemical facies interpretation is used to determine flow pattern and origin of chemical histories of groundwater by plotting the major cations and anions on the Piper diagram [13]. The assessment of groundwater for irrigation purposes based on different irrigation indices is carried out which includes sodium adsorption ratio (SAR), residual sodium carbonate (RSC), %Na. permeability index (PI), potential salinity (PS), salinity hazard, magnesium ratio (MgR), Kelly's ratio (KR), and chloro-alkaline index [14].

Wilcox diagram Wilcox [15] and Doneen permeability index [16, 17] have also been utilized for classification of groundwater for irrigation.

5. Analyses and evaluation of pumping test data

A pumping test is a tool to determine the hydraulic characteristics of water-bearing formations such as transmissivity, storage coefficient, and any relevant hydrogeological properties. Such a test is called an aquifer test.

Analytical methods were applied to determine the aquifer type and hydrogeological properties of the Kuwait Group aquifer of the study area. These methods are Theis type curve [18], Cooper and Jacob straight line method for confined aquifer [19], and Walton method for semi-confined aquifer [20]. In effect, the pumping test data analyses indicated that the Kuwait Group aquifer is confined to semi-confined aquifer as shown in **Figure 2** for the well AT-15 and **Figure 3** for the well AT-18. The aquifer transmissivity ranges between 62.03 and 320.51 m^2/day, where the estimated storage coefficient equals 7.5×10^{-4}. The flow net analysis shows that the groundwater flows from the southwest to the northeast. Recharge to the aquifer is primarily from subsurface flow from adjacent bed rocks and by leakage from the underlying Dammam Formation aquifer. The presence of an aquitard layer (i.e., sandy clay) that bounds the aquifer from the top acts as a semipermeable layer and can leak water into the aquifer in the direction of the hydraulic gradient.

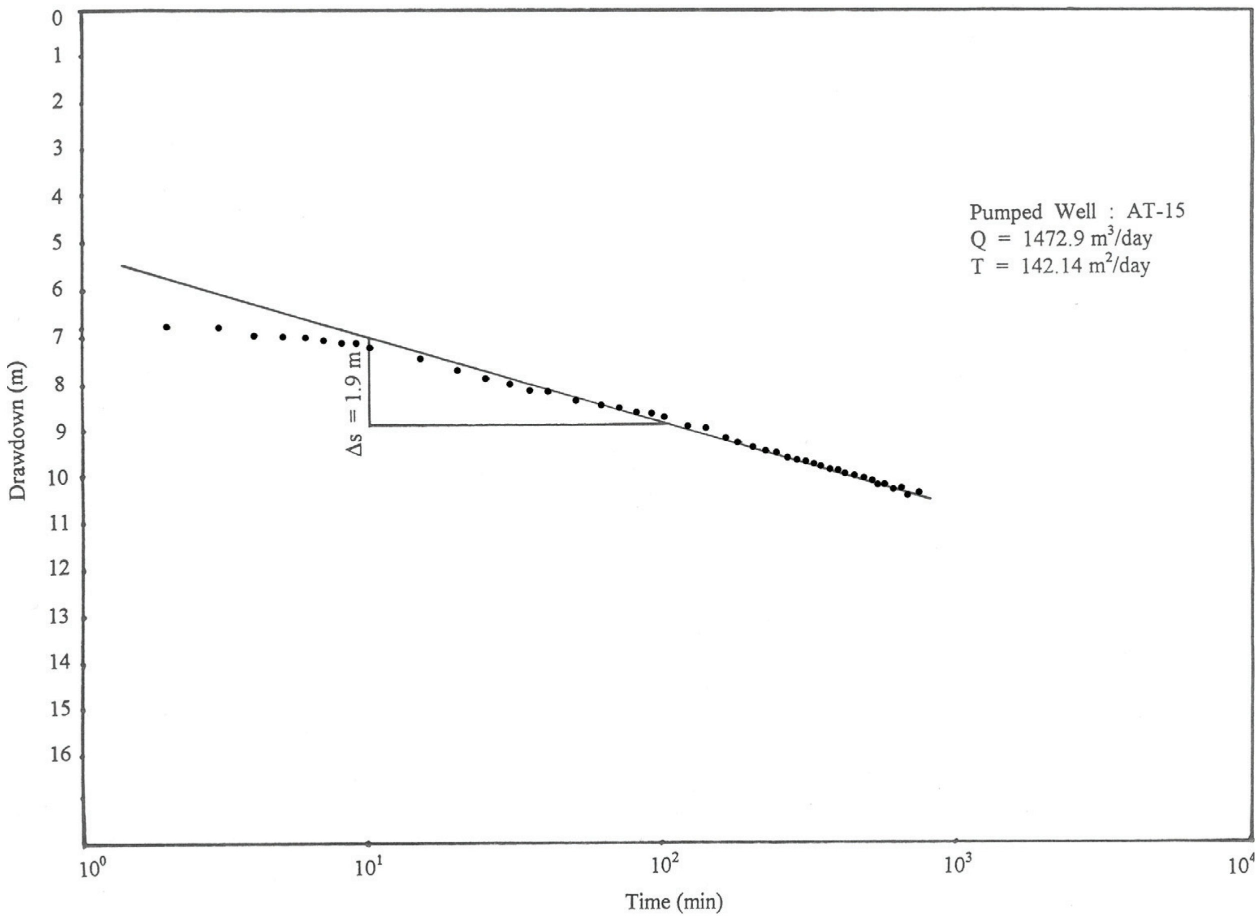

Figure 2. Time-drawdown curve of well no. AT-15, using Cooper and Jacob straight line method.

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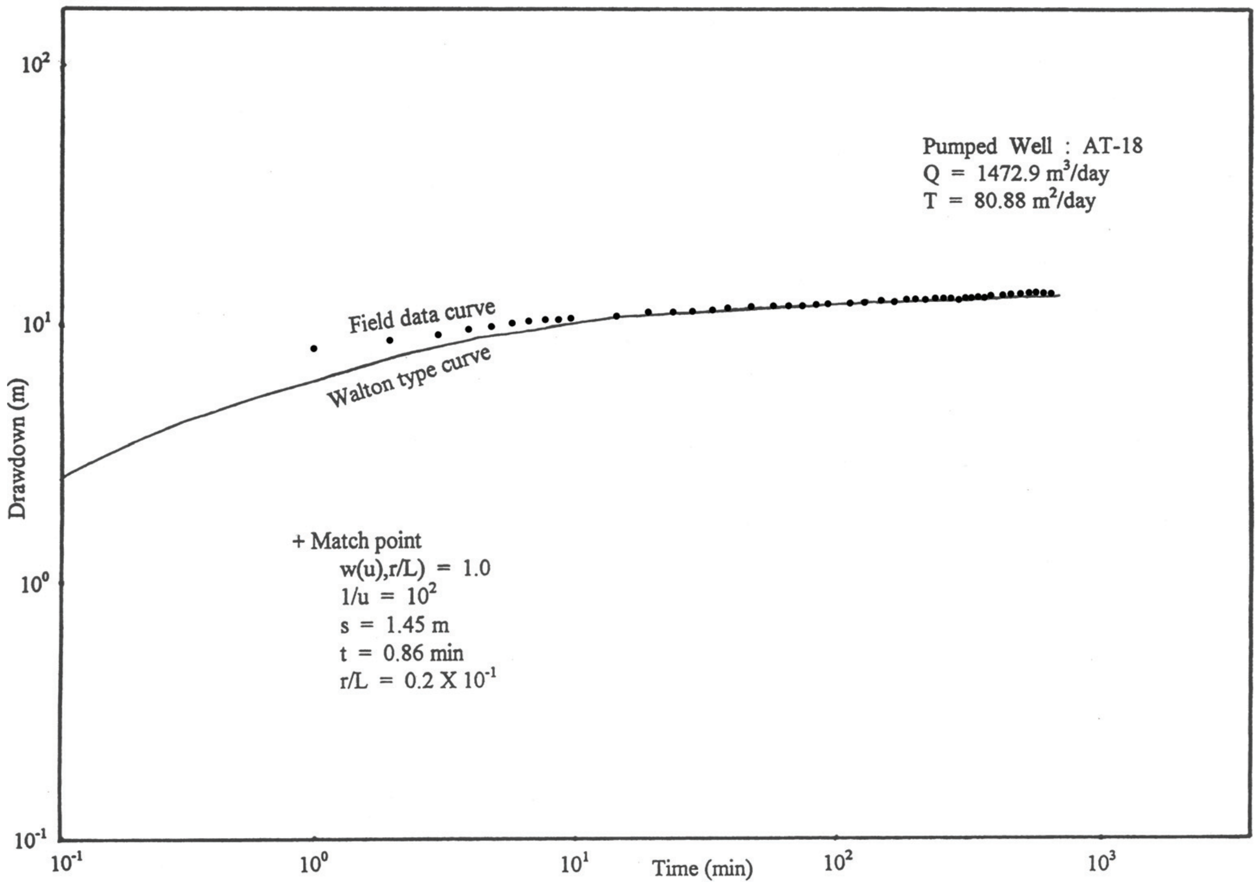

Figure 3. Time-drawdown curve of well no. AT-18, Walton method.

6. Mechanisms of controlling groundwater chemistry

It is important to study the relationship between the water chemistry and the aquifer lithology. Gibbs as mentioned in [12] suggested a diagram that represents the ratio of dominant anions and cations plotted against the value of TDS. These ratios can be divided into two formulas, the first ratio is for the cations $[(Na^+ + K^+)/(Na^+ + K^+ + Ca^{2+})]$ and the second ratio is for the anions $Cl^-/(Cl^- + HCO^-{}_3)$ as a function of TDS. This diagram is widely used to evaluate the functional sources of dissolved constituents such as precipitation dominance, rock dominance, and evaporation dominance. The chemical analyses of the study area are plotted in Gibb's diagram as shown in **Figure 4**, and they showed that the predominant samples fall into the category of rock-water interaction field and few samples are located in evaporation-dominance field and precipitation-dominance field, which revealed that the chemical weathering of rock-forming minerals is influencing the groundwater quality by dissolution of rock through which there is circulation, while the data in the evaporation-dominance field indicate that the increasing ions of Na^+ and Cl^- are in relation with the increasing of the TDS, as evaporation will increase the concentration of total dissolved in groundwater.

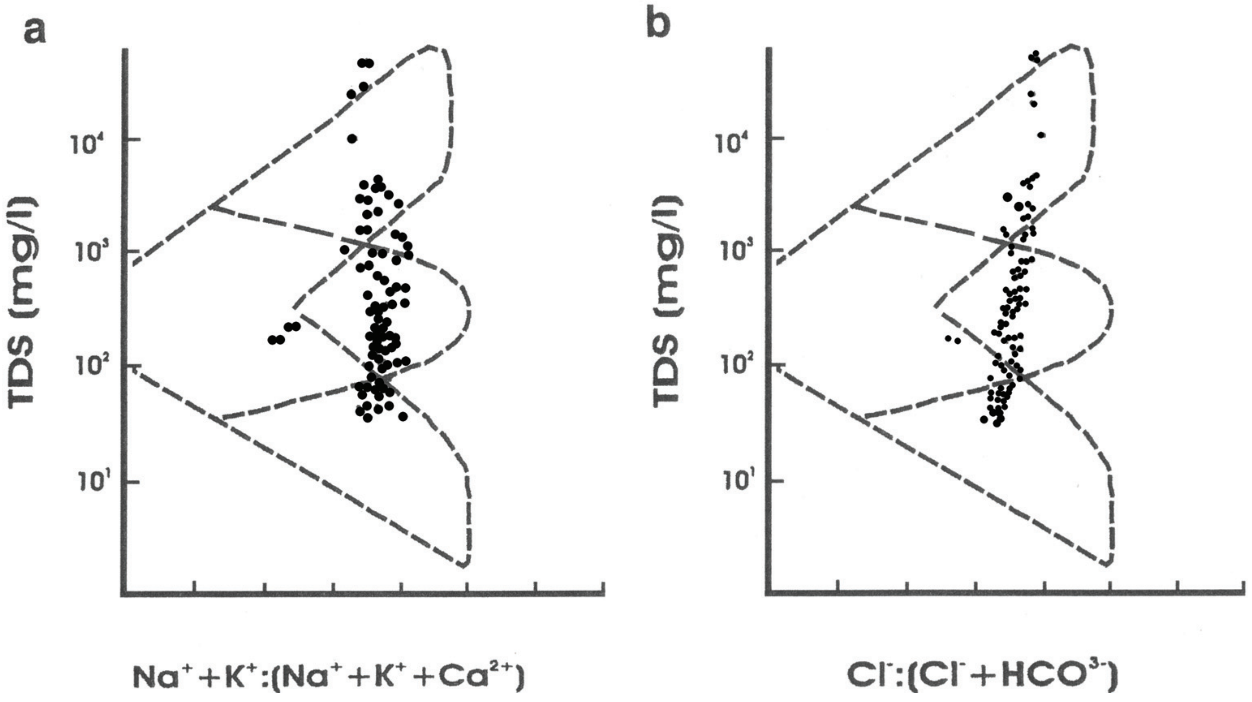

Figure 4. Gibbs plots represent groundwater chemistry and geochemical process in the study area.

6.1. Hydrochemical facies

Hydrochemical facies interpretation using Piper trilinear diagram is a useful tool for determining the flow pattern and origin of chemical histories of groundwater. The Piper trilinear diagram is presented in **Figure 5**. One principal hydrochemical water type has been delineated. The majority of the groundwater samples of the study area fall in $Ca^{2+} – Na^+ – Cl^-$ water type, where alkaline earth ($Ca^{2+} + Mg^{2+}$) exceeds the alkaline ($Na^+ + K^+$) and strong acid (Cl^- and SO_4^{2-}) exceeds the weak acid (HCO_3^- and CO_3^{2-}), and non-carbonate hardness exceeds 50%.

6.2. Saturation index

Geochemical models are tools used to calculate chemical reaction in groundwater system such as dissolution and precipitation of solids, ion exchange, and sorption by clay minerals. In this study, the speciation model has been applied to the groundwater samples of Al-Atraf field to determine the saturation index (SI) of minerals. The SI for a given mineral measures the degree of saturation of that mineral with respect to the surrounding system. The degree of saturation index is defined as follows [21]:

$$SI = \log \frac{K_{iap}}{K_{sp}}, \tag{1}$$

where "iap" is the ion activity product of the dissociated chemical species in solution and "K_{sp}" is the solubility product of the mineral. When SI is <0, it indicates that the groundwater is undersaturated with respect to that particular mineral. When SI > 0, it means that the

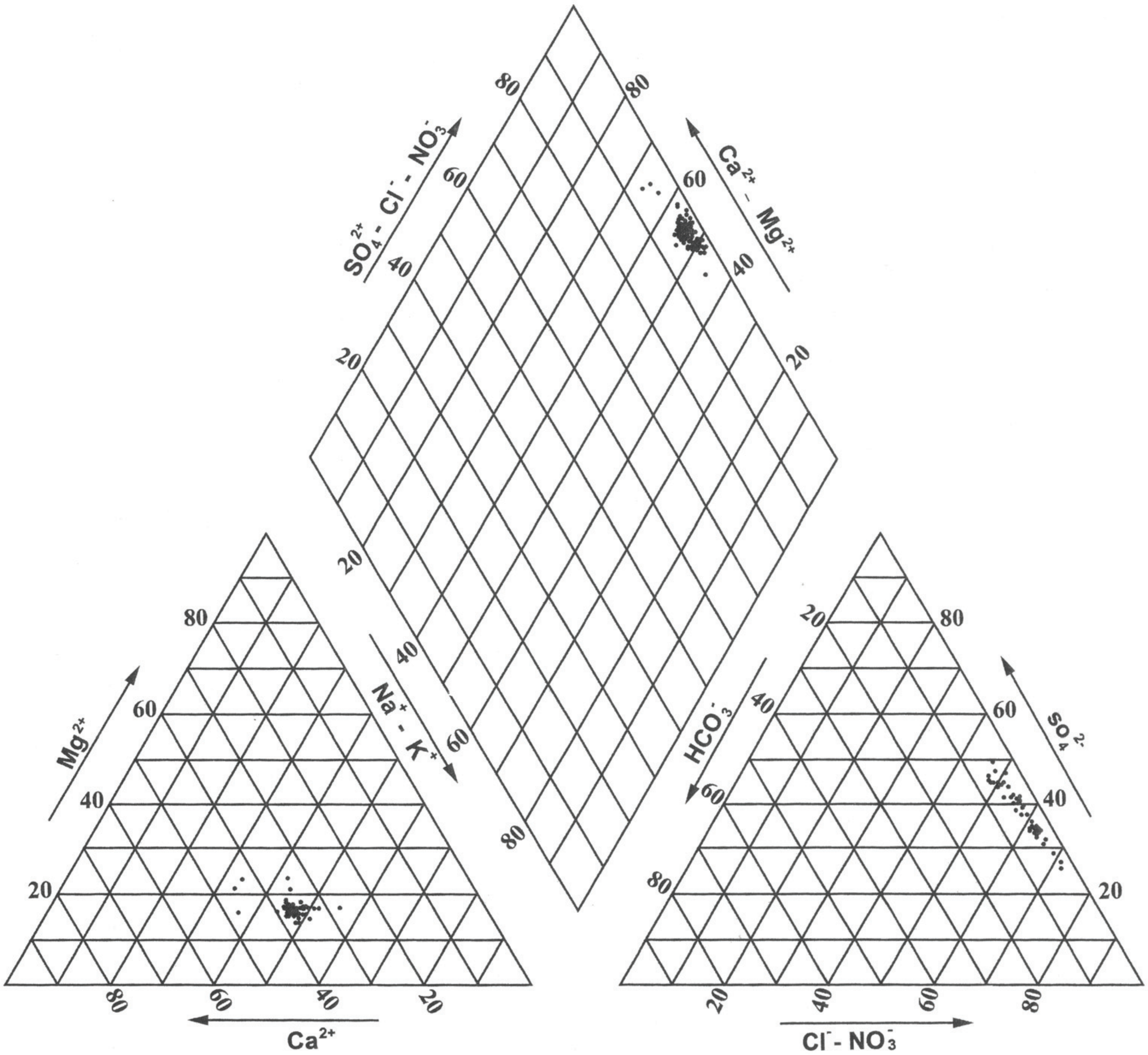

Figure 5. Piper trilinear diagram representing the chemical analysis of the study area.

groundwater is being saturated with respect to the mineral and incapable of dissolving more of the minerals. The oversaturation can also be produced by incongruent dissolution, common ion effect.

Table 1 shows the saturation indices of anhydrite, calcite, gypsum, dolomite, halite, and silica along with Pco_2. Nearly, all groundwater samples of the study area are undersaturated with respect to anhydrite, gypsum, halite, and silica and oversaturated with respect to calcite and dolomite.

The partial pressure of the carbon dioxide value (Pco_2) of the study area ranges between 1.32×10^{-3} and 8.23×10^{-3} atm., with an average value of 3.78×10^{-3} atm. This indicates that the groundwater of the Kuwait Group aquifer becomes charged with CO_2 during infiltration through the soil zones. According to Appelo et al. [22], when Pco_2 values range between $10^{-2.5}$

S.No.	PCO_2	Anhydrite	Cacite	Gypsum	Dolomite	Halite	Silica
	atm.	$CaSO_4$	$CaCO_3$	$CaSO_4.2H_2O$	$Ca\ Mg\ (CO_3)_2$	Na Cl	SiO2
1	2.13E-03	-0.13	0.40	-0.17	0.53	-4.38	-0.19
2	2.88E-03	-0.19	0.38	-0.23	0.49	-4.45	-0.16
3	2.56E-03	-0.19	0.42	-0.23	0.60	-4.47	-0.12
4	3.18E-03	-0.17	0.29	-0.21	0.34	-4.53	-0.19
5	3.97E-03	-0.15	0.26	-0.19	0.26	-4.40	-0.15
6	4.06E-03	-0.14	0.37	-0.18	0.50	-4.65	-0.33
7	3.05E-03	-0.16	0.47	-0.20	-0.27	-4.52	-0.14
8	3.48E-03	-0.17	0.33	-0.20	0.43	-4.50	-0.15
9	4.09E-03	-0.22	0.17	-0.26	0.10	-4.55	-0.24
10	5.47E-03	-0.23	0.22	-0.27	0.24	-4.74	-0.12
11	3.07E-03	-0.19	0.44	-0.23	0.62	-4.65	-0.15
12	8.12E-03	-0.30	-0.19	-0.34	-0.70	-4.68	-0.13
13	2.66E-03	-0.29	0.34	-0.33	0.37	-4.71	-0.23
14	3.69E-03	-0.24	0.40	-0.28	0.57	-4.91	-0.33
15	3.13E-03	-0.30	0.33	-0.34	0.28	-4.88	-0.33
16	2.43E-03	-0.33	0.25	-0.37	0.27	-4.80	-0.23
17	3.53E-03	-0.30	0.24	-0.34	0.26	-4.72	-0.27
18	5.36E-03	-0.32	0.15	-0.36	0.09	-4.79	-0.14
19	5.03E-03	-0.26	0.20	-0.30	0.17	-4.75	-0.18
20	1.32E-03	-0.22	0.80	-0.26	1.40	-4.81	-0.16
21	7.40E-03	-0.22	0.04	-0.26	-0.21	-4.86	-0.15
22	4.26E-03	-0.33	0.19	-0.37	0.11	-4.86	-0.23
23	4.47E-03	-0.30	0.20	-0.34	0.24	-4.82	-0.28
24	3.93E-03	-0.24	0.28	-0.28	0.24	-4.85	-0.18
25	8.23E-03	-0.02	0.25	-0.06	0.27	-5.27	-0.37
26	5.09E-03	-0.24	0.05	-0.28	-0.23	-4.62	-0.32
27	3.58E-03	-0.28	0.16	-0.32	0.04	-4.71	-0.25
28	4.91E-03	-0.28	0.15	-0.32	0.01	-4.86	-0.19
29	3.37E-03	-0.27	0.39	-0.31	0.52	-4.89	-0.22
30	2.23E-03	-0.41	0.11	-0.44	0.09	-4.69	-0.25
31	3.93E-03	-0.18	0.49	-0.22	0.75	-4.84	-0.31
32	3.18E-03	-0.18	0.27	-0.22	0.15	-5.09	-0.30
33	4.70E-03	-0.32	0.11	-0.36	-0.01	-4.81	-0.21
34	2.45E-03	-0.27	0.46	-0.31	0.62	-4.83	-0.29
35	3.60E-03	-0.24	0.24	-0.28	0.24	-4.71	-0.27
36	2.81E-03	-0.25	0.35	-0.29	0.60	-4.74	-0.28
37	4.07E-03	-0.28	0.24	-0.32	0.27	-4.83	-0.34
38	3.96E-03	-0.25	0.09	-0.29	0.05	-4.59	-0.34
39	3.05E-03	-0.21	0.22	-0.25	0.13	-4.56	-0.33
40	2.62E-03	-0.36	0.42	-0.40	0.65	-4.87	-0.31
41	3.00E-03	-0.19	0.22	-0.23	0.21	-4.53	-0.31
42	2.48E-03	-0.21	0.33	-0.24	0.37	-4.60	-0.32
43	3.73E-03	-0.27	0.25	-0.30	0.29	-4.69	-0.30
44	4.85E-03	-0.21	0.02	-0.25	-0.23	-4.48	-0.29
45	2.91E-03	-0.21	0.21	-0.25	0.16	-4.59	-0.30
46	1.60E-03	-0.19	0.39	-0.23	0.47	-4.53	-0.33
47	4.23E-03	-0.25	0.14	-0.29	0.05	-4.61	-0.32
Min.	**0.00132**	**-0.41**	**-0.19**	**-0.44**	**-0.70**	**-5.27**	**-0.37**
Max.	**0.00823**	**-0.02**	**0.80**	**-0.06**	**1.40**	**-4.38**	**-0.12**
Ave.	**0.00378**	**-0.24**	**0.27**	**-0.28**	**0.26**	**-4.71**	**-0.24**

Table 1. Results of thermodynamic speciation calculation of the study area.

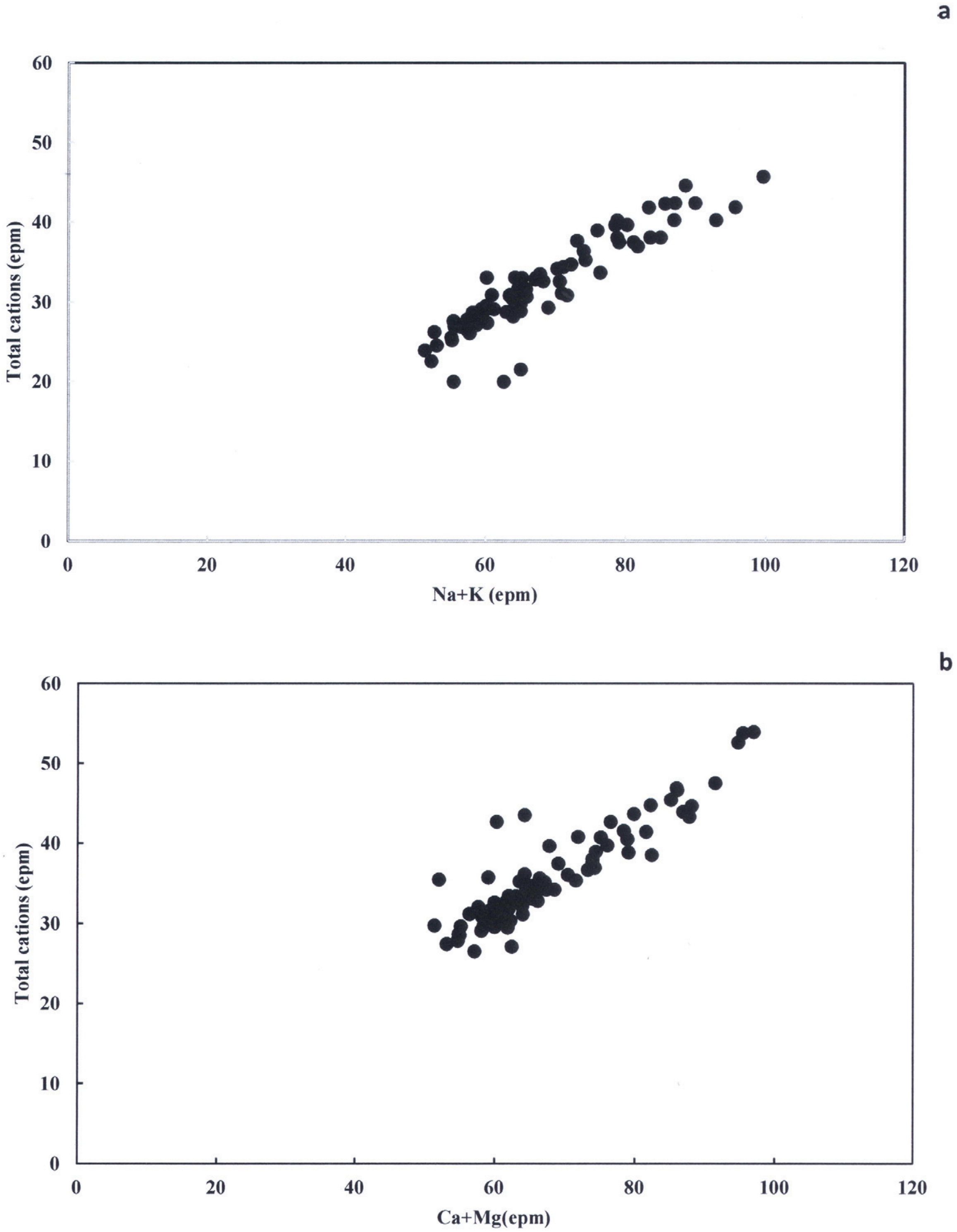

Figure 6. (a) Relation between total cations and (Na+K) in the study area. (b) Relation between total cations and (Ca+Mg) in the study area.

and $10^{-6.4}$ atm., it represents a closed system. Since the Kuwait Group aquifer is acting as a confined to semi-confined aquifer, it is more likely that the groundwater represents a deep, closed environment system. The mass-balance modeling as mentioned in Ref. [11] has been applied to specify the amounts of reacting minerals and to determine the possible source of the major ions in a specific groundwater system. This is in order to deduce groundwater source rock and to determine the nature and the extent of the geochemical reactions that occur in this system, that is, water-rock interaction. By the application of Hounslow concept, all groundwater samples of the study area showed that $Cl^- > Na^+$ indicating that the reverse ion exchange is likely to occur in aquifer. The ratio $Ca^{2+} / Ca^{2+} + SO_4^{2-}$ of most groundwater samples ranged between 0.41 and <0.5 indicating calcium removed by ion exchange or calcite precipitation, and few groundwater samples show a range value of 0.5–0.6, which is due to gypsum dissolution. According to reference [11], waters with $HCO_3^-/SiO_2 < 5$ indicated mainly silicate weathering. However, the ratio HCO_3^-/SiO_2 of the groundwater samples found to be ranged between 1.45 and 4.77 which indicate that silicate weathering is a dominant chemical process in the aquifer. Dissolved silica data show the influences of silicate weathering on water chemistry in the study area. Participation of silicate minerals in the chemical reactions plays a vital role in groundwater chemistry. Silicate weathering can be evaluated by estimating the ratio between $Na^+ + K^+$ and the total cation (e.p.m) as shown in **Figure 6a**. This reveals that the silicate weathering contributes mainly Na^+ and K^+ ions to groundwater [23]. Further, the plot of $Ca^{2+} + Mg^{2+}$ versus total cations of the groundwater samples as in **Figure 6b** has a linear spread, indicating that some of these ions ($Ca^{2+} + Mg^{2+}$) are resulted from the weathering of silicate minerals. In addition, all the groundwater samples exhibited an oversaturation with respect to calcite, which suggest the prevailing of calcite precipitation process in the aquifer.

7. Geochemical evolution of groundwater

The initial composition of groundwater originates from rainfall with low concentrations of dissolved ions. During its return path to the ocean, the water composition is altered by rock weathering and evaporation causing more Ca^{2+}, Mg^{2+}, Na^+, SO_4^{2-}, HCO_3^-, Cl^-, and SiO_2 to be added. The concentration of these ions depends on the rock mineralogy that the water encounters and its rapidity along the flow path. The abundance of the major cations in Al-Atraf field is in the order of $Na^+ > Ca^{2+} > Mg^{2+} > K^+$. The sequence of the anions is in the order of $Cl^- > SO_4^{2-} > HCO_3^-$. The majority of the groundwater samples of the study area (75.36%) exhibited NaCl water chemical type, followed by (23.19%) of Na_2SO_4 and (1.45%) of $CaSO_4$ water chemical types. The average TDS of 4441 mg/l represents brackish groundwater as presented in **Table 2**. Calcium and magnesium present in the groundwater are mainly due to the dissolution of gypsum and anhydrite, the most rock-forming minerals of the Kuwait Group aquifer of the study area. Calcium ions are derived also from cation exchange process. The concentration of calcium ions in the study area ranges from 332 to 743 mg/l with an average value of 484.23 mg/l and magnesium ranges from 85 to 203 mg/l, with an average value of 140.87 mg/l. This indicates that the Ca^{2+} ion concentration in the study area is relatively higher than magnesium ion. Alkalinity is the quantitative capacity of an aqueous solution to neutralize an acid. The ideal range of the total alkalinity is from 80 to 140 mg/l. In natural environment, carbonate alkalinity tends to make up most of the total alkalinity due to the common occurrence and dissolution of carbonate rocks and the presence of carbon dioxide in the atmosphere. The total alkalinity of the study area ranges between 51.2 and 127 mg/l as $CaCO_3$ with an average value of 91.39 mg/l. **Figure 7a** represents $Ca^{2+} + Mg^{2+}$ versus alkalinity + SO_4^{2-} in e.p.m., suggesting that these ions have resulted from weathering of carbonate and sulfate

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S.No.	TDS	pH	Na	K	Ca	Mg	Cl	SO_4	HCO_3	SiO_2	T. Hardnes	T. Alkalinity	Water Chemical Types
1	5974	7.5	950	20	743	203	2346	1334	90.4	36.4	2690	74.10	NaCl
2	5412	7.45	913	19.5	638	180	2068	1247	106	39.2	2333	86.80	NaCl
3	5562	7.5	863	20	630	188	2065	1247	106	42.4	2346	87.00	NaCl
4	5138	7.4	838	19.5	600	180	1850	1363	103	36	2238	85.00	NaCl
5	6366	7.3	913	20.5	720	203	2346	1291	104	39.2	2832	85.20	NaCl
6	4872	7.4	763	18.5	570	173	1525	1508	130	26.4	2134	106.00	NaCl
7	5050	7.4	850	19	578	180	1840	1247	121	41	2183	98.80	NaCl
8	5338	7.4	863	20	600	188	1925	1392	113	40	2271	92.10	NaCl
9	5006	7.3	863	19	549	162	1683	1247	104	32.4	2037	85.30	NaCl
10	4416	7.3	695	17	458	150	1316	1334	136	43.2	1760	112.00	Na_2SO_4
11	5414	7.5	705	17.5	539	156	1640	1334	124	39.9	1987	102.00	NaCl
12	4146	7	750	15.5	458	113	1417	1073	100	42	1609	82.00	NaCl
13	4294	7.5	710	15.1	471	120	1380	1073	106	33.2	1670	86.90	NaCl
14	3753	7.5	600	15.2	408	128	1026	1394	144	26.8	1545	118.00	NaCl
15	3687	7.5	595	14	391	85	1099	1160	121	26.8	1326	99.30	NaCl
16	3860	7.5	660	14.7	408	128	1208	1073	109	33.4	1545	89.50	NaCl
17	4043	7.4	650	17.5	450	143	1495	1125	111	30.4	1711	90.70	NaCl
18	3983	7.3	650	16	383	126	1240	1189	131	41	1482	107.00	NaCl
19	4312	7.3	670	17.5	459	143	1343	1218	125	37.6	1734	102.00	NaCl
20	4181	7.9	675	15.5	459	150	1157	1378	137	39.4	1763	112.00	Na_2SO_4
21	4213	7.15	625	15	440	119	1114	1349	148	40	1588	121.00	Na_2SO_4
22	3784	7.35	610	13.8	408	113	1118	1044	117	33.2	1483	96.10	NaCl
23	4043	7.35	620	15.6	411	150	1230	1204	124	29.4	1643	102.00	NaCl
24	5624	7.2	963	15.5	645	135	2005	1450	62.5	26.8	2166	51.20	NaCl
25	4222	7.45	695	14.5	434	143	1255	1189	116	35.6	1671	95.00	NaCl
26	3883	7.4	590	16.5	451	111	1185	1225	122	37	1583	102.00	Na_2SO_4
27	3763	7.3	640	14	464	153	1193	1125	125	34.8	1787	103.00	NaCl
28	3960	7.3	700	16.5	443	128	1423	1044	94.8	27.6	1632	77.70	NaCl
29	6060	7.2	963	18.5	705	150	2300	1218	75.3	27.2	2378	61.70	NaCl
30	4550	7.2	775	17	512	128	1572	1175	101	27.2	1805	82.40	NaCl
31	4180	7.4	715	15.5	465	120	1424	1131	103	29.2	1655	84.50	NaCl
32	4257	7.35	690	14.3	458	129	1411	1131	100	31.6	1674	82.20	NaCl
33	4442	7.45	700	14.25	456	120	1361	957	103	34	1632	84.10	NaCl
34	3719	7.3	570	16	419	111	1208	1175	120	36.6	1503	98.40	NaCl
35	3575	7.4	540	16	367	111	923	1200	133	34.6	1373	109.00	NaCl
36	3686	7.5	630	14.5	424	122	1025	1218	132	34	1560	108.00	NaCl
37	4976	7.5	700	15.5	570	150	1691	1088	95.9	29	4040	78.60	NaCl
38	4711	7.5	750	17	332	128	1350	1102	87.1	32	1355	71.40	NaCl
39	4505	7.35	740	16.4	503	128	1482	1112	93	29	1782	76.20	Na_2SO_4
40	4261	7.5	655	14	482	147	1118	1450	156	27.6	1808	127.00	NaCl
41	4107	7.5	580	12.5	410	111	1171	1131	112	29.2	1480	91.70	NaCl
42	4357	7.4	450	16	525	113	900	1204	99.4	28.6	1776	81.50	$CaSO_4$
43	4582	7.4	780	30	515	143	1585	1102	88.7	28.8	1874	72.70	NaCl
44	3882	7.3	630	15.4	395	120	1226	1131	115	35	1480	94.20	NaCl
45	3590	7.3	555	15	374	120	997	1189	132	33.6	1427	108.00	Na_2SO_4
46	4070	7.6	670	14.5	425	114	1113	1204	122	29.2	1530	99.80	Na_2SO_4
47	3504	7.6	510	14	375	134	846	1218	137	29.6	1487	112.00	Na_2SO_4
48	4226	7.4	750	16.5	458	138	1316	1305	113	30.4	1711	92.20	Na_2SO_4
49	3618	7.5	615	15	435	120	999	1392	126	30	1580	103.00	Na_2SO_4
50	4092	7.5	665	14.5	473	195	1397	1276	113	29.4	1982	92.60	NaCl
51	3792	7.7	660	16	420	135	1138	1131	125	26.6	1604	103.00	NaCl
52	3784	7.4	650	16	399	128	1152	1276	126	26	1522	103.00	Na_2SO_4
53	3642	7.45	610	15.5	368	125	908	1305	130	25.6	1433	106.00	Na_2SO_4
54	4526	7.3	855	18	473	143	1539	1276	99	26	1769	81.20	NaCl
55	4030	7.4	750	17	413	128	1284	1247	113	26.4	1557	92.40	NaCl
56	4588	7.4	885	18	518	135	1614	1305	97	26.4	1849	79.40	NaCl
57	4180	7.4	745	17	450	143	1241	1363	114	30	1711	94.00	Na_2SO_4
58	3552	7.6	625	16	360	120	1053	1102	129	28	1329	106.00	Na_2SO_4
59	5163	7.4	950	19	570	158	1923	1247	86	30.4	2073	70.00	NaCl
60	4909	7.4	900	19	540	165	1714	1392	96.1	27.2	2500	79.00	NaCl
61	5188	7.4	900	18	518	158	1670	1450	109	28	1943	89.30	NaCl
62	4584	7.5	825	18	518	143	1579	1334	100	27.2	1881	82.00	NaCl
63	5394	7.1	1013	20	608	165	1943	1479	78.2	26	2197	64.10	NaCl
64	4303	7.4	715	18	450	143	1442	1247	117	28	1711	96.10	NaCl
65	3988	7.4	700	17	390	128	1215	1160	108	30	1500	88.70	NaCl
66	5260	7.2	913	19	525	150	1881	1334	97	29	1928	79.40	NaCl
67	4785	7.4	800	18	533	150	1643	1276	93	28.4	1948	76.20	NaCl
68	4964	7.6	850	20	585	150	1790	1276	83	26.4	2078	68.00	NaCl
69	4546	7.3	780	18	488	150	1617	1247	106	27.2	1835	87.00	NaCl
Min.	**3504.00**	**7.00**	**450.00**	**12.50**	**332.00**	**85.00**	**846.00**	**957.00**	**62.50**	**25.60**	**1326.00**	**51.20**	
Max.	**6366.00**	**7.90**	**1013.00**	**30.00**	**743.00**	**203.00**	**2346.00**	**1508.00**	**156.00**	**43.20**	**4040.00**	**127.00**	
Ave.	**4440.97**	**7.40**	**730.12**	**16.85**	**484.23**	**140.87**	**1438.45**	**1237.87**	**111.51**	**31.73**	**1826.22**	**91.39**	

Table 2. Report of physico-chemical parameters of the studied groundwater samples of the study area.

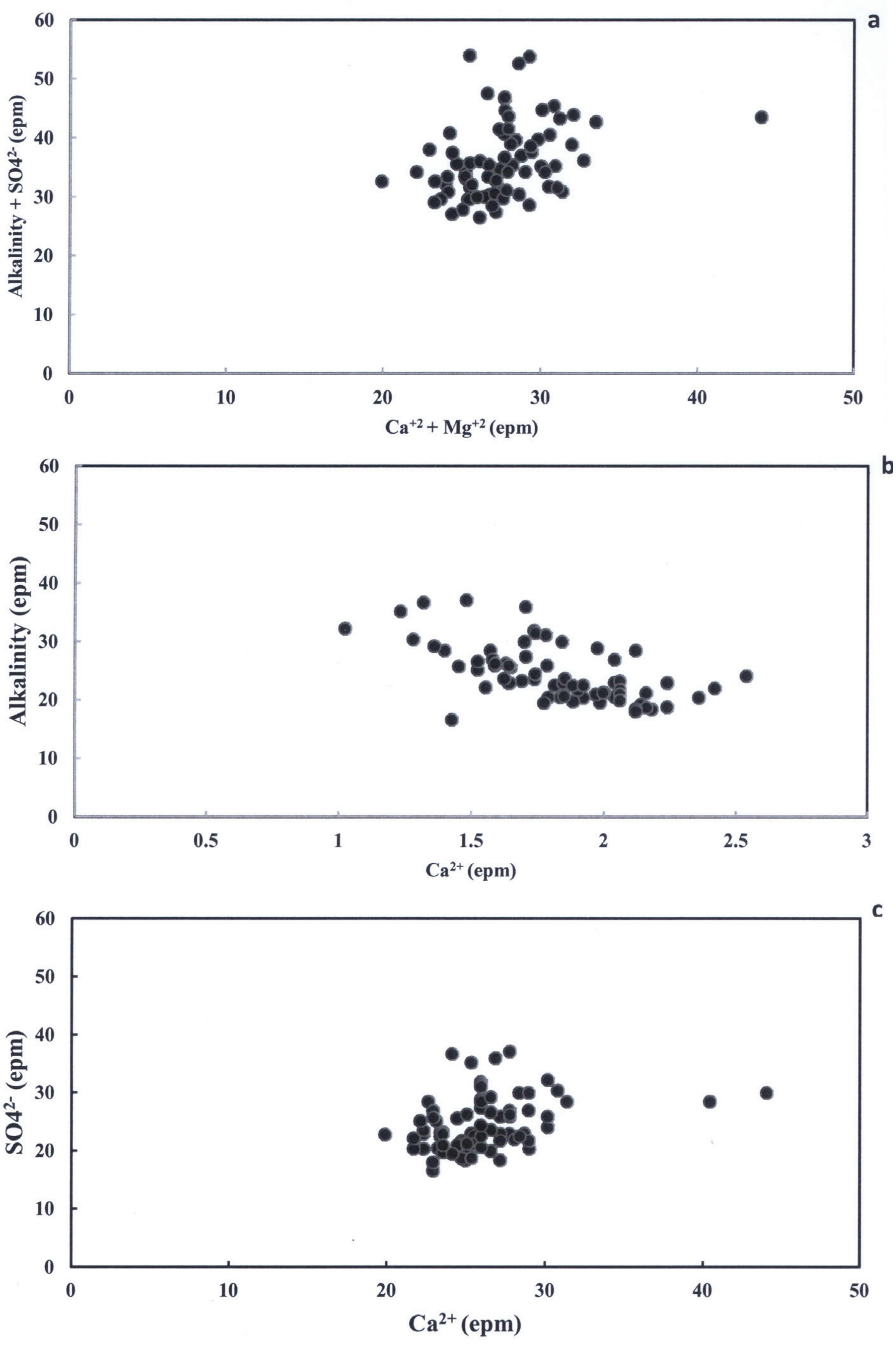

Figure 7. (a) Relation between Ca+Mg and alkalinity + SO_4. (b) Relation between Ca^{2+} and alkalinity. (c) Relation between Ca^{2+} and $SO^{2-}{}_4$.

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S.No.	EC	SAR	% Na	RSC	Kelly's ratio	MgR	CAI	P.I %	P.S.
1	7720	7.97	43.22	-52.29	0.77	31.05	0.37	44.73	80.07
2	8230	8.69	45.32	-52.63	0.84	32.02	0.36	46.72	83.56
3	7380	8.22	45.73	-44.91	0.85	31.74	0.31	47.52	71.32
4	7280	7.75	44.19	-45.16	0.80	32.97	0.35	46.02	71.23
5	6750	7.71	44.62	-43.06	0.81	33.09	0.29	46.49	66.38
6	7140	8.86	48.14	-42.89	0.94	30.39	0.30	49.94	73.35
7	7670	7.74	42.77	-50.92	0.75	31.73	0.39	44.42	79.62
8	6330	7.19	43.48	-40.54	0.78	33.35	0.22	45.67	58.72
9	6560	7.91	45.59	-41.67	0.85	33.92	0.28	47.61	64.89
10	7050	7.88	44.98	-43.55	0.83	34.06	0.30	46.90	68.79
11	6250	8.32	47.67	-39.02	0.92	32.73	0.20	49.64	60.46
12	5600	7.21	45.90	-32.96	0.86	35.06	0.17	48.49	51.01
13	6670	6.88	43.29	-37.70	0.77	32.30	0.33	45.59	60.15
14	5650	8.14	50.06	-30.51	1.01	28.91	0.17	52.34	51.14
15	5590	7.56	47.78	-31.64	0.93	29.58	0.20	50.11	50.10
16	5100	6.64	45.49	-28.53	0.84	34.09	0.08	48.49	43.46
17	5070	7.11	49.07	-24.52	0.98	26.38	0.15	52.10	43.08
18	5510	7.31	47.87	-29.10	0.93	34.09	0.15	50.42	45.25
19	5500	6.84	44.92	-32.40	0.83	34.38	0.32	47.40	53.89
20	5110	7.37	48.62	-27.33	0.96	35.16	0.18	51.50	47.36
21	5620	7.00	45.35	-32.62	0.84	33.93	0.22	47.92	50.57
22	5310	6.99	45.17	-33.00	0.83	35.01	0.09	47.77	46.98
23	5110	6.82	45.84	-29.32	0.86	30.84	0.12	48.78	45.47
24	4500	6.89	46.93	-27.74	0.89	31.35	0.15	49.69	42.41
25	5570	6.65	44.79	-30.82	0.82	37.56	0.21	47.47	47.23
26	7550	9.00	48.95	-42.27	0.97	25.65	0.25	50.37	71.66
27	5260	7.40	47.22	-31.52	0.90	35.20	0.14	49.66	47.78
28	5240	6.45	44.46	-29.64	0.81	28.86	0.22	47.26	46.18
29	4970	6.59	43.54	-33.69	0.78	35.22	0.16	46.04	45.37
30	5280	7.54	47.95	-31.08	0.93	32.26	0.23	50.24	51.01
31	7350	8.59	46.61	-46.28	0.88	25.97	0.35	48.10	77.56
32	5510	7.94	48.01	-34.42	0.93	29.18	0.23	50.15	56.58
33	5040	7.65	48.17	-31.39	0.94	29.85	0.22	50.49	51.94
34	6100	7.34	47.01	-31.83	0.90	31.71	0.24	49.30	51.58
35	5210	7.54	48.00	-30.94	0.93	30.26	0.20	50.34	48.36
36	4820	6.40	44.88	-28.07	0.83	30.40	0.26	47.78	46.31
37	4560	6.34	45.75	-25.26	0.86	33.27	0.08	49.02	38.53
38	4370	6.94	46.47	-29.03	0.88	32.17	0.04	49.28	41.59
39	6410	6.74	42.51	-39.21	0.75	30.26	0.35	44.51	59.03
40	6120	8.86	54.23	-25.67	1.20	38.86	0.13	56.63	49.56
41	5830	7.63	47.17	-34.10	0.90	29.55	0.22	49.29	53.38
42	5560	6.70	43.84	-33.59	0.79	33.46	0.09	46.55	46.63
43	5020	6.56	45.76	-27.75	0.85	30.86	0.23	48.49	44.81
44	5800	4.65	35.28	-33.86	0.55	26.19	0.21	37.86	37.92
45	6150	7.84	47.02	-36.01	0.91	31.40	0.22	49.22	56.18
46	4950	7.13	47.76	-27.70	0.93	33.37	0.20	50.50	46.36
47	4630	6.39	45.50	-26.37	0.85	34.59	0.13	48.62	40.50
48	5020	7.45	48.49	-28.59	0.95	30.66	0.06	51.16	43.93
49	4520	5.75	42.44	-27.49	0.75	37.07	0.06	45.62	36.55
50	5700	7.89	48.51	-32.35	0.95	33.19	0.11	50.85	50.71
51	4850	6.73	45.56	-29.51	0.85	31.26	0.04	48.33	42.67
52	5730	6.50	41.96	-37.79	0.73	40.46	0.26	44.17	52.69
53	4540	7.17	46.93	-30.01	0.90	34.64	0.09	49.60	43.88
54	4980	7.25	47.82	-28.37	0.93	34.59	0.12	50.60	45.78
55	4500	7.01	47.74	-26.52	0.93	35.90	-0.05	50.73	39.20
56	5810	8.84	50.94	-33.74	1.05	33.26	0.13	53.01	56.70
57	5390	8.27	50.82	-29.29	1.05	33.81	0.09	53.30	49.20
58	6030	8.96	50.71	-35.36	1.04	30.05	0.14	52.69	59.12
59	5680	7.83	48.33	-32.35	0.95	34.38	0.06	50.69	49.20
60	4620	7.29	49.05	-25.72	0.98	35.46	0.07	52.05	41.18
61	6910	9.08	49.64	-40.03	1.00	31.36	0.23	51.36	67.23
62	6760	8.70	48.84	-38.94	0.97	33.50	0.18	50.72	62.84
63	6690	8.88	49.90	-37.06	1.01	33.46	0.16	51.91	62.21
64	6020	8.28	48.52	-35.97	0.95	31.28	0.18	50.57	58.43
65	7400	9.40	49.80	-42.63	1.00	30.91	0.19	51.37	70.21
66	5670	7.52	47.28	-32.30	0.91	34.38	0.22	49.74	53.66
67	5320	7.86	50.02	-28.22	1.02	35.11	0.10	52.58	46.35
68	7080	9.05	50.44	-36.95	1.03	32.02	0.24	52.36	66.95
69	6250	7.89	46.90	-37.41	0.89	31.69	0.24	48.87	59.63
70	6910	8.11	46.79	-40.17	0.89	29.71	0.26	48.58	63.78
71	6030	7.92	47.73	-34.95	0.92	33.63	0.25	49.91	58.60
Min.	**4370**	**4.65**	**35.28**	**-52.63**	**0.55**	**25.65**	**-0.05**	**37.86**	**36.55**
Max.	**8230**	**9.40**	**54.23**	**-24.52**	**1.20**	**40.46**	**0.39**	**56.63**	**83.56**
Ave.	**5837**	**7.54**	**46.73**	**-34.31**	**0.89**	**32.48**	**0.19**	**49.07**	**54.17**

Table 3. Irrigation water quality parameters for groundwater samples of the study area.

minerals (gypsum and anhydrite). However, most of the points are placed in Ca^{2+} + Mg^{2+} side, which indicates excess calcium and magnesium derived from other processes such as reverse ion exchange reactions. In Ca^{2+} versus alkalinity diagram, **Figure 7b** indicates the contribution of both calcite and dolomite weathering on groundwater chemistry of the study area. Moreover, in Ca^{2+} versus $SO_4{}^{2-}$ diagram (**Figure 7c**), most of the sample show excess calcium over sulfate, which reveal that the groundwater samples seem to be derived from gypsum or anhydrite dissolution. Moreover, excess sulfate over calcium in few samples expresses the removal of calcium from the system likely by calcite precipitation. Therefore, silicate weathering and carbonate dissolution are the prevailing geochemical processes in the aquifer of the study area.

7.1. Ion exchange

Ion exchange is one of the important processes responsible for the concentration of ions in groundwater.

$$\mathrm{CAI}-1=\frac{\mathrm{Cl}^{-}-(\mathrm{Na}^{+}+\mathrm{K}^{+})}{\mathrm{Cl}^{-}} \tag{2}$$

Where all values are expressed in meq/l. When there is an exchange between Ca^{2+} or Mg^{2+} in groundwater with Na^{+} and K^{+} in the aquifer material, the CAI-1 is negative, and if there is a reverse ion exchange, CAI-1 will be positive [24]. The values of CAI-1 of the study area are positive in most wells, and very few wells show negative, and the CAI-1 ranges from −0.05 to 0.39 with an average value of 0.19 as presented in **Table 3**. Thus, it reveals that reverse ion exchange is the dominant process in the groundwater, whereas normal ion exchange is also noticed in a very few wells.

8. Drinking and irrigation water quality

The assessment of suitability of the groundwater for drinking and irrigation purposes can be determined through the parameters such as EC, TDS, pH, SAR, %Na, RSC, Kelley's ratio, MgR, CAI-1, P.I, and P.S as displayed in **Table 3**.

8.1. Drinking water quality

The suitability of the groundwater in the study area is evaluated for drinking by comparing with the standard guideline values [25]. According to WHO specifications, TDS up to 500 mg/l is the highest desirable and up to 1500 mg/l is the maximum permissible level. Based on this classification, the TDS of the groundwater of the study area ranges between 3504 and 6366 mg/l with an average value of 4441 mg/l, which exceeds the recommended limit. However, the major cations and anions composition of the study area are all above the standard guideline of the WHO for drinking purposes. Water hardness causes more consumption of detergents at the time of cleaning, and some evidences indicate its role in heart disease [26]. The total hardness was determining by the following equation according to [27]:

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$$TH = 2.5\ Ca^{2+} + 4.1\ Mg^{2+}. \tag{3}$$

where Ca^{2+} and Mg^{2+} concentrations are expressed in mg/l as $CaCO_3$. Hardness of water is due to the precipitation of Ca^{2+} and Mg^{2+} salts like carbonate, sulfates, and chlorides. Hardness of water causes scaling of pots, boilers, and irrigation pipes. However, the total hardness of the study area is varying from 1326 to 4040 mg/l as $CaCO_3$, with an average value of 1826.22 mg/l as shown in **Table 2**. The analytical result of TH indicates that the groundwater of the study area is exceeding very hard water type according to [28] as shown in **Table 4**. Therefore, according to TDS and TH standards the groundwater is not suitable for drinking purposes.

8.2. Irrigational suitability

The suitability of groundwater for irrigation depends on the effect of mineral composition of water on the soil and plants. The effect of the salt on soils causes change in soil structure, permeability, and hence it effects on plant growth.

8.2.1. Residual sodium carbonate

Residual sodium carbonate has been calculated to determine the hazard effects of carbonate and bicarbonate on the quality of water for irrigation and is expressed by the equation:

$$RSC = \left(HCO_3^- + CO_3{}^{2-}\right) – \left(Ca^{2+} + Mg^{2+}\right) \tag{4}$$

Where all ionic concentrations are expressed in meq/l. The classification of irrigation water according to the RSC presents in **Table 5** after [29], where water containing more than 2.5 meq/l of RSC are not suitable for irrigation, while those having <1.25 meq/l are good for irrigation. Eaton (1950) indicated that if waters which are used for irrigation contain excess of $HCO_3{}^- + CO_3{}^{2-}$ than its equivalent $Ca^{2+} + Mg^{2+}$, there will be a residue of $Na^+ + HCO_3{}^-$ when evaporation takes place and the pH of the soil increases up to 3 [30]. When total carbonate levels exceed the total amount of calcium and magnesium, the water quality diminished [31]. The calculated RSC values of the groundwater samples of the study area are ranged from −52.63 to

Total Hardness as $CaCO_3$ (mg/l)	Water Class
< 75	Soft
75-150	Moderately hard
150-300	Hard
>300	Very hard

Table 4. Water classes (After [28]).

RSC value	Water quality
<1.25	suitable
1.25-2.5	marginal
>2.5	Not suitable

Table 5. Water classes based on RSC (after [29]).

−24.52 meq/l with an average value of −34.31 meq/l. Negative RSC indicates that sodium buildup is unlikely, since sufficient calcium and magnesium are in excess of what can be precipitated as carbonates [32]. Hence, the groundwater of the study area is safe for irrigation.

8.2.2. Permeability index

The permeability of soil is affected by long-term use of irrigation water and is influenced by sodium, calcium, magnesium, and bicarbonate contents in soil. Doneen (1964) set a criteria for assessing the suitability of water for irrigation based on permeability index; accordingly, waters can be classified as Class I, Class II, and Class III. The Class I and Class II waters are suitable for irrigation with 50–75% or more of maximum permeability, whereas Class III water is unsuitable with 25% of maximum permeability. Therefore, soil permeability is affected by consistent use of irrigation water which increases the presence of sodium, calcium, magnesium, and bicarbonate in the soil [33].

The permeability index is used to measure the suitability of water for irrigation purpose when compared with the total ions in meq/l, and it is expressed as follows:

$$PI = \frac{Na^{+} + \sqrt{HCO_3^{-}}}{Ca^{2+} + Mg^{2+} + Na^{+}} * 100 \tag{5}$$

In the present study, the P.I of the groundwater samples ranged from 37.86 to 56.63% with a mean value of 49.1%, and it is observed that all the groundwater samples fall in Class II category of Doneen Chart (**Figure 8**). Therefore, the groundwater of the study area is good for use in irrigation.

8.2.3. Potential salinity

Doneen as in Ref. [17] introduced an important parameter "Potential Salinity" for assessing the suitability of water for irrigation uses, which defined as chloride concentration plus half of the sulfate concentration expressed in meq/l.

Potential salinity = Cl^{-} + ½ SO_4^{2-}. On the basis of the potential salinity, Doneen [17] subdivided the irrigation water into three classes as presented in **Table 6**. The potential salinity of the majority of the analyzed groundwater samples of the study area ranges between 36.55 and 83.56 meq/l with an average value of 54.17 meq/l, indicating high values of potential

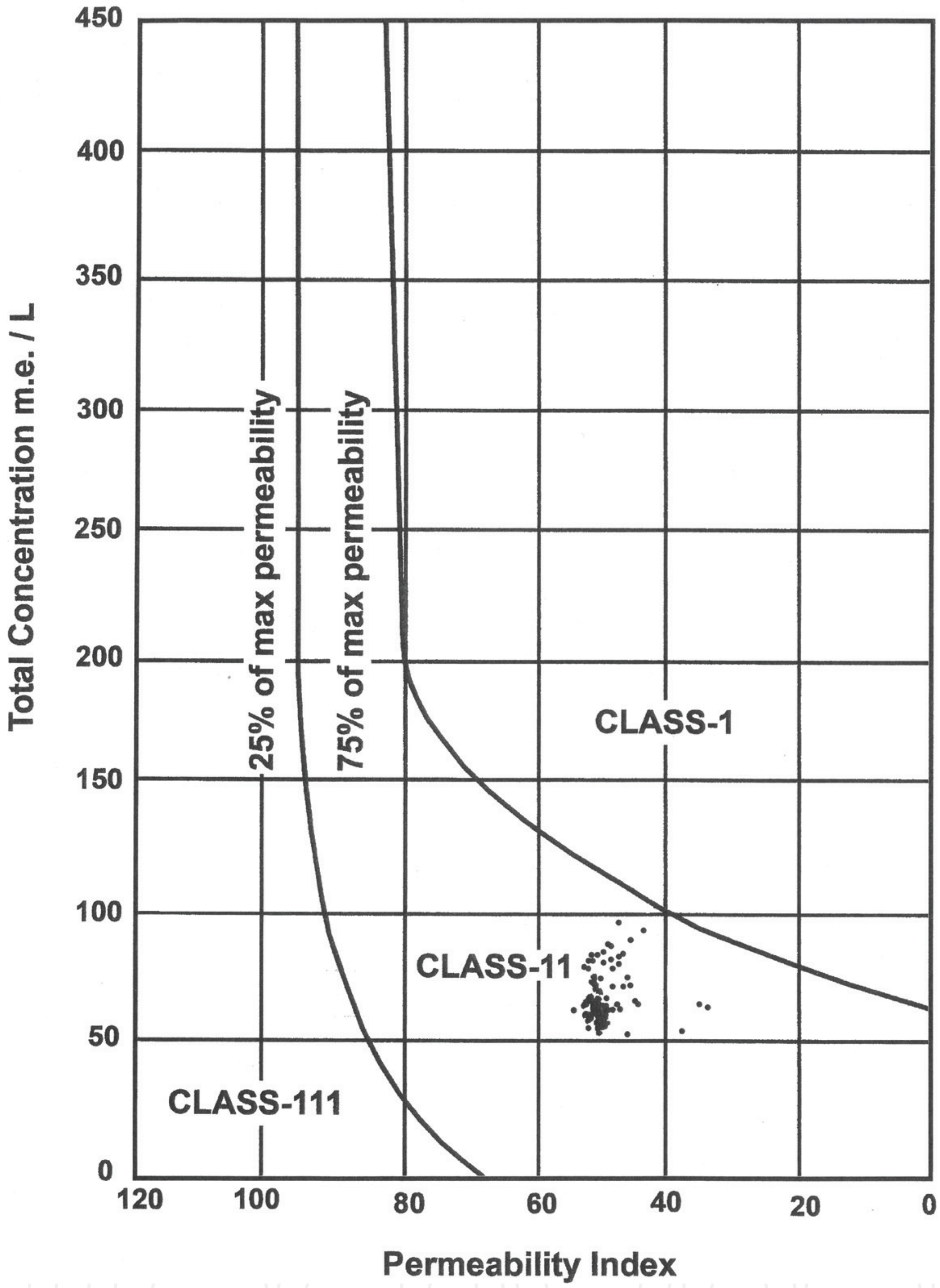

Figure 8. Permeability index diagram of the study area.

Soil Characteristics	Class of Water		
	Class 1	Class 11	Class 111
Soil of low Permeability	<3	3-5	>5
Soil of medium Permeability	<5	5-10	>10
Soil of high Permeability	<7	7-15	>15

Table 6. Classification of irrigation water based on potential salinity.

salinity. However, it is found that the classification of the groundwater of the study area for irrigation purposes fall in Class III; therefore, the groundwater should be used in case of a soil of high permeability.

8.2.4. Sodium adsorption ratio

Sodium concentration is considered an important factor to express reaction with the soil and reduction in its permeability. Therefore, sodium adsorption ratio is considered as a better measure of sodium (alkali) hazard in irrigation water as it is directly related to the adsorption of Na^+ on soil and is the important criteria for estimating the suitability of the water for irrigation. SAR can be computed as follows:

$$\mathrm{SAR} = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+}+Mg^{2+}}{2}}} \tag{6}$$

Where all ionic concentrations are expressed in meq/l. The SAR of the study area ranges between 4.65 and 9.4, with an average value of 7.54. The SAR values of all the study area are found to be <10 and are classified as categories S_1 and S_2, as low and medium sodium water, respectively. Therefore, based on the sodium hazard class the groundwater of the study area is suitable for irrigation.

8.2.5. Salinity hazard

The most important criteria regarding salinity and water availability to the plant is the total salt concentration. Since there exists a straight line correlation between electrical conductivity (EC) and total salt concentration of waters, the most expedient procedure to evaluate salinity hazard is to measure its electrical conductivity measured in (μmohs/cm) [34]. On the basis of salt concentration, the US Salinity Laboratory Staff divided the irrigation waters into four classes. Later on, another class was added to it [35] as given in **Table 7**. Waters having EC values above 1500 μmohs/cm can cause serious damage.

For rating irrigation waters, the US salinity diagram was used, in which the SAR is plotted against EC as shown in **Figure 9**, where the EC values of samples of the study area range from 4370 to 8230 with an average value of 5837 μmohs/cm and water exhibited very high to extensively high water salinity and medium sodium, high sodium type (C_4-S_2, C_4-S_3). Few samples are located on C_4-S_4 type. Therefore, the groundwater can be used with tolerant crops of clayey, sandy loam, and loamy sand soil texture, and special management for salinity control.

8.2.6. Magnesium ratio

In most waters, calcium and magnesium maintain a state of equilibrium. A ratio namely index of magnesium hazard was developed by [36]. According to this, a high magnesium hazard value of >50% has an adverse effect on the crop yield as the soil becomes more alkaline, and effect on the agricultural yield, and a harmful effect on soil will appear.

$$\text{Mg ratio} = \frac{Mg^{2+}}{(Ca^{2+} + Mg^{2+})} \times 100 \quad (7)$$

Where all ionic concentrations are expressed in meq/l.

In the study area, the magnesium hazard values fall in the range value of 25.65–40.46% with an average value of 32.48%, that is, magnesium hazard ratio is <50%, which is recognized as suitable for irrigation.

8.2.7. Sodium percentage (%Na)

Sodium is an important ion used for the classification of irrigation water due to its reaction with soil, reduces its permeability. The %Na is computed as:

$$\%\text{Na}^+ = \left(\frac{(Na + K)^+}{Ca^{2+} + Mg^{2+} + K^+ + Na^+} \right) \times 100 \quad (8)$$

Where all ionic concentrations are expressed in meq/l. According to [15], in all natural waters, $\%Na^+$ is a common parameter to assess its suitability for irrigation purpose as shown in **Table 8**. If the concentration of Na^+ is high in irrigation water, Na^+ gets absorbed by clay particles, displacing Mg^{2+} and Ca^{2+} ions. This exchange process of Na^+ in water for Ca^{2+} and Mg^{2+} in soil reduces the permeability of soil and eventually results in poor internal drainage of

EC (µmohs/cm)	Water Salinity
00 - 250	Low (Excellent quality)
251 -750	Medium (Good quality)
751 - 2250	High (Permissible quality)
2251 - 6000	Very high
6001 - 10000	Extensively high
10001 - 20000	Brines weakly conc.
20001 - 50000	Brines moderately conc.
50001 - 100000	Brines highly conc.
> 100000	Brines extremely conc.

Table 7. Classification of waters based on EC [35].

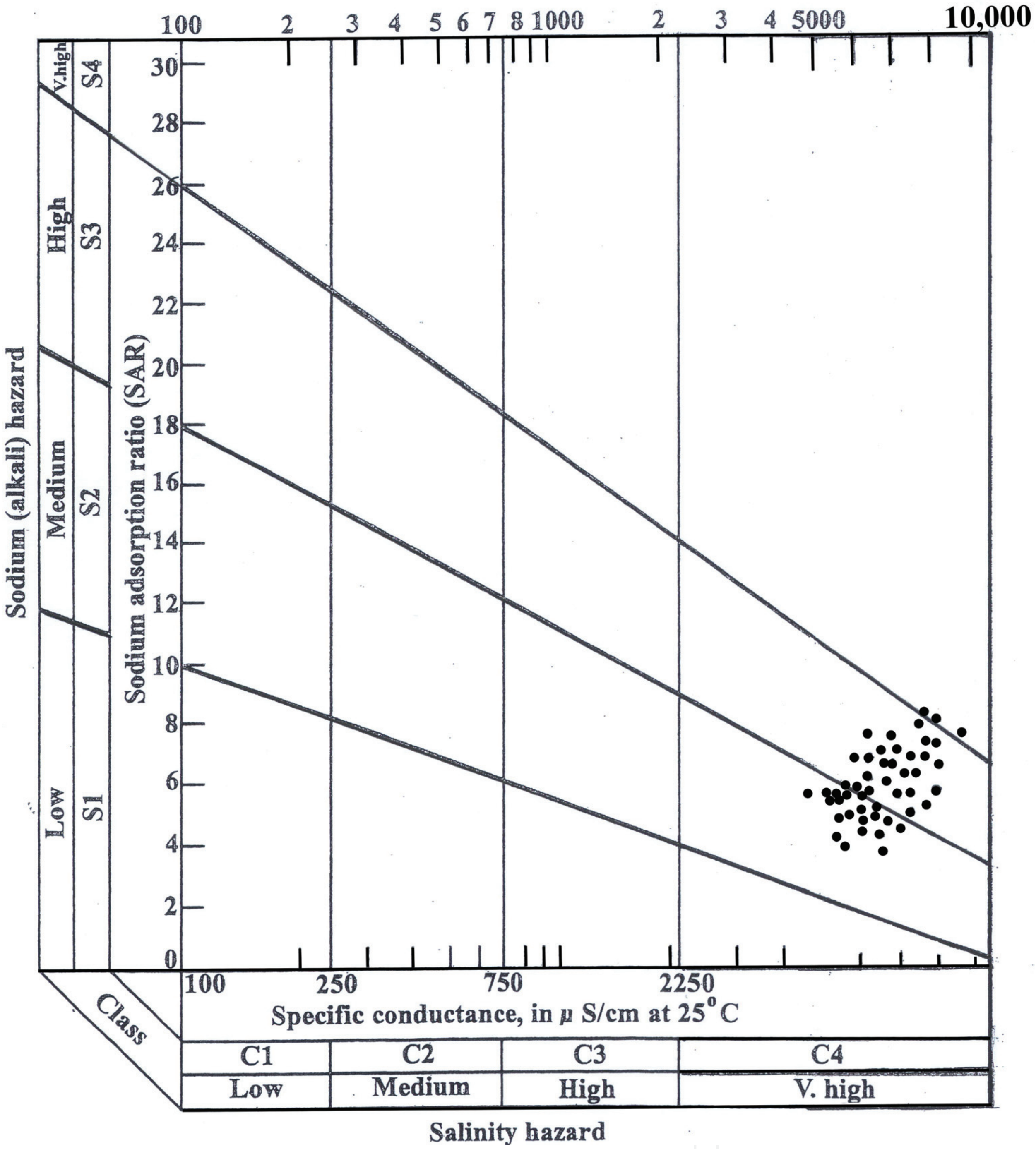

Figure 9. Wilcox diagram illustrating the groundwater quality of the study area.

the soil, and such soils are usually hard when dry [37]. The values of %Na^+ of the study area varies from 35.28 to 54.23% with an average value of 46.73% which fall in good to permissible category, showing that the groundwater of the study area is suitable for irrigation; meanwhile, the EC ranges between 4370 and 8230 μmohs/cm, in which the groundwater salinity is classified as very extensively high as presented in **Figure 10**; therefore, the groundwater can be used for irrigation under specific conditions.

Water Quality	Sodium %
Excellent	< 20
Good	20 – 40
Permissible	40 – 60
Doubtful	60 – 80
Unsuitable	> 80

Table 8. Classification of groundwater based on %Na [15].

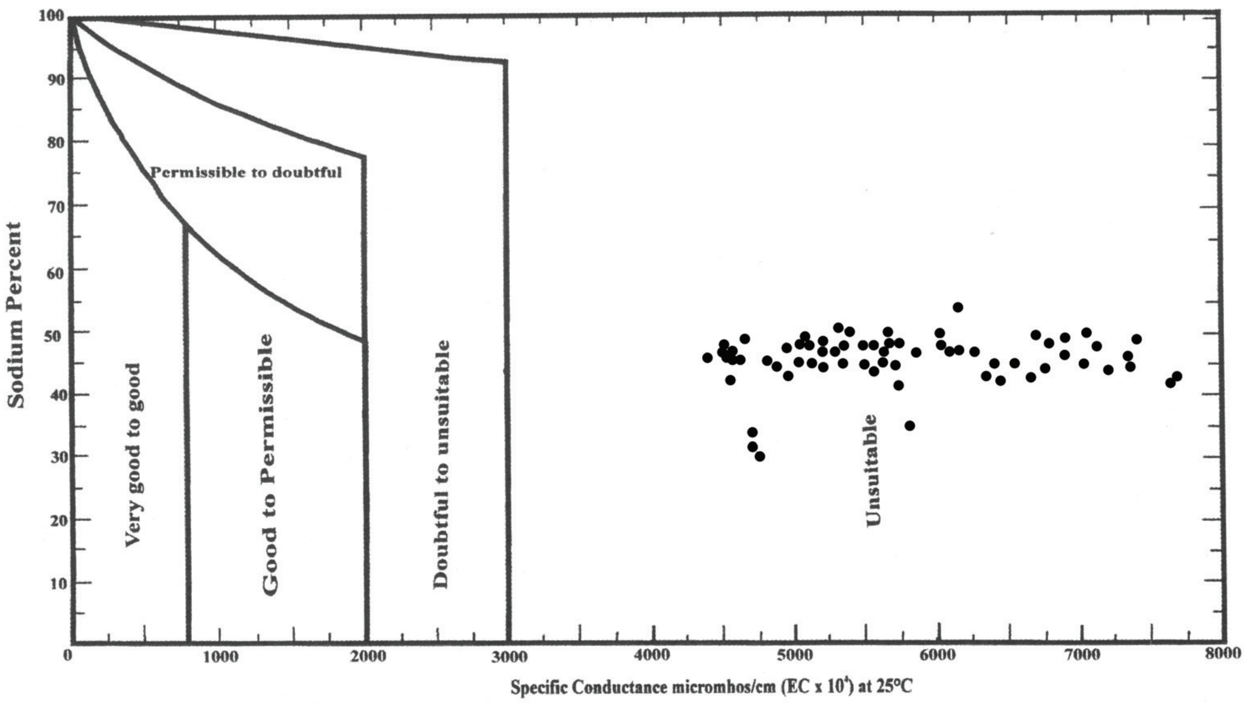

Figure 10. A plot of percentage of sodium vs. electrical conductivity of groundwater of the study area.

8.2.8. Kelly's ratio

Kelly's ratio is used for the classification of water for irrigation purposes. A Kelly's index (>1) indicates an excess level of sodium in waters [38]. Therefore, water with a KR (<1) is suitable for irrigation. KR is calculated by using the formulae, where all the ions are expressed in meq/l.

$$\text{Kelly's ratio} = \frac{Na^{+}}{(Ca^{2+} + Mg^{2+})} \tag{9}$$

The values of the KR in the present study varied between 0.55 and 1.2 with an average value of 0.89 which is <1. It is found that 87.32% of the groundwater samples have KR <1, and 12.68% KR > 1. Accordingly, the groundwater of the study area is suitable for irrigation.

9. Conclusion

The study area is located in the southwest of Kuwait. It includes 83 wells that produce brackish groundwater from Kuwait Group aquifer. Pumping test analyses revealed that the aquifer is acting as a confined to semi-confined aquifer, and transmissivity ranges between 62.03 and 320.51 m^2/day and increases toward N-NE. The estimated storage coefficient is 7.5×10^{-4}.

In the present study, the pH values range from 7 to 7.9, indicating an alkaline type of groundwater. The total alkalinity ranges from 51.2 to 127 mg/l with an average value of 91.39 mg/l. The electrical conductivity values range from 4370 to 8230 μmohs/cm with an average value of 5837 μmohs/cm. Total dissolved solids vary from 3504 to 6366 mg/l, with an average value of 4441 mg/l representing brackish groundwater. The majority of the groundwater samples of the study area exhibited NaCl water chemical type, followed by Na_2SO_4, and $CaSO_4$ water chemical types, respectively.

The groundwater is very hard, where the average TH is 1826 mg/l as $CaCO_3$. The sequence of the abundance of the major cations and anions is $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $Cl^- > SO_4^{2-} > HCO_3^-$. The dominant hydrochemical facies of the groundwater in the study area is Ca-Na-Cl. According to Gibb's plot, most of the samples of the study area are under the category of rock interaction and few samples are found to have the category of evaporation. Few samples fall in the precipitation-dominance area suggesting the influence of precipitation on the groundwater. Silicate weathering is the dominant weathering process in the study area; however, the carbonate weathering processes are also responsible for the supply of some ionic species to the groundwater. The calculation of the saturation indices revealed that the groundwater is oversaturated with respect to calcite and dolomite and undersaturated with respect to gypsum, anhydrite, halite, and SiO_2.

The positive index of base exchange for most of the samples (>98%) indicates that there exists a chloro-alkaline equilibrium, and there is an ion exchange of Na^+ and K^+ from water with magnesium and calcium in the rock, except one well, where the value is negative, revealed cation-anion exchange (chloro-alkaline disequilibrium).

Most of the TDS and TH values obtained are beyond the permissible limits making the groundwater of the study area unsuitable for drinking and for various domestic activities.

The suitability of groundwater for irrigation was evaluated based on the irrigation quality parameters like RSC, permeability index, potential salinity, SAR, salinity hazard, magnesium ratio, %Na, and Kelley's ratio. The majority of the groundwater samples exhibited very high salinity to extensively high water salinity class, medium and high sodium water type, respectively, According to the values of these parameters, the groundwater of the study area was found to be used for irrigation under high soil permeability, good drainage, and plants with good salt tolerance should be selected.

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