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Groundwater quality assessment for irrigation purposes: Case study Badra Region, North East Wasit Governorate, southeast of Iraq

Hind Fadhil Al-Gburi[1]*, Iman Ahmed Al-Ali[1], Ahmed Hussein Majeed[2], and Raghad Mouhamad[3]

[1]Department of Geology, College of Science, University of Baghdad, Baghdad, Iraq

[2]Kirkuk Directorate of Education, Al-Mutafawiqat Secondary School, Kirkuk, Iraq

[3]Scientific Research Commission, Baghdad, Iraq

***Corresponding author:**
Hind F. Al-Gburi
(hind.abdullah1108@sc.uobaghdad.edu.iq)

Abstract

The present study assessed the groundwater for irrigation purposes in the Badra region, northeast of Wasit Governorate, southeast of Iraq. Seventeen groundwater samples were collected from the study area and were analyzed to determine hydrochemical ions. The results of hydrochemical analyses revealed high mineralization, with a mean electrical conductivity (EC) of 6,151 $\mu S \cdot cm^{-1}$ and total dissolved solids (TDS) of 4,118 $mg \cdot L^{-1}$, indicating elevated salinity. Cation and anion dominance followed this order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $SO_4^{2-} > Cl^- > HCO_3^-$, respectively. Validity indices for irrigation showed sodium adsorption ratio values and permeability index within the low hazard category, while magnesium hazard and total hardness exceeded the acceptable limits in wells 1, 2, 6, 7, 10, 11, 13, 14, 15, 16, and 17; and in wells 1, 12, 13, 15, 16, and 17, respectively. All groundwater samples detected with high EC and TDS levels of more than 2,250 $\mu S \cdot cm^{-1}$ and 2,000 $mg \cdot L^{-1}$, respectively. This indicates that the groundwater of the study area is unsuitable for irrigation due to high salinity. The findings highlight the influence of evaporitic formations and carbonate dissolution from interbedded limestone in the Fatha Formation on groundwater chemistry and emphasize the need for sustainable water management strategies to mitigate salinity risks in the Badra agricultural zone.

Keywords: Sodium adsorption ratio; Magnesium hazard; Permeability index; Salinity

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1. Introduction

In several countries where river surface water resources are insufficient, the groundwater has emerged as an alternative water source for agriculture.[1] Consequently, inadequate groundwater quality for purposes has been a major issue in recent years and frequently made severe by overusing chemical fertilizers.[2,3] Aquifer hydrogeochemical processes, rainfall amount, recharge water characteristics, and land-use/land-cover practices all affect groundwater quality.[4,5] In Iraq, water scarcity has intensified due to several factors, including climate change, upstream water policies, and population growth, leading to a significant reliance on groundwater resources.[6,7] The quality of these resources varies greatly across the country, influenced by geological formations, hydrogeological processes, and human uses such as fertilizer application and land use practices.[8–10] While several studies have evaluated groundwater quality in central and southern Iraq, limited attention has been paid to the northeastern parts of Wasit Governorate, where groundwater is the main source for irrigation. The Badra region is particularly important due to its agricultural potential and the strategic location near the Iraqi–Iranian border. Farmers in this region heavily depend on groundwater for irrigation because of the intermittent nature of surface streams and frequent drought conditions.[11] Despite its significance, detailed hydrochemical assessments of groundwater quality in Badra remain scarce. Therefore, this study aims to evaluate the hydrochemical characteristics and ionic distribution pattern of groundwater in the Badra region and to assess its suitability for irrigation purposes using standard indices such as sodium adsorption ratio (SAR), magnesium hazard (MH), permeability index (PI), and the salinity index, and total dissolved solids (TDS). The findings are expected to contribute to sustainable groundwater management strategies and provide guidance for agricultural development in northeastern Wasit Governorate.

1.1. The study area

The study area occupied an area of 1,164.48 km^2, between coordinates (33°00'–33°20') N latitudes, and (45°50'–46°15') E longitudes, within the Wasit Governorate, Iraq (Figure 1). From the east, it is bounded by the border between Iraq and Iran and the Hamrin hills. In contrast, it is bounded by Galal Wadi from the north and Hor Al-Shiwacha from the south.[12]

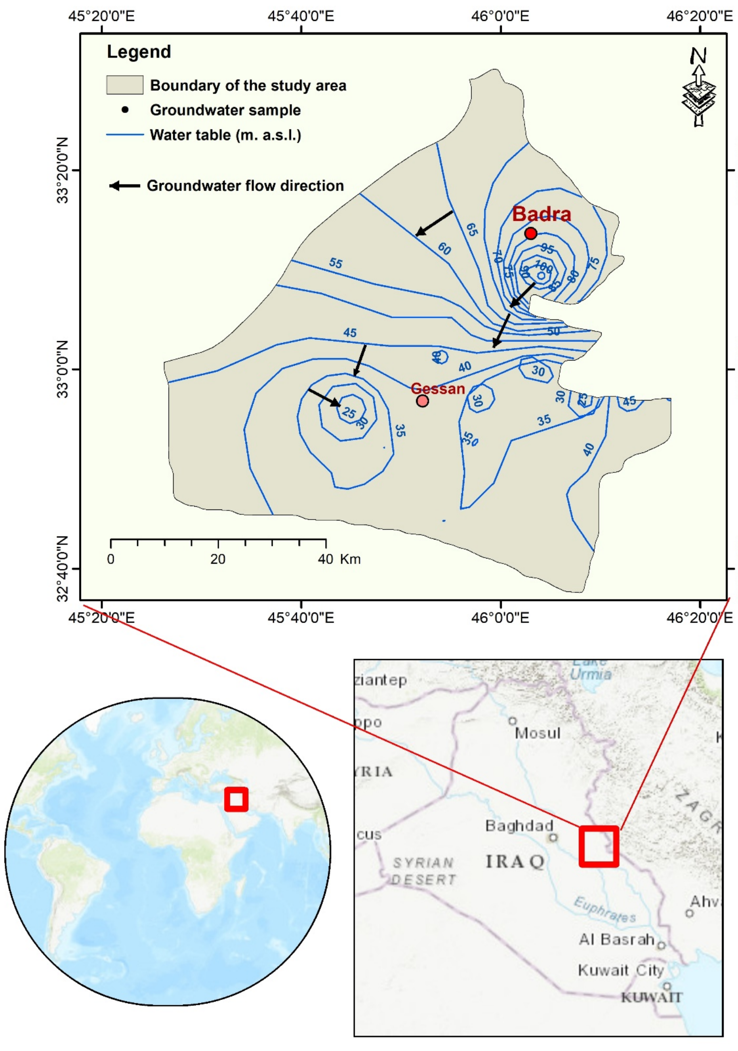

Figure 1. Location of the study area (Badra, Wasit governorate, Iraq) with the locations of groundwater wells

Geomorphology of the study area is characterized by low relief with few isolated hills in the east of the study area.[13] The elevation range is between 0 and 318 m above sea level (Figure 2). About 75% of the study area is plain, with only a gentle slope in the southwestern parts, while the rest of the area is characterized by high topographic relief in the northeast part of the study area. There are intervening synclinal valleys with low anticlinal folds.[13] The streams in Galal are characterized by intermittent flow and end up in the temporary marshes on the plain of the delta. These streams are formed during periods of intense rainfall and flooding originating from the far northeast side of the Badra region, flooding the flat terrains to the west. The Galal–Badra River represents the main stream within the study area, with an average monthly discharge of approximately 2.5 $m^3 \cdot s^{-1}$ during drought conditions, increasing to about 100 $m^3 \cdot s^{-1}$ during flood periods.[14]

The exposed geological formations in the study area range in age from the Upper Miocene to the recent. Younger formations crop out in the western part of the area and progressively become older toward the east. The region is primarily covered by the deposit of alluvial and lacustrine Pliocene-age or younger of the Injana, Mukdadiyah formations, and Quaternary deposits (Figure 2).[15] From a tectonic perspective, the Iraqi territory is divided into two principal structural units: the stable shelf and the unstable shelf.[15] The stable shelf is characterized by a relatively thin sedimentary cover and an absence of folding, whereas the unstable shelf exhibits a thicker sedimentary sequence that is intensely folded. These folds typically occur as narrow, elongated anticlines separated by broad, gently dipping synclines.[16] Most of the study area lies within the stable shelf region, represented by the Mesopotamian Plain, and a limited portion extends into the unstable shelf near the border, within the folded zone.[17]

The groundwater aquifer in the study area is composed of two kinds of hydrogeological units; the first one is quaternary deposits forming the shallow

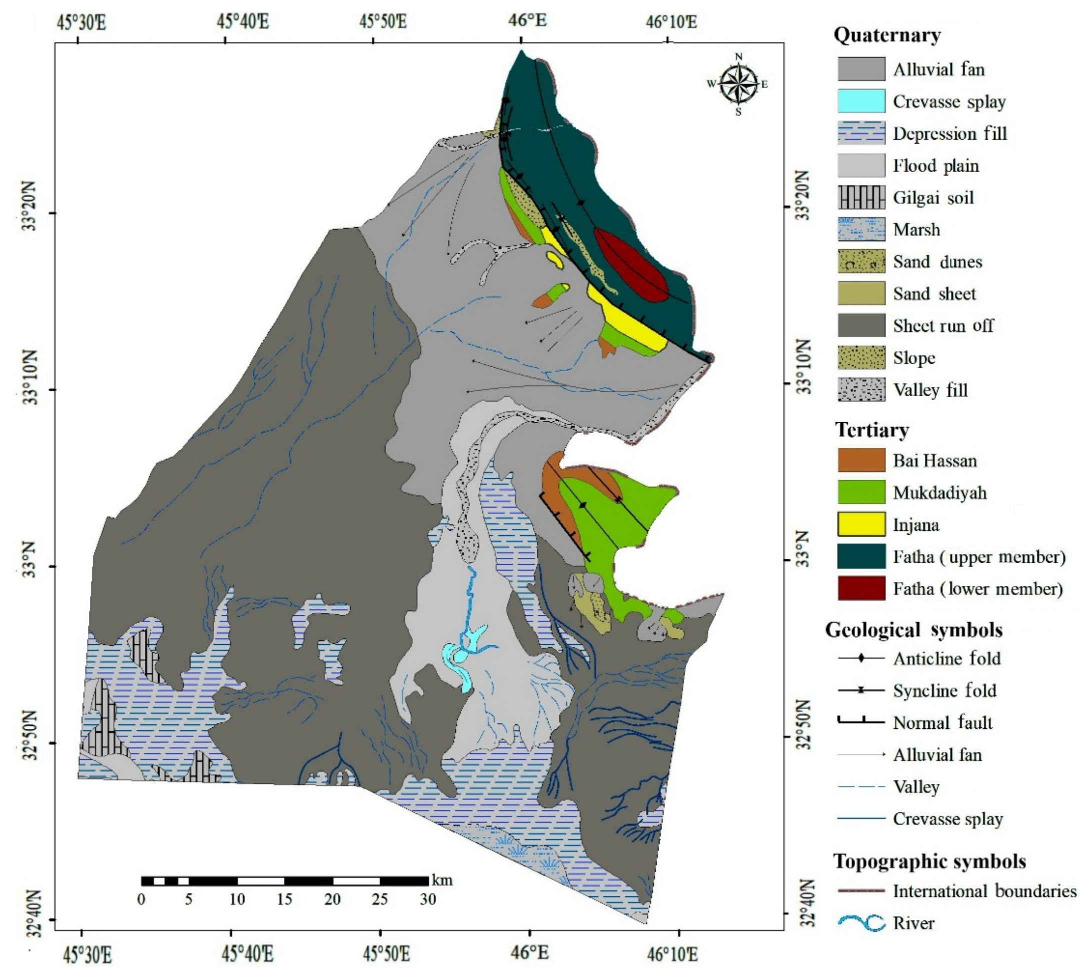

Figure 2. Geological map of the study area (Badra, Wasit governorate, Iraq)[18]

unconfined aquifer, consisting primarily of beds of sand and gravel with superimposed clay and silt. The second hydrogeological unit type is a confined and semi-confined aquifer originating from the Mukdadiya formation.[12] The flow direction of groundwater in the Badra region is from northeast to southwest (Figure 1).

The study area is generally characterized by hot and dry weather with absent rainfall in dry months from June to September, while the rainy season is in wet months (rainy months) from October to May. Meteorological data were obtained from the National Aeronautics and Space Administration (NASA) Langley Research Centre's Prediction of Worldwide Energy Resources project funded through the NASA Earth Science Division,[19] for the investigation period from 1984 to 2024. When calculated, the meteorological data for the investigation period revealed that the total annual rainfall is 106.03 mm, and the monthly mean temperature is 23.44 °C (Figure 3).

2. Materials and methods

2.1. Sampling and analyses

The 17 groundwater samples were gathered from the Badra region in the north–eastern part of Wasit governorate during the period from 2022 to 2023 during the wet seasons. The groundwater well depths ranged between 36 and 72 m, and the water table ranged between 23 and 107 m. The samples were all stored instantly at 4 °C after being sent to the lab for various hydrochemical tests. A portable multi-meter was used to measure the pH, electrical conductivity (EC), and TDS for all groundwater samples taken from the study area. The other chemical characteristics of the samples were analyzed in a laboratory using methods advised by the American Public Health Association.[20] The ethylene diamine tetraacetic acid procedure was adapted for the determination of NO_3^-. The hydrochemical ions Ca^{2+}, Mg^{2+}, Na^{+}, and K^+ were determined by the flame photometry procedure.[21] HCO_3^- and alkalinity were determined by using a titration procedure with an indicator titration against HCl. SO_4^{2-} was determined by the turbid metric procedure.[22] Cl^- was determined by the silver nitrate procedure.[23] NO_3^- was determined by the ultraviolet spectrophotometer procedure.[24] The above analyses were done by the Iraqi General Commission for Groundwater in the year 2023. Analytical reliability for solute analysis was verified by checking the ionic balance in Aq.QA software. However, the ionic balance of each groundwater sample was lower than 5% (Table 1). To ensure the reliability of hydrochemical analyses, the quality assurance/quality control procedures were performed in the lab. During the groundwater analyses, standard hydrochemical analysis protocols recommended by United States Environmental Protection Agency,[25] American Public Health Association,[26] and ISO 5667-11:2009 were followed.

These procedures included blank analysis and a triplicate of the chosen groundwater sample.

2.2. Hydrogeochemical model

The hydrogeochemical model was utilized to determine saturation indices of selected minerals using PHREEQC software version 3.8.6. Mineral saturation conditions are useful for determining which minerals govern ion concentrations and for understanding the potential chemistry in groundwater aquifers. The saturated index (SI) is defined as the logarithm of the ratio of the ion activity product (IAP) to the mineral equilibrium constant. Similar in structure to the equilibrium constant (K_{sp}), the IAP incorporates the actual activities. The SI is determined by using **Equation 1**.[27]

$$SI = \log \frac{IAP}{Ksp} \tag{1}$$

2.3. Irrigation indices

For evaluating the groundwater of the study area's suitability for irrigation of crops, the following indices were calculated:

2.3.1. Sodium adsorption ratio

Classification of irrigation water by SAR is purely dependent upon the impact of the exchangeable sodium on the physical status of the soil. Moreover, salt-sensitive crop varieties could be damaged by the build-up of sodium ions in crop cells. The SAR is defined by[28]:

$$SAR = \frac{Na^+}{\sqrt[2]{0.5\left(Ca^{2+} + Mg^{2+}\right)}} \tag{2}$$

Based on the SAR value, irrigation water can be classified into four categories. The first class has SAR values that range from 1–9 and is considered to pose a low sodium hazard; however, caution is required when using this water for sodium-sensitive crops. The second class includes SAR values of 10–17 and is classified as a medium sodium hazard; in this case, soil amendments (such as gypsum) and leaching are needed. The third class comprises SAR values ranging from 18–25 and represents a high sodium hazard, making the water generally unsuitable for continuous use. Finally, the fourth class has SAR values greater than 26 and is classified as a very high sodium hazard, and is generally unsuitable for irrigation use.[29]

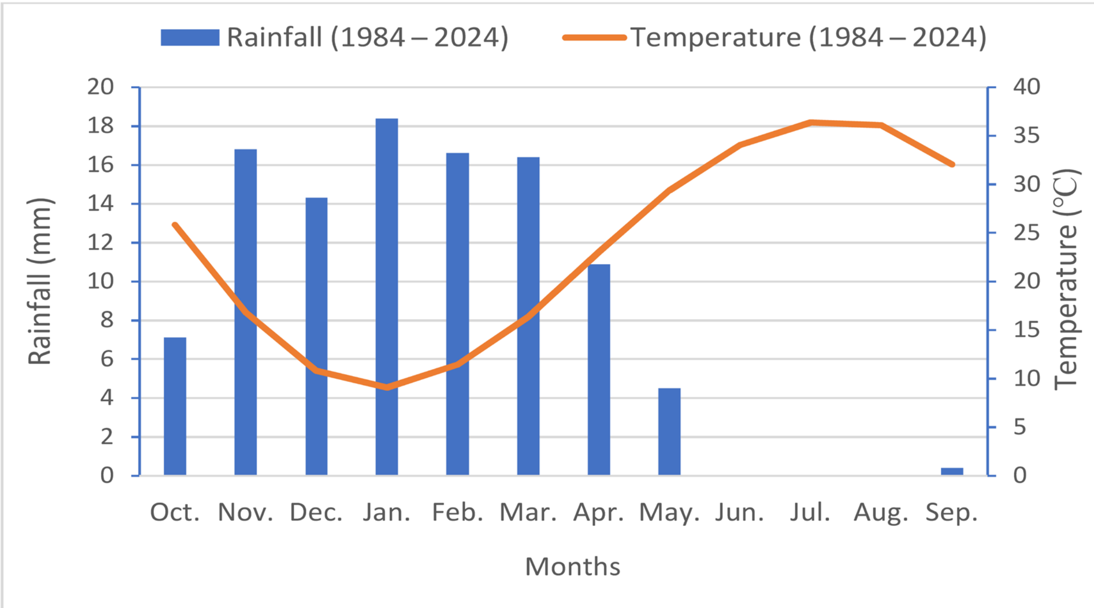

Figure 3. Historical meteorological data of mean monthly rainfall and temperature of 1984–2024 of the study area

Table 1. Ionic balance of groundwater samples for the present study

Sample	Ionic balance
W1	4.26
W2	0.77
W3	2.97
W4	3.65
W5	4.79
W6	0.96
W7	3.73
W8	4.43
W9	4.16
W10	4.39
W11	4.94
W12	3.57
W13	2.97
W14	3.65
W15	4.73
W16	4.69
W17	3.25

2.3.2. Magnesium hazard

In groundwater systems, calcium and magnesium ions typically exist in a state of chemical equilibrium.[30] To evaluate the suitability of irrigation water with respect to magnesium content, Szabolcs and Darab (1964)[31] introduced the MH index, which is expressed as follows:

$$MH = \frac{Mg^{2+}}{\left(Ca^{2+} + Mg^{2+}\right) * 100} \quad (3)$$

As all concentration units are expressed in meq·L^{-1}, MH values > 50 indicate that the water is harmful and unsuitable for irrigation purposes.

2.3.3. Permeability index

The PI is used to assess whether water is suitable for irrigation. The permeability, or the capacity of soil to carry water, is impacted by the prolonged usage of high-salinity water in irrigation. It is also impacted by the soil's Na^+, Ca^{2+}, Mg^{2+}, and HCO_3^- ions. Doneen[32] established the PI formula, expressed as **Equation 4**, to evaluate soil permeability to water movement and to assess the suitability of different water sources for irrigation.

$$PI = \frac{Na + \sqrt{HCO3_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \times 100 \quad (4)$$

All ion concentrations used in the PI calculation were expressed in meq·L^{-1}. Based on PI values, irrigation water can be classified into three types: Type 1 has PI values greater than 75 % and is considered suitable for irrigation; type 2 has PI values ranging from 25–75 % and is classified as good-quality water for irrigation; and type 3 has PI values less than 25% and is classified as unsuitable for irrigation.[32]

2.3.4. Salinity index

The dissolved solids of cations, anions, and all the minerals and nutrients are represented by the water salinity index. The main factor affecting the increase in TDS in water is weathering, which acts as a catalyst in dissolving rocks in water.[2,33] Also, the high rates of evaporation work to increase the concentration of salts at the roots of plants, which prevents the plants from being able to suck water from the soil, causing moisture stress.[34] Based on TDS, irrigation water suitability is categorized into two categories: water with TDS values less than 450 mg·L^{-1} is considered suitable for irrigation; on the other hand, water with TDS values greater than 2,000 mg·L^{-1} is considered unsuitable for agricultural purposes.[35]

2.3.5. Total hardness measurement

Major cations (Ca^{2+} and Mg^{2+}) contribute to water hardness; therefore, the total hardness (TH) can be estimated using **Equation 5**.[36]

$$TH = 2.5 \times Ca^{2+} + 4.1 \times Mg^{2+} \tag{5}$$

Based on TH, water is classified as soft when TH ranges from 0–60 mg·L^{-1} , moderately hard when TH ranges from 60–120 mg·L^{-1}, hard when TH ranges from 120–180 mg·L^{-1}, and very hard when TH exceeds 180 mg·L^{-1}.[37]

3. Results and discussion

3.1. Hydrochemical analysis

Hydrochemical analysis of groundwater in the Badra region revealed high variability in major ion concentrations and salinity. TDS ranged from 1,993 to 8,877 mg·L^{-1} (Table 2), with an average of 4,118 mg·L^{-1}, while EC values varied between 2,820 and 13,750 µS·cm^{-1} and had a mean of 6,151 µS·cm^{-1}, indicating highly mineralized water. The ionic composition followed the trend $Na^+ > Ca^{2+} > Mg^{2+} > K^+$ and $SO_4^{2-} > Cl^- > HCO_3^-$ for cations and anions, respectively (Table 2), reflecting the dissolution of evaporitic deposits and carbonate minerals within the groundwater aquifer. The results obtained were compared with the national and world standard limits of Iraqi Quality Standards (IQS)[38] and World Health Organization (WHO)[39] to determine the suitability of this groundwater for human consumption (Table 2).

The results of the hydrochemical analysis of the groundwater samples showed that TDS varied between 1,993 and 8,877 mg·L^{-1}, and EC ranged from 2,820 to 13,750 µS·cm^{-1}, with a mean of 6,151 µS·cm^{-1} (Table 2). This indicated elevated rates of salinity.

Based on the results of pH, the groundwater was slightly alkaline with a pH mean value of 7.184.[39] The concentrations of Cl^- ranged from 59 to 1,760 mg·L^{-1}, with a mean value of 833 mg·L^{-1}. The EC of the groundwater samples ranged from 2,820 µS·cm^{-1} to 13,750 µS·cm^{-1}, with a mean of 6,151 µS·cm^{-1}, indicating highly mineralized water.[40] However, the mean values of Ca^{2+}, Mg^{2+}, Na^+, and K^+ were 395, 235, 580, and 46 mg·L^{-1}, respectively. The mean values of HCO_3^-, SO_4^{2-}, and Cl^- were 570, 1,387, and 833 mg· L^{-1}, respectively (Table 2).

The concentrations of Na^+ ranged from 251 to 1,203 mg·L^{-1}. Ca^{2+} and Mg^{2+} concentrations ranged between 194–850 mg·L^{-1} and 126–527 mg·L^{-1}, respectively. The increased concentrations of Ca^{2+} and Mg^{2+} could originate from dissolution of carbonate minerals within quaternary deposits and Mukdadiya Formation, which represent the main aquifers of the groundwater in the study area. The excessive concentrations of Mg^{+2} in water negatively affect crop production and can lead to saline soil alteration.[41,42] The high concentrations of Cl^- and Na^+ ions in groundwater may be caused by the high solubility of halite mineral from the Fatha Formation, especially during the flooding periods in the spring season. The sulfate ion concentrations in groundwater exceeding the permissible limits of SO_4^{2-}, which were sourced by dissolution of gypsum rocks within the Fatha Formation, may cause laxative effects on humans.[43] The SO_4^{2-} concentration ranges between 555 and 2,788 mg·L^{-1}, with an average of 1,387 mg. L^{-1} (Table 2). The cation concentrations were arranged according to this order: $Na^+ > Ca^{2+} > Mg^{2+} > K^+$, while the anions were arranged according to this order: $SO_4^{2-} > Cl^- > HCO_3^-$. All the cations and anions exceeded the permissible limits recommended by the (IQS, 2009) and (WHO, 2018).[38,39] The current study shows variations in the concentration of hydrochemical ions due to the dissolution of evaporated deposits and the effect of agricultural activities in the study area. The hydraulic connection between surface and groundwater is noted, with surface water as the main source of groundwater recharge in the region.[44] The main source of groundwater recharge, especially in areas with nearby river channels, is from alluvial fan deposits and rainwater infiltration through soil layers. The groundwater of the Badra region is recharged by drainage through the Galal–Badra catchment, and this water has high salt concentrations that accumulate from leaching of the highlands and are collected in the lowlands. This is the reason for the increased salinity of the groundwater.

The comparison with the previous study,[14] shows that the salinity, TDS, EC and major hydrochemical ions concentrations in the present study were found to be significantly higher (Table 2). This indicates a deterioration in water quality over time due to the increasing impact of human and natural activities that have affected water quality.

3.2. Hydrogeochemical model

The results of the hydrogeochemical model revealed that the minerals of anhydrite, aragonite, calcite, dolomite, and gypsum were oversaturated (had a SI more than 1) with mean values of 1.53, 2.79, 2.93, 5.71, and 1.78, respectively (Table 3 and Figure 4). The minerals halite and sylvite were undersaturated, indicating that they are in a state of dissolution (Table 3 and Figure 4), which may contribute Na^+, Cl^-, and K^+ ions to the groundwater. The salt source in groundwater could be derived from salt intrusion from surface water infiltration. On the other hand, the salt dissolution from the unconfined aquifer of quaternary deposits, which have secondary salt accumulation from weathering of the Fatha Formation.[45]

3.3. Spatial distribution of hydrochemical ions

The spatial distribution maps illustrated the spatial variations of hydrochemical cations and anions (Figures 5 and 6). The spatial distribution map shows that the lowest concentrations of Ca^{2+} were detected in the central and southeast of the study area in groundwater wells 2, 4, 6, 7, 8, 9, and 10. High concentrations of Ca^{2+} were detected in the lower central parts of the study area in wells 11 and 15. On the other hand, the highest values of Mg^{2+} cation concentrations were detected in wells 1, 15, and 16. In contrast, the lowest Mg^2 values were detected in wells 2, 3, 4, 6, 7, 8, 9, 11, 12, 13, 14, and 16.

The highest values of Na^+ cation concentrations were distributed in wells 1, 15, and 16. The lowest values of Na^+ concentrations were detected in wells 2, 3, 5, 6, and 8. The highest values of K^+ ion concentrations were observed in well 17 only, while the low K^+ concentrations were distributed in wells 2, 3, 4, 5, 6, 8, 9, 11, 12, and 14. Regarding anion distributions in the study area, the highest values of HCO_3^- and SO_4^{2-} concentrations are observed in wells 1, 15 and 16, while the lowest values of HCO_3^- and SO_4^{2-} are detected in central and eastern parts of the study area (wells 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, and 14). The spatial distribution maps show that the high concentrations of Cl^- and NO_3^- are detected in the lower central, southern and northeastern parts of the study area in wells 1, 15, and 16, whereas the low values of Cl^- and NO_3^- are detected in the central and southeastern parts of the study area (wells 6, 7, 8, 9, 10, 11, 12, and 14). For NO_3^-, the lowest values were detected in the middle part of the study area and in the eastern parts (wells 2, 4, 5, 13, and 16), whereas high concentrations of NO_3^- are observed in wells 1 and 6.

3.4. Hydrochemical facies

Hydrochemical characteristics of groundwater of Badra region, as depicted by the Piper diagram (Figure 7), show that most groundwater samples belong to the Ca^{2+}–Mg^{2+}–SO_4^{2-}–Cl^- facies. In the cation circle, Ca^{2+} and Mg^{2+} predominated over Na^+ and K^+, whereas in the anion circle, Cl^- and SO_4^{2-} ions were dominant.

This hydrochemical signature is indicative of the overriding effect of regional geology, consisting mainly of carbonate and evaporate rocks. Dissolution of limestone and dolomite supplies calcium and magnesium, respectively, whereas dissolution of gypsum and halite contributes sulfate and chloride to groundwater from the Fatha Formation that outcrops at the northern site of the studied area. Badra's hydrogeological setting in the central part of the eastern Mesopotamian Plain, close to the Zagros Fold–Thrust Belt, further clarifies these facies: groundwater replenishment emanates basically by rain as well as Zagros foothill runoff, yet aridity restricts dilution, as well as much faster rates of evaporation increase the concentration of hydrochemical ions.[46] Furthermore, longer groundwater–rock contact along flow paths increases mineralization as a result of the prevalence of hard saline waters. Human effects, such as irrigation return flow, can also exaggerate concentrations of SO_4^{2-} as well as Cl^- in certain wells. Overall, these processes defined Ca^{2+}–Mg^{2+}–SO_4^{2-}–Cl^- as the typical Badra groundwater facies indicative of both the lithological framework and semi-arid hydrogeological regime of the study area.

3.5. Irrigation indices

Irrigation indices indicated that all samples were classified as the low-sodium hazard class based on SAR values. However, the MH showed that most samples had values exceeding 50, indicating that they are harmful and not suitable for irrigation, except for groundwater samples 3, 4, 5, 8, 9, and 12, which showed MH values less than 50 (Table 4). PI values ranged from 31.4% to 52.31% (Table 4), which is acceptable for irrigation, suggesting potential long-term effects on soil structure and infiltration capacity.

The irrigation indices results were compared with standards for agricultural and irrigation use, revealing that all groundwater samples were suitable for irrigation

Table 2. Results of hydrochemical analysis for the present study with drinking water standard limits (IQS and WHO)[38,39] and Al-Shammary[14]

Sample no	Min	Max	Mean	SD	IQS[38]	WHO[39]	Previous study (mean)[14]
Ca^{2+} ($mg \cdot L^{-1}$)	194	850	395	218.46	150	100	310
Mg^{2+} ($mg \cdot L^{-1}$)	126	527	235	148.21	100	125	180
Na^{+} ($mg \cdot L^{-1}$)	251	1,203	580	318.01	200	200	520
K^{+} ($mg \cdot L^{-1}$)	4	145	46	43.78	–	12	28
HCO_3^{-} ($mg \cdot L^{-1}$)	129	1,410	570	414.27	–	200	460
SO_4^{2-} ($mg \cdot L^{-1}$)	555	2,788	1,387	771.40	400	250	1,250
Cl^{-} ($mg \cdot L^{-1}$)	59	1,760	833	465.13	350	250	790
TDS ($mg \cdot L^{-1}$)	1,993	8,877	4,118	2,309.88	1,000	1,000	4,100
EC ($\mu S \cdot cm^{-1}$)	2,820	13,750	6,151	3,665.89	–	1,530	6,200
pH	7.11	7.25	7.184	0.042	6.5–8.5	6.5–8.5	7.2
NO_3^{-} ($mg \cdot L^{-1}$)	0.3	2.3	1.05	0.525	–	50	–

Abbreviations: EC: Electrical conductivity; IQS: Iraqi Quality Standards; SD: Standard deviation; TDS: Total dissolved solids; WHO: World Health Organization.

Table 3. Summary statistics of the saturation index for the groundwater of the present study

Mineral	Minimum	Maximum	Mean	SD
Anhydrite	1.15	2.07	1.53	0.29
Aragonite	2.17	3.45	2.79	0.43
Calcite	2.31	3.60	2.93	0.43
Dolomite	4.52	7.13	5.71	0.85
Gypsum	1.43	2.27	1.78	0.26
Halite	−2.89	−1.64	−2.48	0.37
Sylvite	−4.11	−2.20	−3.16	0.58

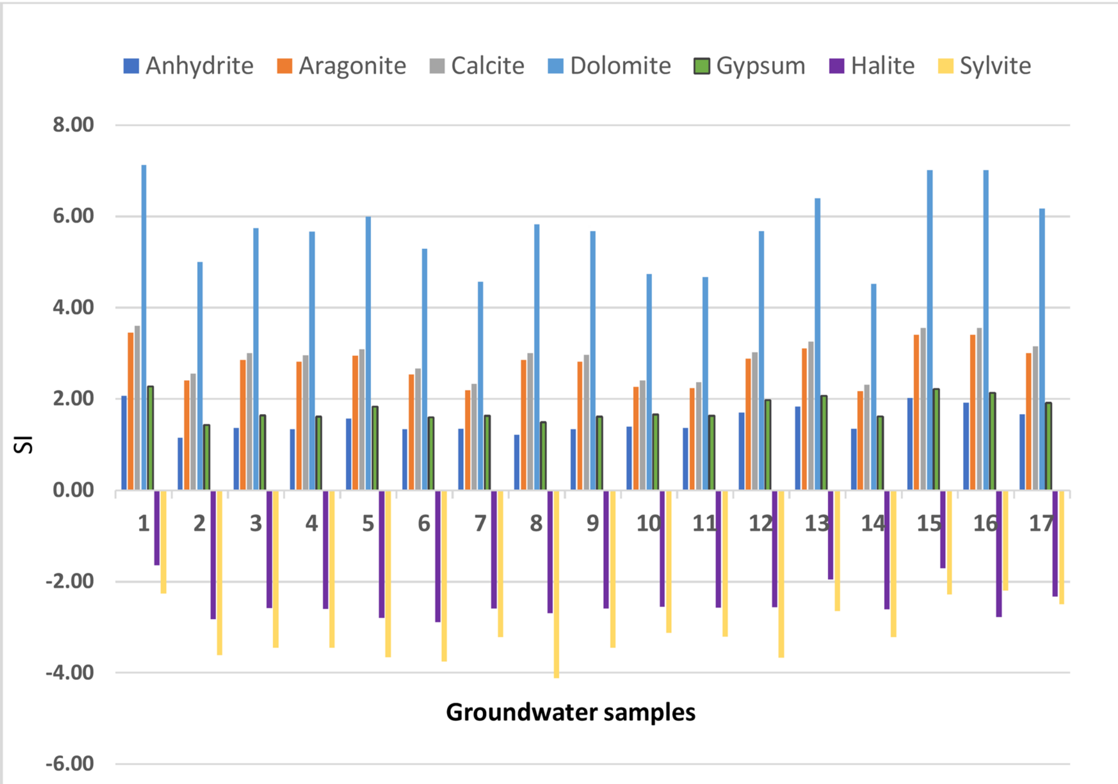

Figure 4. Distribution of SI in groundwater samples
Abbreviation: SI: Saturation index.

with respect to SAR and PI. Regarding MH, groundwater samples 3, 4, 5, 8, 9, and 12 were considered suitable; whereas samples 1, 2, 6, 7, 10, 11, 13, 14, 15, 16, and 17 were not suitable for irrigation. In terms of TH, samples 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, and 14 were classified as suitable, while samples 12 and 17 were classified as hard water, and samples 1, 13, 15, and 16 were classified as very hard water.[37] TDS and EC exceeded the permissible limits in all samples (Table 4). Furthermore, the irrigation index results of the present study were compared with those reported by Al-Sudani[11], showing that the mean values of TDS and EC in the present study were higher than those reported in the previous study[11] (Table 4). These variations may be attributed to the dilution of groundwater solutes due to increased recharge, as reported in the previous study.[11]

The spatial distribution map of SAR in groundwater shows that the lowest values were detected in the eastern part of the study area, particularly in wells 5 and 6, whereas the highest SAR values were recorded in wells 1, 15, and 16. The distribution pattern of MH (Figure 8) shows that the lowest MH values were detected in wells 3, 4, 5, 8, 9, 11, 12, and 14. In contrast, the highest MH values were detected in the central south and eastern parts of the study area, specifically in wells 2, 6, 7, 10, 13, and 16.

The distribution patterns of PI show that the lowest PI values were detected in the eastern parts of the study area, particularly in wells 5 and 6, while the highest values were recorded in wells 4, 7, 9, and 10 (Figure 8). For TH, the lowest values were detected in wells 1, 2, and 3; while the highest values occurred in wells 13, 15, 16, and 17. Groundwater in the study area was classified for irrigation purposes based on SAR and EC values according to the United States Salinity Laboratory (USSL) classification[47] (Figure 9), and was grouped into C4S1, C4S2, and C4S3 classes. This indicates a very high salinity hazard with a SAR ranging from low to high. All groundwater samples exhibited high EC values exceeding 2,250 μS·cm^{-1} (Table 4 and Figure 9), indicating that the groundwater of the study area is generally not suitable for irrigation due to high salinity. The highest EC values were recorded in groundwater well 1, followed by wells 13, 15, and 16. The elevated groundwater salinity is attributed to salts from surface water recharge

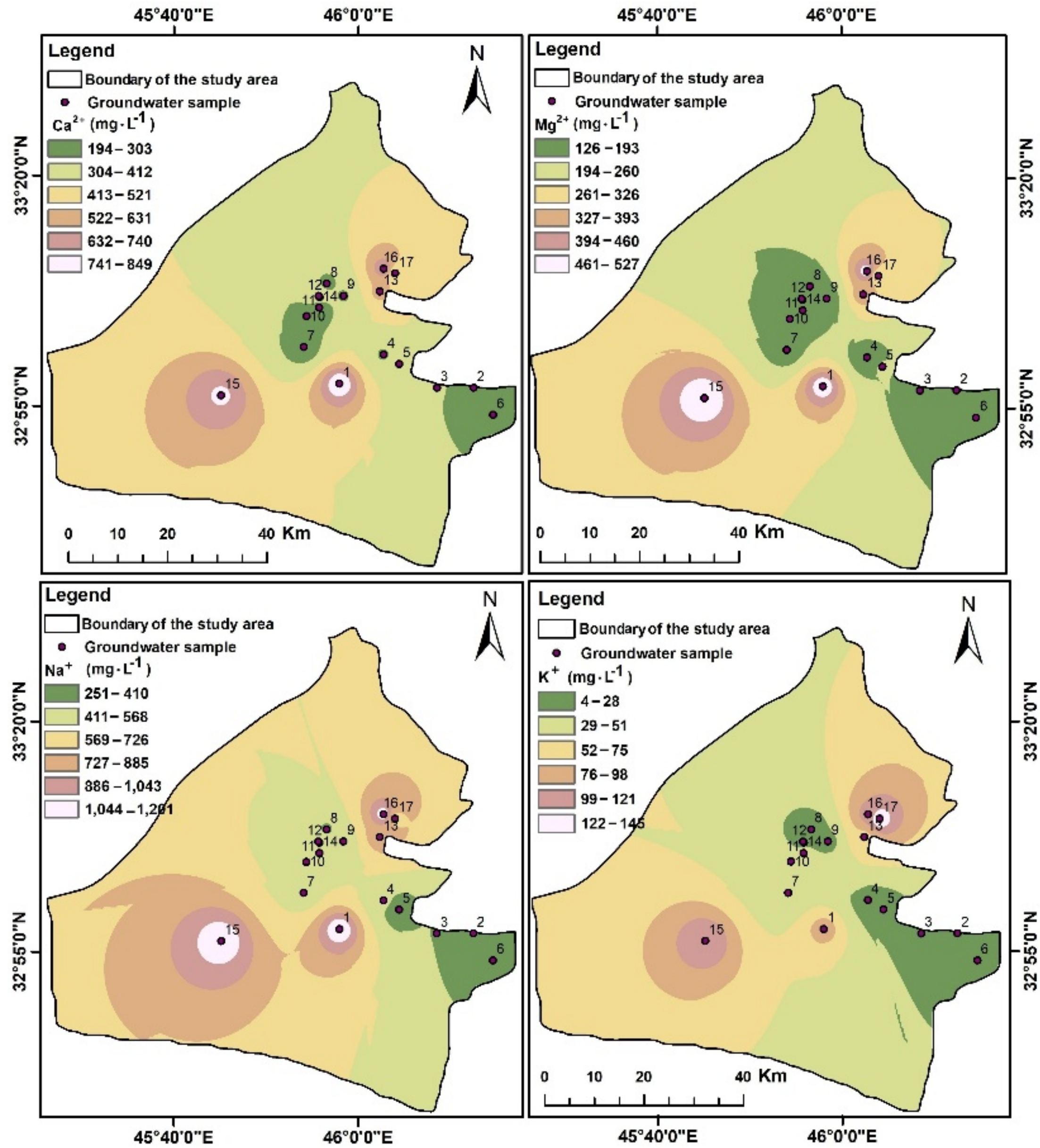

Figure 5. Spatial distribution of hydrochemical cations in groundwater samples

areas, which are influenced by evaporite beds of the Fatha Formation exposed in the northeastern part of the study area. Moreover, quaternary deposits composed of gypsum, carbonate, and salt-bearing sediments also contribute to the salinity.[48] Infiltration of such surface water into the aquifer increases groundwater salinity, as reported in previous studies.[49,50] Elevated EC reflects increased dissolved constituents such as salts or potential industrial pollutants in contaminated aquifers.[51] Additionally, high–salinity irrigation water adversely affects soil structure, permeability, and agricultural productivity, leading to reduced crop yields, soil deterioration, and long-term sustainability challenges. Aquifer vulnerability also plays a crucial role in regulating contaminant accumulation, as poorly protected aquifers are more susceptible to both salinity build-up and pollutant infiltration. These findings demonstrate that different contamination sources can produce similar environmental and agricultural impacts, emphasizing the importance of integrated groundwater management.

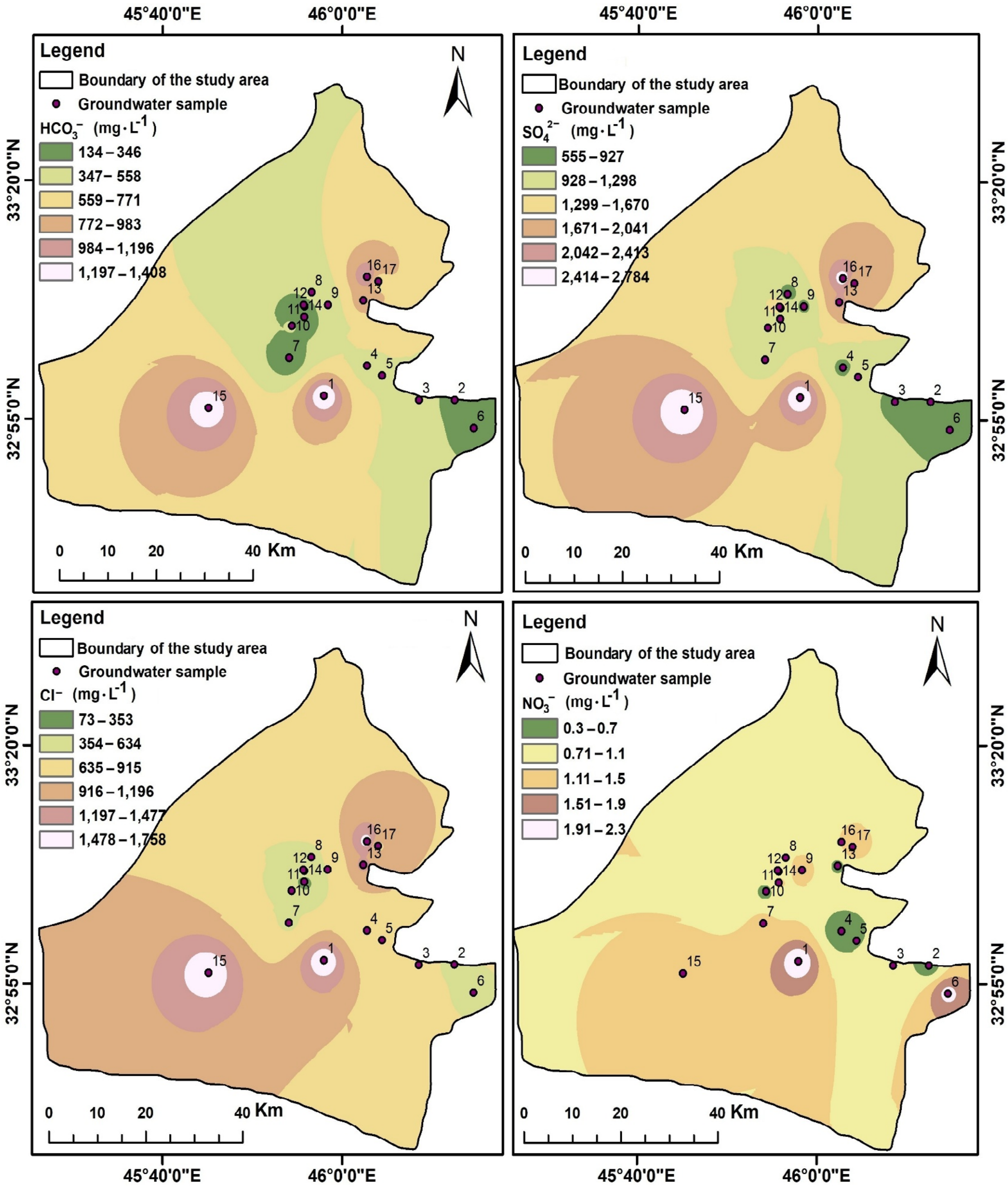

Figure 6. Spatial distribution of hydrochemical anions in groundwater samples

3.5. Salinity management strategies

The combination of arid climate conditions characterized by high evaporation rates and the dissolution of evaporation formations governs the hydrochemical characteristics of groundwater in the Badra region, resulting in elevated salinity concentrations. According to the USSL classification, the studied groundwater samples are classified as very high salinity, which severely limits their suitability for irrigation. Such water can only be used sustainably under strict management practices, including effective salt leaching, improved drainage, and the cultivation of salt-tolerant crops.[28]

Leaching involves the application of irrigation water in excess of crop evapotranspiration requirements to dissolve and transport soluble salts below the effective root zone.[52] However, its effectiveness strongly depends on the availability of efficient drainage systems. In the alluvial plains of Wasit, where soils often exhibit low permeability and shallow groundwater tables, inadequate drainage can lead to waterlogging and secondary salinization, thereby exacerbating soil degradation.[53] Therefore, the integration of subsurface drainage networks or open drainage channels

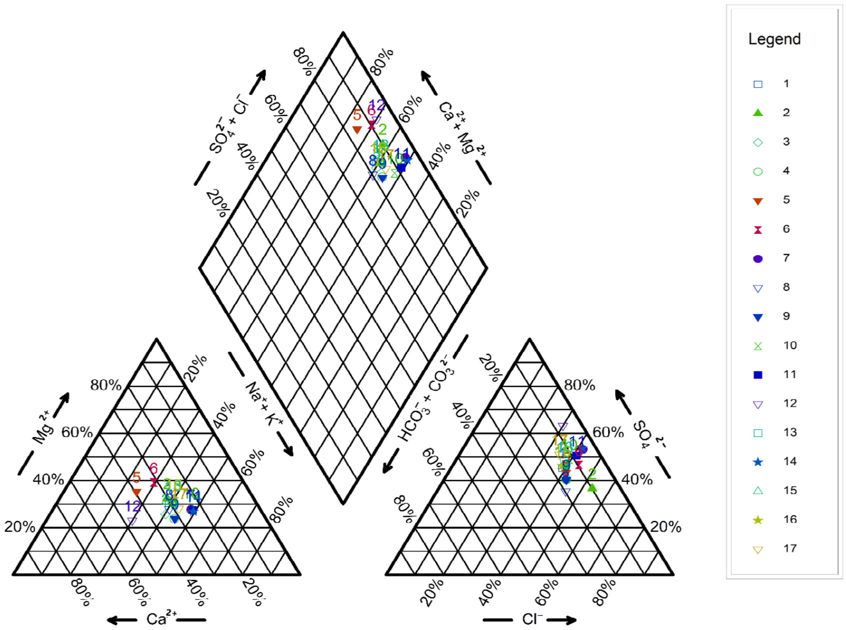

Figure 7. Piper diagram of groundwater samples from the Badra region

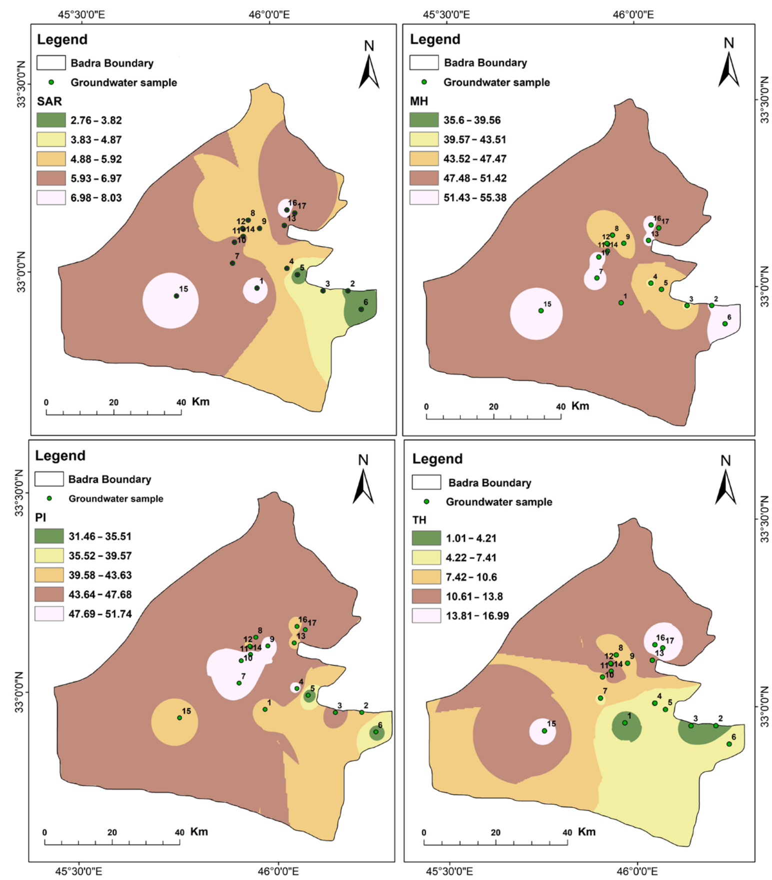

Figure 8. Values of irrigation indices in the study area
Abbreviations: MH: Magnesium hazard; PI: Permeability index; TH: Total hardness.

Table 4. Irrigation indices for groundwater samples

Sample ID	SAR	MH	PI %	TH ($mg \cdot L^{-1}$)	TDS ($mg \cdot L^{-1}$)	EC ($\mu S \cdot cm^{-1}$)
1	8.033	50.024	41.642	280.136	8,877	13,750
2	3.695	51.718	42.734	66.720	1,993	3,080
3	4.840	42.931	46.089	86.110	3,100	4,530
4	5.499	42.596	50.036	79.920	2,850	4,410
5	2.752	47.232	31.399	111.736	3,770	2,820
6	2.986	55.385	34.262	90.546	2,410	3,730
7	5.972	53.283	50.544	75.566	2,680	4,140
8	4.709	46.686	47.442	78.382	2,533	3,900
9	5.570	42.693	50.231	80.373	2,860	4,420
10	6.251	54.357	51.747	86.231	2,835	4,370
11	6.320	53.686	52.310	79.272	2,733	4,220
12	3.886	32.819	33.439	127.387	3,210	4,960
13	6.897	52.454	42.864	195.948	6,160	9,180
14	6.195	53.016	51.791	73.260	2,662	4,100
15	7.947	53.346	41.923	272.642	8,365	12,940
16	7.945	53.181	42.120	267.536	8,280	12,800
17	6.211	50.000	45.504	134.706	4,686	7,210
Minimum	2.75	32.82	31.40	66.72	1,993	2,820
Maximum	8.03	55.39	52.31	280.14	8,877	13,750
Mean	5.63	49.14	44.48	128.62	4,118	6,150.6
SD	1.64	5.98	6.63	75.94	2,309.88	3,665.9
Previous study[11]					3,236.1	3,898.6

Abbreviations: EC: Electrical conductivity; MH: Magnesium hazard; PI: Permeability index; SAR: Sodium adsorption ratio; SD: Standard deviation; TDS: Total dissolved solids; TH: Total hardness.

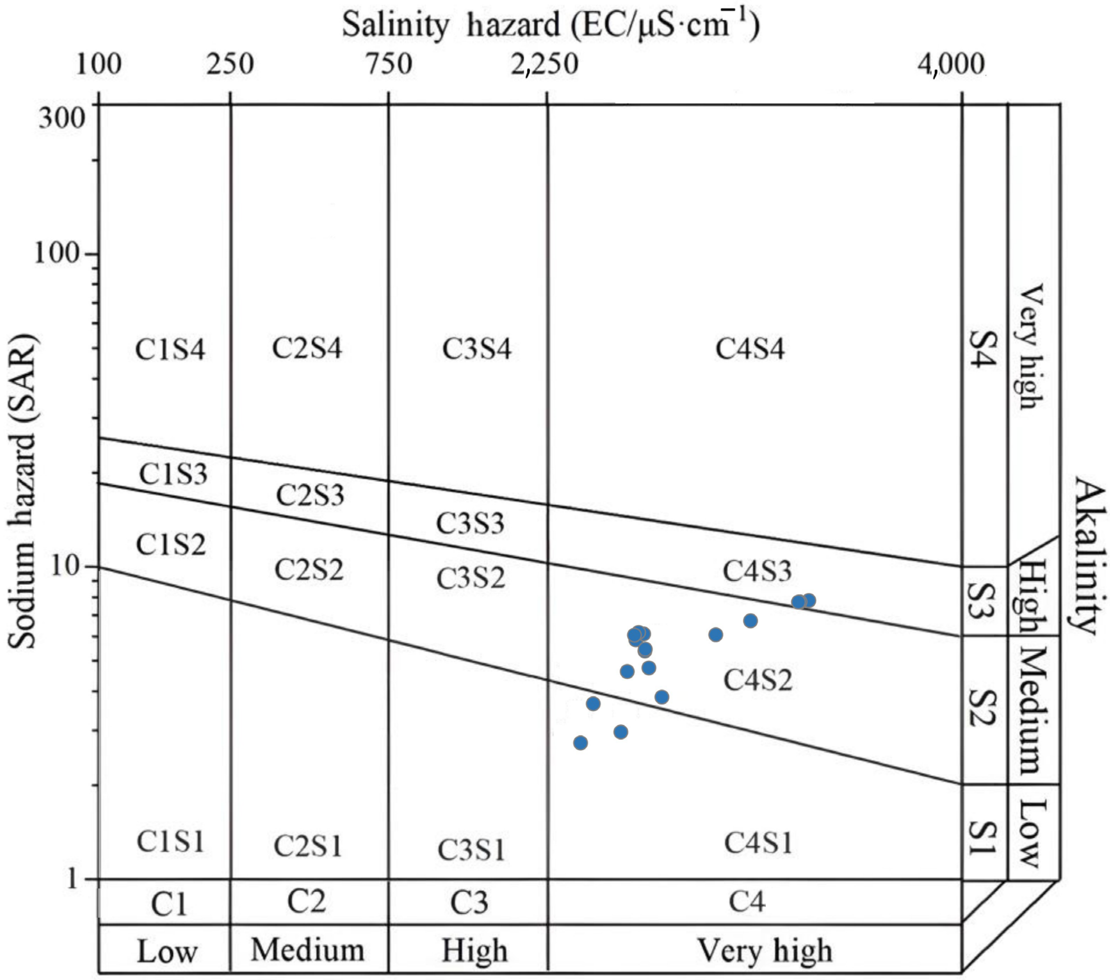

Figure 9. Classification of groundwater (blue dots represent well samples) for irrigation using the United States Salinity Laboratory diagram[47]
Abbreviations: EC: Electrical conductivity; SAR: Sodium adsorption ratio.

is essential to ensure the long-term sustainability of leaching practices. In addition to leaching, the use of salt-tolerant crops represents a critical adaptive strategy for utilizing saline groundwater. Crops such as barley, cotton, sugar beet, sorghum, and date palm have demonstrated relatively high tolerance to saline conditions.[28] Modern irrigation techniques, such as drip irrigation, can enhance water use efficiency and reduce salt accumulation in the immediate root zone by maintaining localized moisture conditions.[54] Alternatively, furrow irrigation systems can be designed to redistribute salt away from plant roots. In water-scarce regions such as Badra, the blending of saline groundwater with relatively fresher surface water, where available, may also reduce overall salinity levels and improve irrigation suitability.[52] The incorporation of organic matter enhances soil aggregation, increases infiltration rates, and supports microbial activity, all of which contribute to improving salt leaching efficiency.[55] Furthermore, mulching reduces surface evaporation and thus limits salt accumulation in the upper soil layers. Finally, the regulation of groundwater abstraction for agriculture use could allow aquifer recovery and reduce the groundwater salinity.

4. Conclusion

The climatic conditions of the study area, characterized by low rainfall and high evaporation, have significantly influenced groundwater quality. The hydrogeological setting of Badra, located in the eastern Mesopotamian Plain, close to the foothill zone, is primarily recharged by rainfall and runoff from the Zagros foothills. Spatial distribution maps of hydrochemical ions indicate that wells 1 and 15 exhibit high ionic concentrations. Overall, the results reveal a clear trend of groundwater deterioration, particularly in the lower central and southern parts of the study area, where salinity hazards increased significantly. The high salt content of groundwater is mainly due to salt input from surface runoff during flooding and agricultural activities, in addition to the dissolution of evaporite minerals within Quaternary deposits that constitute the aquifer material. These processes are further intensified by high rates of evaporation. The shallow depth of the groundwater table increases the risk of surface salt intrusion and raises groundwater salinity. The results are consistent with recent regional studies in southern Iraq that reported similar salinization trends; however, the present study highlights greater spatial heterogeneity and identifies critical zones of accelerated deterioration. Therefore, this study established the foundational data for the application of salinity management techniques (such as crop selection, leaching, and soil amendments).

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: Hind Fadhil Al-Gburi
Formal analysis: Hind Fadhil Al-Gburi, Iman Ahmed Al-Ali, Raghad Mouhamad
Investigation: Hind Fadhil Al-Gburi, Iman Ahmed Al-Ali, Ahmed Hussein Majeed
Methodology: Hind Fadhil Al-Gburi
Writing–original draft: Hind Fadhil Al-Gburi, Iman Ahmed Al-Ali
Writing–review & editing: All authors

Availability of data

Data are available from the corresponding author upon reasonable request.

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