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Article

# Assessing the Suitability of Groundwater for Drinking and Irrigation Using Hydrochemical Indicators in Kirkuk, Northern Iraq

Zakiya Shihab Hamad Al-Obeidi[1]
[1]*Department of Soil and Water Sciences, College of Agriculture, Kirkuk University, Kirkuk, Iraq.*

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Correspondence
*E-mail: hafamos@uokirkuk.edu.iq

**ABSTRACT**

This study aims to evaluate the groundwater quality of selected wells in Kirkuk City, Northern Iraq, and to assess its suitability for drinking and irrigation purposes using hydrochemical indices. Six groundwater samples were collected during the spring season and analyzed for key physicochemical parameters, including electrical conductivity (EC), total dissolved solids (TDS), pH, major cations ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $K^{+}$), and major anions ($HCO_3^{-}$, $SO_4^{2-}$, $Cl^{-}$). In addition, irrigation water quality indices such as sodium adsorption ratio (SAR) and sodium percentage (Na%) were calculated. The results revealed considerable spatial variability in groundwater chemistry, with EC and TDS values indicating a range from freshwater to brackish conditions. The hydrochemical facies were predominantly Ca–$SO_4$ and Ca–$HCO_3$ types, reflecting the influence of carbonate and evaporite mineral dissolution. Comparison with Iraqi standards and World Health Organization (WHO) guidelines showed that several samples exceeded permissible limits, particularly in terms of TDS and sulfate concentrations, rendering them unsuitable for drinking purposes. However, the calculated SAR (0.449–1.865) and Na% (13–34%) values indicate that most groundwater samples fall within excellent to good categories for irrigation, with low sodium hazard and minimal impact on soil structure. Salinity remains the primary limiting factor for agricultural use. The study highlights the combined effects of natural hydrogeochemical processes and anthropogenic activities on groundwater quality in the study area. It emphasizes the need for continuous monitoring and the implementation of sustainable groundwater management strategies to ensure safe utilization of this vital resource.

## INTRODUCTION

Groundwater is one of the most critical natural resources, essential for sustaining human life and supporting environmental and economic development globally. It resides beneath the Earth's surface within the pores and fractures of soil and rock formations, forming aquifers that play a pivotal role in the hydrological cycle. In arid and semi-arid regions, groundwater often serves as the primary and most reliable source of water for drinking, irrigation, and industrial activities [1].The increasing demand for water, driven by rapid population growth, agricultural expansion, and industrialization, has heightened reliance on groundwater resources.

In northern Iraq, including Kirkuk, groundwater is extensively exploited due to the scarcity and

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variability of surface water, making its protection and management vital for long-term sustainability [2]. Hydrogeochemical processes naturally influence groundwater quality. Water–rock interactions, including the dissolution of carbonate and silicate minerals, can elevate concentrations of major cations such as calcium and magnesium, shaping the overall water chemistry [3]. However, anthropogenic activities have emerged as dominant contributors to groundwater pollution. Improper waste disposal, leakage from sewage systems, overuse of fertilizers and pesticides, and industrial effluents introduce contaminants that degrade water quality and pose risks to human health and the environment [4].In oil-producing regions like Kirkuk, industrial activities, especially petroleum extraction and refining, are significant sources of groundwater contamination. Pollutants such as hydrocarbons, heavy metals, and nitrates adversely affect water chemistry, reducing its suitability for human consumption and agricultural use [5]. Urban expansion and inadequate waste management further exacerbate contamination, facilitating the infiltration of pollutants into aquifers and accelerating groundwater deterioration [6].Recent studies have raised serious concerns regarding groundwater quality in Kirkuk.

Assessments using heavy metal pollution indices have revealed that a substantial portion of groundwater samples exceeds permissible drinking water limits [7]. Hydrochemical analyses also indicate that regional groundwater chemistry is strongly influenced by geological formations and evaporite dissolution, often resulting in elevated salinity levels [8]. Despite these studies, there remains a gap in comprehensive evaluations that integrate hydrochemical indices for assessing both drinking and irrigation water suitability.Kirkuk City, with a population of approximately two million people, major oil fields, and extensive agricultural and industrial activities, exerts considerable pressure on groundwater resources. This makes systematic evaluation of groundwater quality and its sustainable management a critical need.Therefore, this study aims to investigate the physicochemical characteristics of groundwater from selected wells in Kirkuk City and assess its suitability for drinking and irrigation using hydrochemical indices, compared against both national and international standards, particularly those established by the World Health Organization (WHO) [9]. This research provides essential baseline data for sustainable water resource management in a region facing increasing anthropogenic pressures.

## MATERIALS AND METHODS

The study area is located in Kirkuk city, northern Iraq between the longitude (44° 23′ 24) east and latitude (35° 28′ 12) north. 240 km away from the capital Baghdad. This study involved six groundwater wells located in Kirkuk City, Northern Iraq, sampled during the spring season (Table 1). The exact locations of the wells were determined using a Global Positioning System (GPS) [10]. Prior to sampling, each well was pumped for 10 minutes to ensure collection of representative water samples. The samples were then collected in clean polyethylene bottles, which were rinsed multiple times with the sample water to prevent contamination, and transported to the Kirkuk Water and Sanitation Directorate laboratories for analysis [11].

Physical and chemical parameters were measured to assess the quality of groundwater. Cations including calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), sodium ($Na^{+}$), and potassium ($K^{+}$), as well as anions such as chloride ($Cl^{-}$), sulfate ($SO_4^{2-}$), and bicarbonate ($HCO_3^{-}$) were determined. Additional parameters measured included electrical conductivity (EC), total dissolved solids (TDS), water hardness, pH, and temperature. The measured values were compared with Iraqi Standard Specifications (IRS 2021) and World Health Organization (WHO) guidelines for drinking water [12, 13].

Sodium percentage (Na%) and Sodium Absorption Ratio (SAR) were calculated to evaluate the suitability of groundwater for irrigation purposes using the following equation

$$Na\% = \frac{Na+K}{Na+Ca+Mg+K} * 100 \ldots\ldots (1)$$

The sodium absorption ratio is calculated from the following equation

$$SAR = \frac{Na}{\frac{\sqrt{Ca+Mg}}{2}} \quad \ldots\ldots\ldots\ldots (2)$$

These indices are widely applied in hydrochemical studies to assess the risk of soil sodicity and water suitability for agricultural use [12, 13].

## RESULTS AND DISCUSSION

### Hydrochemical Characteristics of Groundwater

The analytical results( Table1) of groundwater samples (S1–S6) indicate significant spatial variability in physicochemical parameters, reflecting the combined influence of lithological composition, hydrogeochemical evolution, and semi-arid climatic conditions in the Kirkuk region. Such spatial heterogeneity is typical of groundwater systems in northern Iraq, where water chemistry is strongly controlled by geological formations and evaporation processes (14).

**Table 1.Hydrochemical Characteristics and Suitability Assessment of Groundwater for Drinking and Irrigation in Kirkuk City, Northern Iraq**

| Na% | $Cl^-$ (mg/L) | $SO_4^{2-}$ (mg/L) | $HCO_3^-$ (mg/L) | $K^+$ (mg/L) | $Na^+$ (mg/L) | $Mg^{2+}$ (mg/L) | $Ca^{2+}$ (mg/L) | SAR | pH | TDS (mg/L) | EC (µS/cm) | No. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19.216 | 165 | 1300 | 180 | 3 | 170 | 139 | 400 | 1.865 | 7.7 | 1780 | 2650 | S1 |
| 18.968 | 161 | 1220 | 1220 | 3.5 | 158 | 143 | 360 | 1.781 | 7.3 | 1292 | 2020 | S2 |
| 17.873 | 58 | 390 | 390 | 1.68 | 55 | 57 | 130 | 1.011 | 7.2 | 840 | 1332 | S3 |
| 34.388 | 68 | 260 | 260 | 6 | 25 | 57 | 140 | 0.449 | 7.3 | 1020 | 1603 | S4 |
| 13.522 | 71 | 302 | 302 | 0 | 41 | 60 | 144 | 0.724 | 7.9 | 846 | 1762 | S5 |
| 13.014 | 44 | 125 | 188 | 1.4 | 22.6 | 30.5 | 84 | 0.531 | 7.1 | 546 | 865 | S6 |

#### *pH*

The pH values ranged from 7.2 to 7.9, indicating neutral to slightly alkaline conditions across all samples and falling within acceptable drinking water limits. The relatively narrow pH range suggests a well-buffered groundwater system dominated by carbonate equilibria.

This alkalinity is primarily attributed to the dissolution of carbonate minerals such as calcite and dolomite, which regulate hydrogen ion concentration. The stability of pH further indicates limited influence of anthropogenic acidic contamination and highlights the effectiveness of the bicarbonate buffering system. Similar findings have been reported in groundwater studies in Kirkuk, where carbonate lithology plays a key role in controlling pH (14).

#### *EC and TDS*

Electrical conductivity (865–2650 µS/cm) and TDS (546–1780 mg/L) values reveal a wide variation in salinity, ranging from freshwater to brackish conditions (Table1). Samples S1 and S2 exhibit elevated salinity levels, indicating advanced hydrochemical evolution and higher degrees of mineralization. In contrast, samples S3–S6 represent relatively less evolved groundwater with lower dissolved solids.

The observed salinity variations can be attributed to:

- Prolonged water–rock interaction
- Dissolution of evaporitic minerals (particularly gypsum)
- Evaporation-induced concentration under semi-arid conditions

These findings are consistent with regional studies in Kirkuk, which demonstrate that groundwater salinity is strongly influenced by evaporite-bearing formations and climatic factors (15). Notably, TDS values in S1 and S2 exceed WHO permissible limits, rendering these samples unsuitable for drinking purposes.

### *Major Ions and Geochemical Processes*

*Calcium–Magnesium*

Calcium (84–400 mg/L) and magnesium (30.5–143 mg/L) are the dominant cations in all samples, indicating strong control by carbonate and dolomitic lithology. These elevated concentrations are primarily attributed to the dissolution of calcite and dolomite minerals during water–rock interaction within the aquifer system. In some locations, additional contributions from gypsum dissolution may also enhance calcium levels.

The variation in $Ca^{2+}$ and $Mg^{2+}$ concentrations among samples reflects differences in groundwater residence time and geochemical evolution, where longer interaction with host rocks leads to higher mineralization. From a water quality perspective, high concentrations of calcium and magnesium contribute to total hardness, which may cause scaling in pipes and reduce the efficiency of domestic and industrial water use. However, these ions are not typically associated with significant health risks at the observed levels and can be beneficial in moderate concentrations.

Their elevated concentrations reflect:

- Intensive dissolution of limestone and dolomite
- Additional contribution from gypsum dissolution

This geochemical signature is typical of groundwater systems in Kirkuk (14).

*Sodium*

Sodium concentrations (22.6–170 mg/L) show higher values in S1 and S2, suggesting ( Table1) :

- Cation exchange processes ($Ca^{2+}$ replaced by $Na^{+}$)
- Evaporation effects
- Possible mixing with deeper groundwater

Such mechanisms are widely reported in clay-rich aquifers of northern Iraq (14).

*Potassium*

Table1 show Potassium concentrations remain low (0–6 mg/L), reflecting its limited mobility and strong adsorption onto clay minerals. This behavior is consistent with typical sedimentary aquifer systems.

### *Major Anions and Mineral Sources*

*Sulfate*

Sulfate concentrations (125–1300 mg/L) (Table 1) show significant enrichment, particularly in sample S1, indicating gypsum dissolution as a dominant hydrogeochemical process. This is mainly related to the presence of evaporitic formations in the Kirkuk region, where minerals such as gypsum and anhydrite contribute to elevated sulfate levels through water–rock interaction. The semi-arid climate further enhances sulfate concentration via evaporation processes.

Variations in sulfate among samples may also reflect differences in groundwater flow paths and

residence time, while anthropogenic activities such as agriculture and industrial operations may locally increase sulfate levels. Elevated sulfate concentrations negatively affect water quality by increasing salinity and limiting its

*Bicarbonate*

Bicarbonate concentrations (180–1220 mg/L) reflect active carbonate weathering and $CO_2$ interaction within soil and aquifer systems, confirming the dominance of carbonate geochemistry (14). These elevated levels are primarily generated through the dissolution of carbonate minerals such as calcite and dolomite, facilitated by the presence of carbon dioxide derived from soil respiration and organic matter decomposition, which forms weak carbonic acid.

The variation in bicarbonate concentrations among samples may be attributed to differences in groundwater recharge conditions, residence time, and the extent of water–rock interaction. Higher bicarbonate levels generally indicate more advanced geochemical evolution and stronger buffering capacity of the groundwater system.

From a water quality perspective, bicarbonate plays a key role in stabilizing pH and maintaining alkaline conditions; however, excessive concentrations may contribute to scaling problems in water supply systems and can influence irrigation suitability by affecting soil alkalinity.

*Chloride*

Table 1 show Chloride concentrations (44–165 mg/L) indicate minor salinity influence, likely associated with evaporation and limited mixing with saline water. As a conservative ion, chloride serves as an indicator of groundwater evolution.

**Drinking Water Suitability**

The spatial variation of hydrochemical parameters in Kirkuk groundwater (Figure 1) reveals significant heterogeneity, reflecting differences in geological formations, groundwater flow paths, and the influence of anthropogenic activities across the study area. Comparison with WHO (2022) and Iraqi (IRS, 2021) standards (Table 2) indicates that samples S1 and S2 exceed the permissible limits for TDS and sulfate, rendering them unsuitable for drinking purposes. The elevated concentrations in these samples may be attributed to intensive water–rock interaction, particularly the dissolution of evaporitic minerals such as gypsum, as well as possible impacts from agricultural return flows and industrial activities.

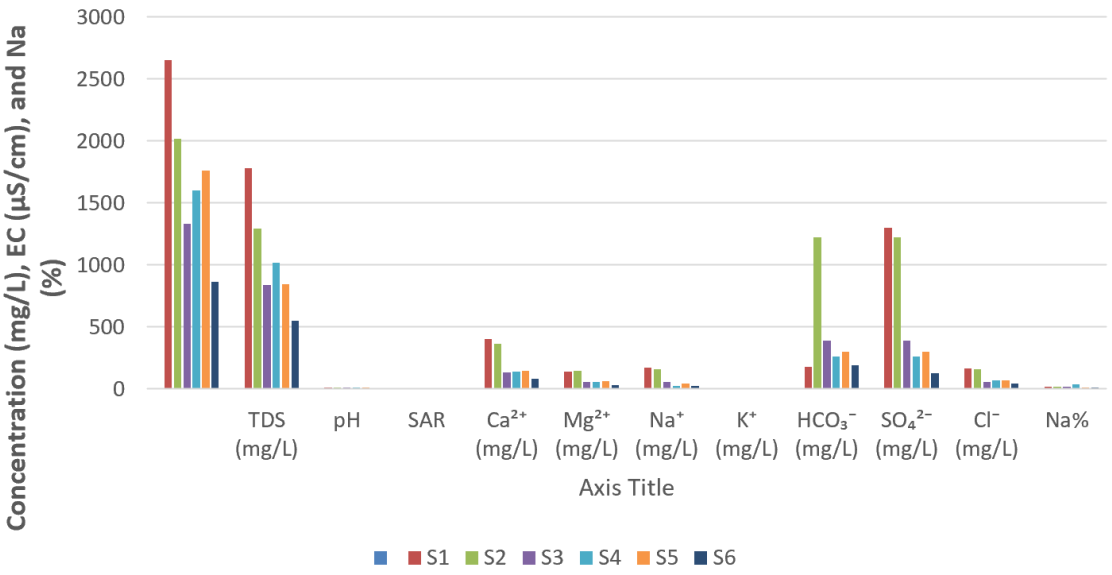



**Figure 1. Spatial variation of hydrochemical parameters in groundwater in Kirkuk city, northern Iraq**

**Table 2. Comparison of groundwater physicochemical parameters with international and national standards for drinking water suitability**

| No. | Chemical analyses | Global Health Organization (WHO.2022 ) | Iraqi specifications (IRS.2021 ) |
|---|---|---|---|
| 1 | Ph | 6.5 – 8.5 | 6.5 – 8.5 |
| 2 | EC (µS/cm) | ≤ 1500 | ≤ 1500 |
| 3 | TDS (mg/L) | ≤ 1000 | ≤ 1000 |
| 4 | $Ca^{2+}$ (mg/L) | ≤ 200 | ≤ 200 |
| 5 | $Mg^{2+}$ (mg/L) | ≤ 150 | ≤ 150 |
| 6 | $Na^{+}$ (mg/L) | ≤ 200 | ≤ 200 |
| 7 | $K^{+}$ (mg/L) | ≤ 12 | ≤ 12 |
| 8 | $SO_4^{2-}$ (mg/L) | ≤ 250 | ≤ 400 |
| 9 | $HCO_3^{-}$ (mg/L) | ≤ 500 | ≤ 500 |
| 10 | $Cl^{-}$ (mg/L) | ≤ 250 | ≤ 350 |

In contrast, samples S3–S6 generally comply with the recommended standards, although TDS values approach the upper permissible limits. This suggests that while the water is currently acceptable for drinking, it may require minor treatment (e.g., desalination or dilution) to ensure long-term safety and palatability. The relatively lower salinity in these samples indicates less geochemical evolution and shorter residence time within the aquifer. The pH values and concentrations of major cations and anions remain within acceptable limits for all samples, indicating a chemically stable groundwater system with minimal risk from acidity or toxic ion concentrations. This stability is largely controlled by carbonate buffering processes within the aquifer matrix.

Overall, groundwater quality in the study area varies spatially, with salinity and sulfate identified as the primary limiting factors for drinking water suitability. These findings highlight the importance of continuous groundwater monitoring, identification of contamination sources, and implementation of targeted water management strategies to ensure safe and sustainable use of groundwater resources in Kirkuk.

## Irrigation Water Suitability

**Table 3. Evaluation of groundwater suitability for irrigation based on physicochemical parameters and hydrochemical indices**

| No. | Chemical analyses | Global Health Organization (WHO.2022 ) | Iraqi specifications (IRS.2021 ) |
|---|---|---|---|
| 1 | Ph | 6.5 – 8.4 | 6.5 – 8.4 |
| 2 | EC (µS/cm) | <700 Excellent 700–3000 Average >3000 Poor | ≤ 3000 |
| 3 | TDS (mg/L) | <450 Excellent / 450– 2000 Pass >2000 Weak | ≤ 2000 |
| 4 | $Ca^{2+}$ (mg/L) | 0 – 400 | 0 – 400 |
| 5 | $Mg^{2+}$ (mg/L) | 0 – 150 | 0 – 150 |
| 6 | $Na^{+}$ (mg/L) | prefers <200 | <200 |
| 7 | $K^{+}$ (mg/L) | – | – |
| 8 | $SO_4^{2-}$ (mg/L) | ≤ 400 | ≤ 400 |
| 9 | $HCO_3^{-}$ (mg/L) | <300 Good 300–500 Pass >500 Not preferred | ≤ 500 |
| 10 | $Cl^{-}$ (mg/L) | <140 Excellent 140–350 Average >350 Harmful | ≤ 350 |
| 11 | %Na | Excellent / 20–40 Good / 40–60 / Unsuitable >60 | - |
| 12 | SAR | Excellent <10 Medium / 10–18 High / 18–26 | - |

Table 3 that reveals:

- Sodium hazard is low: SAR values range from 0.449 to 1.865, indicating minimal risk to soil structure.
- Sodium percentage (Na%) values between 13–34% classify the groundwater as excellent to good for irrigation purposes.
- Salinity is the main limiting factor: Samples S1 and S2 exhibit elevated EC and TDS, which may affect salt-sensitive crops, while S3–S6 fall within safe salinity levels for most agricultural uses.
- Major ions ($Ca^{2+}$, $Mg^{2+}$, $Na^{+}$, $HCO_3^{-}$, $Cl^{-}$, $SO_4^{2-}$) are generally within acceptable ranges, indicating minimal risk of ion toxicity or soil sodicity for irrigation.

Groundwater in Kirkuk is largely suitable for irrigation, with low sodium hazard, but proper salinity management is required in areas with higher EC and TDS to prevent potential adverse effects on crop yield and soil quality.

## CONCLUSION

Groundwater quality in Kirkuk shows notable spatial variability influenced by natural hydrogeochemical processes and human activities. While most samples meet acceptable standards for irrigation, with low sodium hazard (SAR and Na%), salinity remains the main limiting factor in some locations. For drinking purposes, certain wells exceed permissible limits, particularly in TDS and sulfate, making them unsuitable without treatment. Continuous monitoring and sustainable groundwater management are essential to ensure safe and efficient use of this resource.

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