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Groundwater quality assessment for the wells system in Zurbatiyah, Iraq, for civil and irrigation uses by two water quality index approaches

Marwan Arkan Hussein[1*], Sadiq S. Muhsun[2], Zaidun Naji Abudi[2]

[1] Environmental Engineering Department, College of Engineering, Mustansiryiah University, Baghdad, Iraq
[2] Mustansiryiah University, College of Engineering, Baghdad, Iraq
* Corresponding author's e-mail: marwana.hussein@uomustansiriyah.edu.iq

ABSTRACT

Groundwater quality in the Zurbatiyah sub-district, eastern Iraq, was assessed using the arithmetic water quality index (AWQI) and the Canadian water quality index (CCME-WQI). Field data were collected from six wells over a five-month period, and twelve physico-chemical parameters were analyzed. AWQI scores ranged from 5.46 to 84.77, classifying water quality from "excellent" to "poor", depending on the well and season. In contrast, CCME-WQI scores ranged from 49.5 to 58.6, with all wells classified under the "marginal" category, indicating frequent exceedances of permissible limits. The findings reflect high spatial and temporal variability, with parameters such as EC (1.750–6.120 μS/cm) and TDS (805–4.590 mg/L) often exceeding national and international guidelines. These results suggest moderate to severe salinization, particularly during peak irrigation months. Overall, CCME-WQI was found to provide a more conservative and realistic assessment of water quality risk, while AWQI tended to overestimate quality under certain seasonal conditions. The study highlights the need for continuous groundwater monitoring and sustainable water management in semi-arid regions. Based on Iraqi and FAO standards, none of the wells were suitable for drinking, while only two were deemed conditionally suitable for irrigation purposes.

Keywords: groundwater quality, seasonal variation, water quality index, semi-arid region, hydrochemical assessment.

INTRODUCTION

Among the most pressing global challenges in the 21st century are ensuring sustainable access to water, food, and energy. Addressing these interconnected crises requires a shift in perspective – particularly in how we manage water resources. Increasingly, domestic wastewater and groundwater are being viewed not as waste but as valuable resources that can be harnessed and treated to alleviate water scarcity (Alcamo, 2019; Zaidun Naji Abudi, 2018). Much of the pollution loads occurring in the water result from the excessive use of water resources, which has led to the deterioration of groundwater quality in many developing countries (Noor et al., 2022). With limited and often migratory surface water availability over the season due to climatic changes and transboundary water disagreements (Al-Yasiri, 2021; Noga et al., 2024; Zolnikov, 2013), In arid and semiarid regions like Iraq, groundwater is a primary source of water for industry, agriculture, and drinking. Iraq has been suffering from chronic water stress for the last twenty years as a result of upstream damming, water mismanagement and less precipitation, pushing communities in many governorates – including Wasit – to depend heavily on groundwater as an alternative supply (Al-Sudani, 2024; Eltaif et al., 2024). Seepage through porous media is influenced by multiple factors, including the type of soil, hydraulic gradient, fluid properties, and the structural nature of the system. Understanding seepage mechanisms is essential in groundwater movement and contamination studies. Researchers have developed various approaches to analyze seepage flow, including analytical, experimental, and numerical methods (Ahmed et al., 2020). However, groundwater quality in Iraq has significantly deteriorated due to multiple factors including the lack of wastewater treatment infrastructure, excessive use of chemical fertilizers, infiltration of contaminants into shallow aquifers, and complex geologic structures rich in evaporitic and carbonate rocks (Al-Sheikh et al., 2019; Al-Sudani and Fadhil, 2024). These natural and anthropogenic influences have led to elevated concentrations of dissolved ions, such as chloride, sulphate, calcium, and total hardness, making groundwater increasingly unsuitable for drinking or irrigation without prior assessment and treatment (Muslim et al., 2024). The Zurbatiyah subdistrict, which is part of the area where groundwater is a major source of water for domestic and agricultural needs, is located on the eastern side of the Wasit Governorate, close to the Iraqi-Iranian border. All over the area, Quaternary sediments are overlapping older formations including Fatha and Mukdadiyah behind the geochemical complexity of aquifer system(Al-Shamaa and Ali, 2012; Hassan et al., 1977). Previous regional hydrochemical studies and field observations (Muslim et al., 2024; Rdhewa et al., 2023) showed that Badra–Zurbatiyah groundwater generally is saline and defaulting with both hardness and high anions (sulphate, chloride). Analyzing groundwater quality in the focus of particular constituent only does not give appropriate the flexibility of use. In this context, numerous WQIs have been designed to aggregate multiple parameters into a single value, which encapsulates a general status of the water quality. Of these indices, the AWQI (Rubio-Arias et al., 2012) and the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) have gained more popularity and have been more used for water classification and monitoring (Chandra et al., 2017; Ramadhan et al., 2018; Wagh et al., 2017). This study has generally aimed to evaluate the groundwater physicochemical quality in the Zurbatiyah sub-district using two commonly practiced water quality models, specifically the Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) and the AWQI. The assessment covers five consecutive months and includes spatial and temporal variations across six wells. This study provides a novel integration of AWQI and CCME-WQI approaches to evaluate groundwater quality under semi-arid hydrogeological conditions. Unlike previous studies, this research simultaneously applies both indices across multiple wells and time periods, enabling a comparative analysis that captures seasonal irrigation patterns, groundwater over-extraction, and their effects on water quality. The purpose of the research is to improve decision-making for household and agricultural use in at-risk areas and promote the long-term viability of groundwater management.

MATERIALS AND METHODS

Description of the study area

The research was conducted in the Zurbatiyah subdistrict of Iraq's Wasit Governorate, which is close to the international border with Iran. This area lies within the Badra–Jassan Basin, a hydrogeologically active zone characterized by semi-arid climatic conditions, low and irregular rainfall, and high evaporation rates. Because of the scarcity in surface water, the local community, who are mainly rural dwellers, depend mainly on groundwater resources for drinking and irrigation(Al-Shamaa and Ali, 2012). The region is generally flat, and gentle slopes allow for infiltration in the rainy season. Quaternary alluvial deposits cover most of the area with older Fatha and Mukdadiyah Formations found underneath. These formations comprise gypsum, anhydrite, limestone and clay, which affect the groundwater with markedly high sulphate, calcium and total hardness contents (Al-Sheikh and AL-Shamma'a, 2019; Hassan et al., 1977). The aquifer system in Zurbatiyah is primarily unconfined to semi-confined aquifers with water table depths varying from 8 m and 20 m due to flow directions and distance from recharge areas (northern up slopes). Surface water entering the soil as a result of rainfall and lateral sub-surface flow from neighbouring regions is where regional groundwater recharge takes place (Al-Sudani, 2024). The six monitored wells in three main residential and agricultural sites – Al-Ta'an, Old Zurbatiyah, Arafat, and Warmizyar – were selected. The locations were identified using official maps and well data GCM (General Commission for Ground Water) in Baghdad, which were the main references for determining the study area. Figure 1 shows the location map of the Zurbatiyah sub-district, with the study area outlined in red.

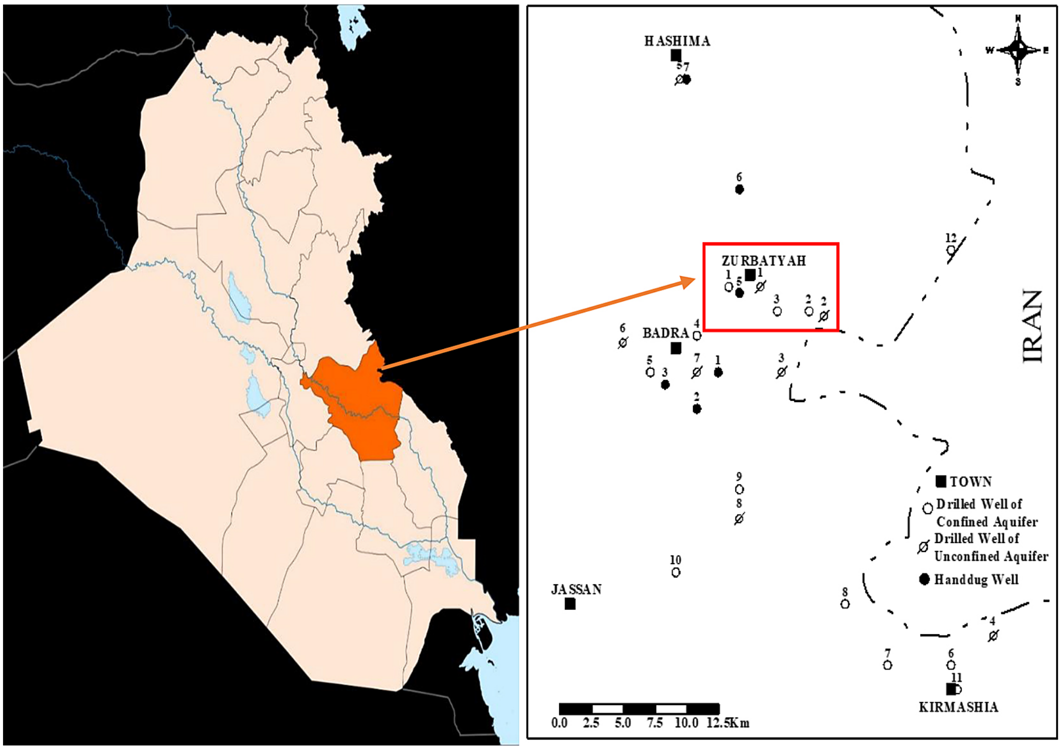

Figure 1. Zurbatiyah sub-district, Wasit Governorate, Iraq location map. Red box outlines the study area

SAMPLING AND DATA COLLECTION

Groundwater samples have been taken from a total of six wells scattered in the Zurbatiyah district. A sampling campaign was conducted over five periods: December, February, April, May, and June. To ensure data integrity, all samples were obtained in spotless polyethylene containers, stored at 4 °C, and inspected no more than 24 hours after collection.In laboratory experiment, twelve physical and chemical parameters were determined: pH, electrical conductivity (EC), total dissolved solids (TDS), turbidity, nitrate (NO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), total hardness, calcium (Ca^{2+}), magnesium (Mg^{2+}) sodium (Na^+), iron (Fe) All analyses were conducted by the American Public Health Association's (APHA) standard protocols (Association et al., 1917) and compared with Central Organization for Standardisation and Quality Control (COSQC) and FAO irrigation water guidelines as appropriate. Table 1 provides detailed information about the depth and location of the six monitoring wells, including the names of the areas where they are situated.

WATER QUALITY INDICES (WQIS)

Two WQI models were applied to assess the groundwater quality:

Arithmetic water quality index (AWQI)

The AWQI is a composite metric designed to evaluate overall water quality. It is derived by

Table 1. Location and depth of the groundwater monitoring wells in the Zurbatiyah sub-district

Aquifer type / Well construction	Site No.	Location	Depth
Confined 1(o)	SITE 1	Al-Ta'an	(60 m)
Confined 2(o)	SITE 2	Old Zurbatiyah	(60 m)
Confined 3(o)	SITE 3	(Arafat)	(61 m)
Unconfined 1(Ø)	SITE 4	Warmazyar	(45 m)
Unconfined 2(Ø)	SITE 5	Old Zurbatiyah	(45 m)
Handdug well 5(•)	SITE 6	Al-Ta'an	(45 m)

assigning a weight to each parameter relative to its significance and standard limit. The calculation follows a series of steps:

- Step 1: Calculate the unit weight w_n for each parameter using its standard permissible value Sn

$$k = \frac{1}{\sum \frac{1}{Sn}} \quad (1)$$

$$w_n = \frac{k}{s_n} \quad (2)$$

where: w_n – the unit weight of the nth parameter, s_n – standard allowable value for the n^{th} parameter, k – proportionality constant.

- Step 2: Compute the quality rating scale (sub-index) for each parameter

$$Qn = 100 \times \frac{Vn}{Sn} \quad (3)$$

where: Qn – quality ranking for the nth parameter, Vn – measured concentration of the nth parameter, Sn – standard permissible value for the n_{th} parameter.

- Step 3: Compute the overall AWQI

$$AWQI = \Sigma(WnQn) \quad (4)$$

The weighting of each parameter was determined according to its relative significance for human health and water suitability, in alignment with methodologies adopted by earlier research (Alikhan et al., 2020; Chandra et al., 2017). The AWQI results in this study were interpreted using the classification system shown in Table 2, which classifies water quality on a scale from excellent to unsuitable for drinking, following the framework proposed by Chandra et al. (2017).

Canadian water quality index (CCME-WQI)

The CCME-WQI (Fatih Ali et al., 2021) was computed using the Canadian Council of Ministers of the Environment's (CCME, 2001) F1–F2–F3 model. This index uses the following criteria to evaluate water quality:

- F1 (scope) – number of parameters above thresholds.

$$F_1 = \frac{\text{NO.}\, Fail\,d\ variables}{Total\ number\ of\ variables} \times 100 \quad (5)$$

- F2 (frequency) – the percentage of individual tests not meeting guidelines

$$F_2 = \frac{\text{NO.}\, Faild\ tests}{Total\ number\ of\ tests} \times 100 \quad (6)$$

- F3 (amplitude) – the excess of failed tests over the objectives

$$F_3 = \frac{nse}{0.01nse + 0.01} \quad (7)$$

where: nse – normalised SUM excursion.

- Final index derived from

$$\text{CCME WQI} = = 100 - \frac{\sqrt{F1^2 + F2^2 + F3^2}}{1.732} \quad (8)$$

The CCME-WQI classification system is detailed in Table 3.

WATER QUALITY STANDARDS FOR EVALUATION

Measured parameter values were compared to known national and international norms for drinking and irrigation uses to assess groundwater suitability. The permissible limits according to the FAO irrigation guidelines and Iraqi standards for drinking water (COSQC, 2009) are shown in Table 4 (Ayers and Westcot, 1985).

RESULTS AND DISCUSSION

Physico-chemical characteristics of groundwater

PH

The pH values of groundwater across all wells ranged from 7.7 to 8.6, indicating slightly alkaline conditions. These values remained within the acceptable limits for both drinking and irrigation

Table 2. Water quality classification according to AWQI scores (Chandra et al., 2017)

WQI	WQS
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
> 100	Unfit for consumption

Table 3. CCME-WQI classification of water quality (Al-Obaidy et al., 2022)

CCME WQI	Ranking
95–100	Excellent
80–94	Good
65–79	Fair
45–64	Marginal
0–44	poor

water as per Iraqi and FAO standards (IQS 417, 2009; FAO, 1985). Spatial variation was minimal among the wells, suggesting homogeneity in aquifer geochemistry. Temporally, no clear seasonal pattern was observed, which reflects the buffering capacity of carbonate-rich formations underlying the study area (Al-Sheikh and AL-Shamma'a, 2019). Figure 2A illustrates the seasonal and spatial variation in pH values across the six monitored wells.

Electrical conductivity (EC)

Electrical conductivity (EC) is a key indicator of salinity, reflecting the total concentration of dissolved ions in groundwater. During the monitoring period, EC values across the six wells ranged from 1750 µS/cm (Well 3 – May) to 6120 µS/cm (Well 4 – February). These levels significantly exceed the Iraqi standard for drinking water (2000 µS/cm) and often surpass the FAO threshold for irrigation (3000 µS/cm), raising concerns about salinity impacts on both domestic and agricultural uses (IQS 417, 2009; FAO, 1985).

Well 4 consistently recorded the highest EC values, likely due to underlying Fatha Formation deposits rich in halite and gypsum, which promote mineral dissolution(Al-Sudani, 2024; Hassan et al., 1977). In contrast, Well 3 recorded the lowest values, possibly reflecting localized recharge and dilution effects.

High EC during winter irrigation months (December–April), followed by slight reductions in late spring, indicates that excessive pumping may drive short-term salinity accumulation, with partial recovery occurring during the harvest period (April to June) when pumping is reduced. Figure 2B displays the temporal and spatial distribution of EC across all sampling wells.3.1.3**.**

Total dissolved solids (TDS)

Total dissolved solids (TDS) concentrations in groundwater samples varied significantly, ranging from 805 mg/L (Well 3 – May) to 4590 mg/L (Well 4 – December). All wells exceeded the Iraqi standard for drinking water (1000 mg/L), and most readings surpassed the FAO limit for irrigation (2000 mg/L), indicating elevated salinity levels that could impair both domestic use and agricultural productivity (IQS 417, 2009; FAO, 1985).

Spatially, Well 4 recorded the highest salinity across all seasons, likely due to its geological setting rich in evaporitic formations such as gypsum and halite(Al-Sudani and Fadhil, 2024; Hassan et al., 1977). In contrast, Well 3 exhibited notably lower values in May and June, possibly reflecting seasonal recharge and reduced abstraction. The seasonal trend showed higher TDS levels in winter (Dec–Apr), coinciding with intensive

Table 4. Permissible limits for drinking and irrigation water quality, Ayers and Westcot, 1985

Parameter	Unit	Iraq standard (drinking)	FAO guideline (irrigation)
pH	-	6.5–8.5	6.5–8.4
EC	µS/cm	2000	3000
TDS	mg/L	1000	2000
Turbidity	(NTU)	5	—
Nitrate (NO_3^-)	mg/L	50	50–100 (general)
Chloride	mg/L	350	700
Sulphate	mg/L	400	900
Hardness	mg/L (as $CaCO_3$)	500	600–750
Calcium	mg/L	150	400
Magnesium	mg/L	100	250
Sodium	mg/L	200	300
Iron	mg/L	0.3	—

groundwater extraction for irrigation, and a relative decline in late spring (May–June), likely due to reduced pumping during the harvest period(Al-Sudani, 2024). Figure 2C shows the variation in TDS concentrations across wells during the five-month monitoring period.

Turbidity

Turbidity values in the monitored wells ranged from 1.3 NTU (Well 1 – May) to 22 NTU (Well 5 – April) with several readings exceeding the Iraqi standard limit for drinking water, which is set at 5 NTU (IQS 417, 2009). Although turbidity is not a direct indicator of chemical contamination, it plays a critical role in microbial water quality and aesthetic acceptability. High turbidity can shield pathogens from disinfection and indicates potential contamination by suspended solids or organic matter. Spatially, Well 4 consistently recorded higher turbidity levels, likely due to shallow depth and possible surface infiltration. Seasonal patterns showed elevated turbidity during the winter months (December–February), which may be attributed to increased water extraction, disturbed sediments, and possibly surface runoff entering the aquifer system. These findings are consistent with previous regional studies in similar geological contexts (Al-Sheikh and AL-Shamma'a, 2019). Figure 2D presents the turbidity levels recorded in the groundwater samples across all wells and seasons.

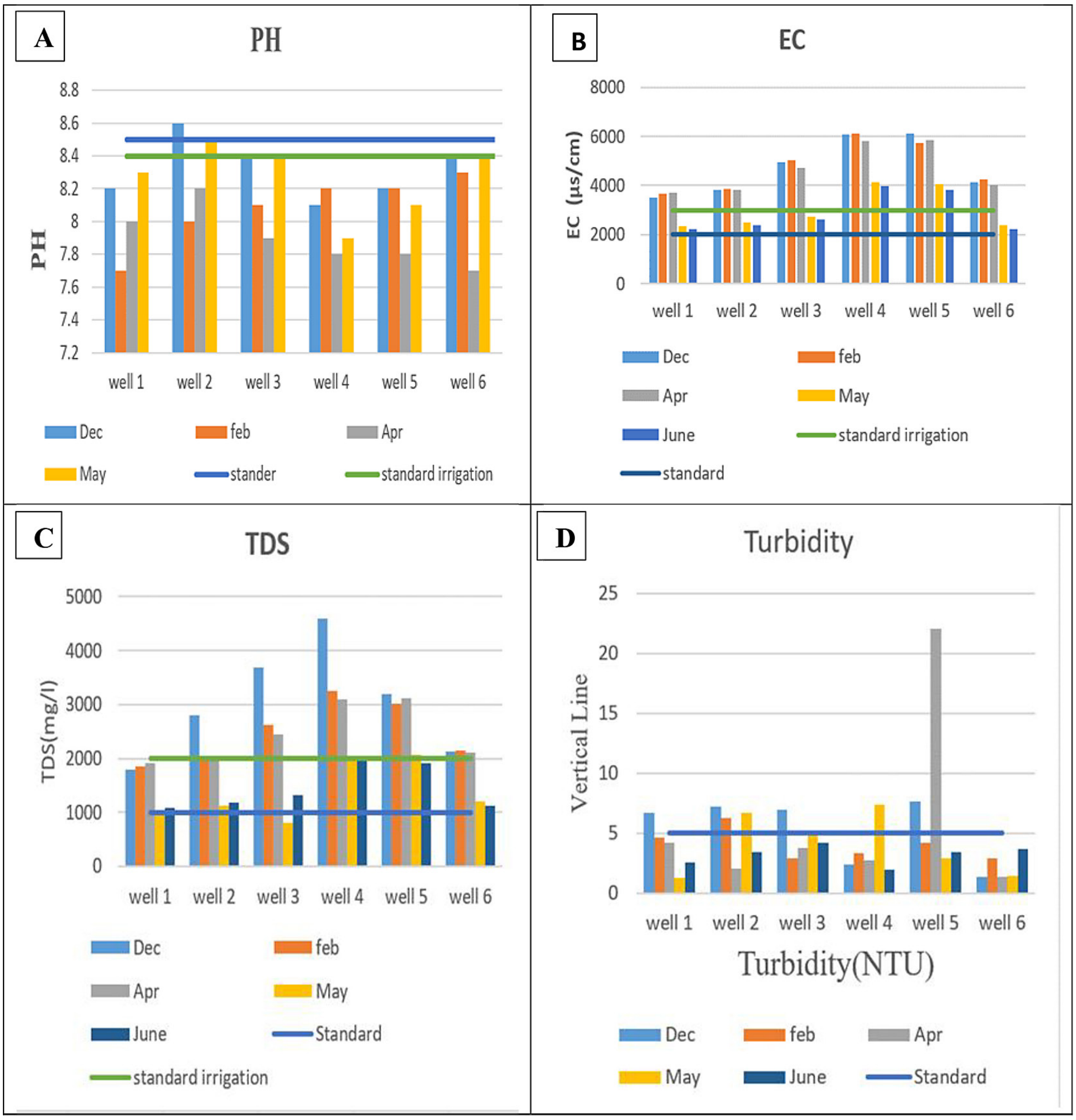

Figure 2. Seasonal and spatial distribution of physical parameters: (A) pH, (B) electrical conductivity, (C) total dissolved solids, (D) turbidity

Nitrate (NO_3^-)

Nitrate is a key indicator of groundwater contamination, primarily resulting from nitrogen-based fertilizers and wastewater infiltration (Al-Sudani and Fadhil, 2024; Hassan et al., 1977). Concentrations in this study ranged from 4.41 mg/L (Well 6 – December) to 16.1 mg/L (Well 6 – May), all within the Iraqi drinking water limit of 50 mg/L (IQS 417, 2009). Although FAO does not prescribe a strict nitrate threshold for irrigation, levels up to 50–100 mg/L are generally acceptable for most crops (Ayers and Westcot, 1985). The highest values observed in Well 6 during May suggest nitrate accumulation from prior fertilization. This may persist post-harvest, given nitrate's mobility in the soil profile (Chidiac et al., 2023). Figure 3A shows the seasonal and spatial variation of nitrate concentrations across all sampled wells.

Chloride (Cl^-)

Chloride concentrations in the groundwater samples ranged from 739.7 mg/L (Well 2 – June) to 2,739 mg/L (Well 4 – February), significantly exceeding the Iraqi drinking water standard of 350 mg/L (IQS 417, 2009) across all wells and sampling periods. The elevated levels reflect the geologic nature of the aquifer system, particularly the presence of evaporitic formations such as gypsum and halite in the Fatha Formation (Al-Sheikh and AL-Shamma'a, 2019; Hassan et al., 1977). Additionally, prolonged groundwater pumping during the irrigation season (December–April) likely contributes to salt concentration due to reduced recharge and increased evaporation. Well 4 (Warmizyar) consistently recorded the highest chloride concentrations, suggesting either localized salinity accumulation or reduced dilution potential. In contrast, Wells 1 and 2 had relatively lower concentrations, although still well above permissible limits. According to FAO guidelines (Ayers and Westcot, 1985), chloride concentrations exceeding 700 mg/L are unsuitable for irrigation use. High chloride content in groundwater poses risks for both domestic and agricultural use, as it can cause corrosion in plumbing systems and reduce soil permeability over time. Figure 3B

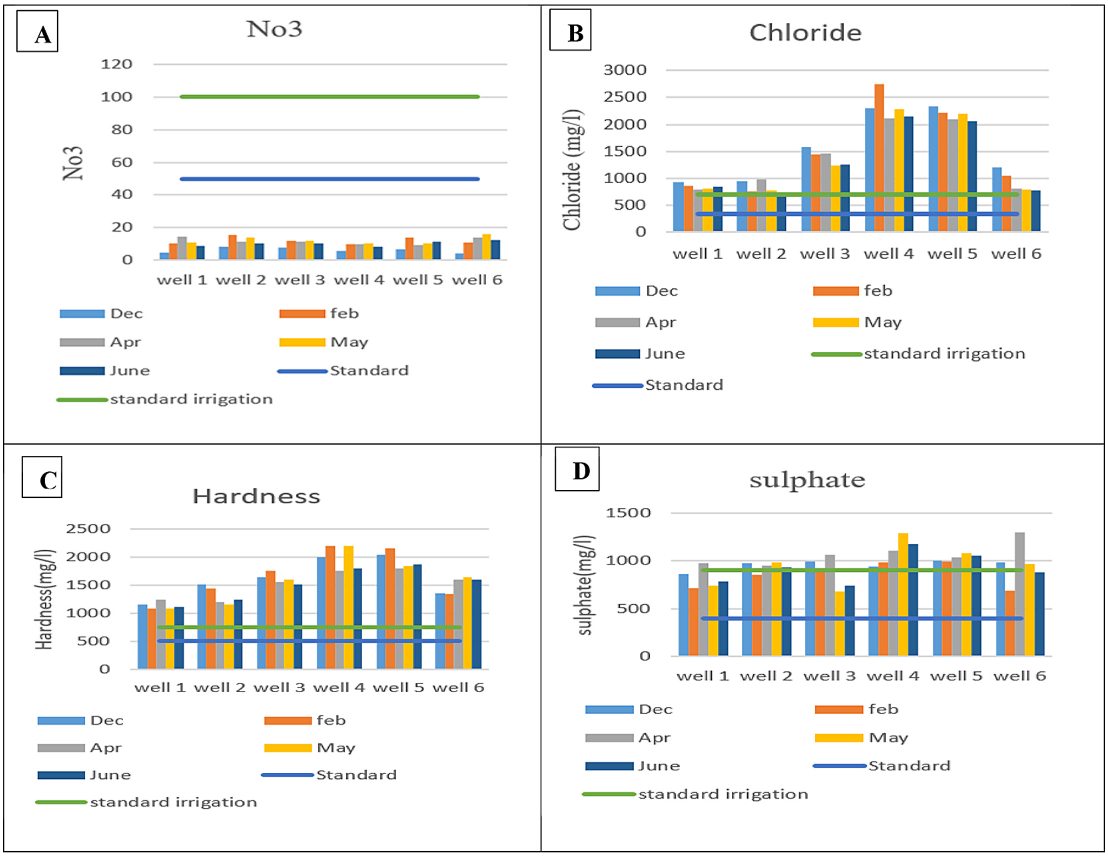

Figure 3. Monthly and spatial variation of major anions and hardness: (A) nitrate, (B) chloride, (C) sulphate, (D) total hardness

illustrates the chloride levels measured at each well during the monitoring period.

Total hardness

Total hardness (TH) in groundwater is a measure of the concentration of divalent metal ions – mainly calcium (Ca^{2+}) and magnesium (Mg^{2+}) – and reflects the degree of mineralization resulting from the interaction between water and the aquifer's lithology. In Zurbatiyah, the dominance of carbonate and sulfate minerals within the Fatha Formation leads to high natural hardness (Alfalahi and Aldhamin, 2025; Al-Sheikh and AL-Shamma'a, 2019). In this study, TH values ranged from 1080 mg/L (Well 1 – Feb and May) to 2200 mg/L (Well 4 – Feb and May).

All wells substantially exceeded the Iraqi drinking water standard (500 mg/L), indicating that the groundwater is classified as very hard. Such water is associated with scaling, reduced soap efficiency, and may require softening before domestic use. From an agricultural perspective, according to FAO (1985), water with total hardness above 600–750 mg/L can cause soil structure degradation and reduce water infiltration rates, thereby posing challenges for sustainable irrigation (Ayers and Westcot, 1985). The peak hardness levels observed in Well 4 during February and May coincide with periods of high groundwater withdrawal for agricultural irrigation. This may have led to ion concentration due to limited recharge and evapoconcentration effects. Figure 3 presents the monthly variation in total hardness across all monitored wells. Figure 3C presents the hardness values across all wells and sampling months.

Sulfate (SO_4^{2-})

Sulphate (SO_4^{2-}) is one of the most prevalent elements in groundwater chemical composition, its origins are majorly through gypsum and anhydrite solution from sediment rocks (Ibrahim et al., 2021). These formations are highly present in the areas of Fatha and Mukdadiyah in the Zurbatiyah region, and they contribute the sulfate in abundance (Al-Sheikh and AL-Shamma'a, 2019).

In the current study, sulfate concentrations ranged from 677.8 mg/L (Well 3 – May) to 1304 mg/L (Well 6 – April). All recorded values surpass the Iraqi permissible limit for drinking water (400 mg/L), suggesting that the groundwater is not suitable for human consumption unless properly treated. From an irrigation perspective, FAO guidelines consider water containing up to 900 mg/L of sulfate generally suitable for some crops.

However, concentrations above this level may pose risks such as soil salinity, reduced crop yield, and accumulation of salts in poorly drained soils. The highest values were recorded during April and May, likely due to intensive groundwater pumping for pre-harvest irrigation. Reduced aquifer recharge during these months may have intensified evapoconcentration, elevating sulfate levels in the wells. Figure 3D displays the monthly and spatial distribution of sulphate concentrations across the six wells.

Calcium (Ca^{2+})

Calcium concentrations ranged from 123.3 mg/L (Well 1 – December) to 768 mg/L (Well 4 – May), exceeding the Iraqi drinking standard of 150 mg/L (IQS 417, 2009) in most samples. These elevated levels are mainly attributed to the dissolution of gypsum and limestone from the Fatha and Mukdadiyah formations (Al-Sheikh and AL-Shamma'a, 2019; Hassan et al., 1977). Peak values occurred during the irrigation season (February–May), likely due to increased water extraction and lower dilution. Well 4 recorded the highest concentrations, aligning with its high total hardness and sulfate levels. According to FAO guidelines (Ayers and Westcot, 1985), calcium levels above 400 mg/L may render groundwater unsuitable for irrigation. Elevated calcium contributes to water hardness and scaling issues. Figure 4A shows the seasonal distribution of calcium concentrations across all wells.

Magnesium (Mg^{2+})

Magnesium levels ranged from 29.2 mg/L (Well 2 – May) to 229.3 mg/L (Well 5 – February), with many samples exceeding the Iraqi drinking standard of 100 mg/L (COSQC, 2009). The source of magnesium is primarily the dissolution of dolomite and gypsum in the aquifer matrix (Muslim et al., 2024). Elevated concentrations during February and April align with peak irrigation withdrawal. According to FAO guidelines (Ayers and Westcot, 1985), magnesium concentrations above 250 mg/L are considered hazardous for irrigation purposes. While FAO (1985) provides no strict threshold, high magnesium levels may reduce soil permeability and increase alkalinity, especially in clay-rich soils (Chidiac et al., 2023; Ewaid et al., 2019). Magnesium also contributes to permanent hardness and scaling in domestic systems. Figure 4B presents the spatial and temporal variation in magnesium levels throughout the study area.

Iron (Fe)

Iron concentrations ranged from 0.0001 mg/L (Well 3 – April) to 0.2526 mg/L (Well 5 – February), remaining within the Iraqi drinking water limit of 0.3 mg/L (COSQC, 2009). Slightly elevated values in Wells 4 and 5 during colder months may result from local lithology, organic matter decomposition, or corrosion of well components (Ewaid et al., 2019).

Although these levels pose no direct health risk, iron may cause taste issues, staining, and biofouling in water systems. Reducing aquifer conditions during wet seasons may further enhance iron mobility. Figure 4C displays the iron concentrations across the six wells during all sampling periods.

Sodium (Na^+)

Sodium concentrations ranged from 142 mg/L (Well 1 – February) to 874 mg/L (Well 5 – April), with most values – particularly from April to June – exceeding the Iraqi standard of 200 mg/L for drinking water (COSQC, 2009). According to FAO guidelines (Ayers and Westcot, 1985), concentrations above 300 mg/L are considered unsuitable for irrigation due to their adverse effects on soil permeability. High sodium levels can pose health risks for sensitive populations and contribute to scaling in plumbing systems (Chidiac et al., 2023). From an agricultural perspective, sodium negatively impacts soil structure and permeability, especially in clay-rich soils, potentially reducing crop productivity (Ayers and Westcot, 1985). Elevated values in Wells 4 and 5 are likely due to lithological influences and return flows from irrigated fields. Figure 4D illustrates the sodium content variations observed in groundwater samples across different wells and seasons.

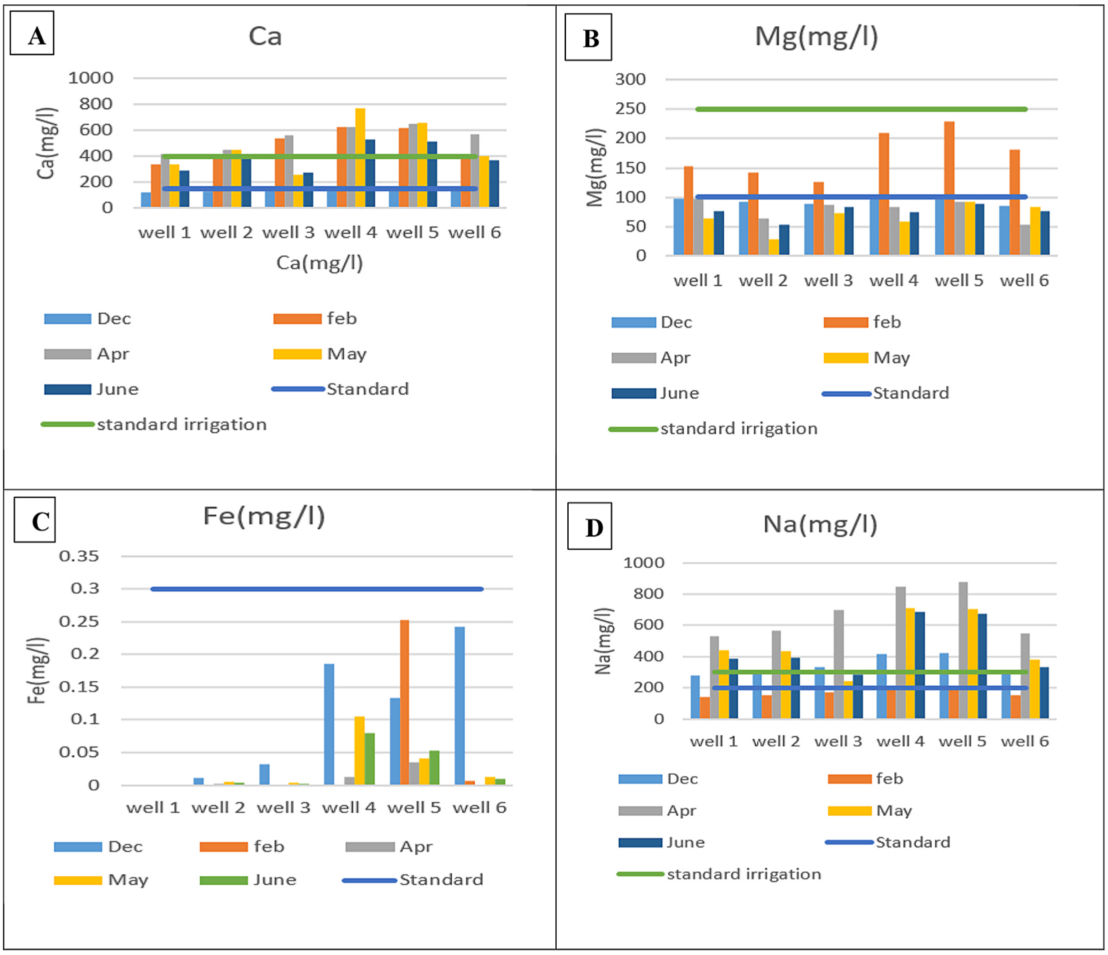

Figure 4. Distribution of major cations and trace metals: (A) calcium, (B) magnesium, (C) iron, (D) sodium

GROUNDWATER QUALITY ASSESSMENT USING WQI METHODS

The AWQI and the CCME-WQI were employed to evaluate the overall quality of groundwater. Both indices integrate multiple water quality parameters into a single numerical value, facilitating the interpretation of water suitability for domestic and agricultural applications.

AWQI results showed monthly and spatial variability. Most wells during February, April, and June fell into the "excellent" or "good" categories, while higher index values were observed in Site 6 (December) and Site 4 (May), reflecting seasonal influences and localized contamination. Table 5 presents the AWQI results across all wells and months, while Figure 5 visualizes their spatial trends. AWQI values were computed for each well during December, February, April, May, and June. The results are summarized in Table 5.

CCME-WQI values for all sites ranged between 49.6 and 58.6, classifying all groundwater samples as "marginal" quality. This reflects frequent exceedances of critical parameters such as TDS, EC, chloride, and sodium. While the water may still be usable, treatment or blending is required for safe domestic use. Table 6 summarizes CCME-WQI scores, and Figure 6 illustrates site-wise variation. When compared, CCME-WQI yielded more conservative classifications than AWQI, capturing frequency and magnitude of violations – making it more aligned with field observations in this semi-arid setting.

COMPARATIVE ANALYSIS OF AWQI AND CCME-WQI

A comparative evaluation of the two applied indices – AWQI and CCME-WQI – revealed significant differences in how groundwater quality was classified across the six monitoring wells. While AWQI often rated the water as Excellent to Good, especially during non-irrigation periods (May and June), the CCME-WQI consistently categorized all sites as Marginal. This divergence stems from methodological differences: AWQI relies on arithmetic averaging, which can mask occasional parameter exceedances, whereas CCME-WQI incorporates the frequency and magnitude of exceedances relative to standard thresholds, providing a more conservative and realistic classification.

The tendency of AWQI to overestimate water quality makes it less reliable in semi-arid regions like Zurbatiyah (Ouhakki et al., 2024; Ramadhan et al., 2018; Wagh et al., 2017), where seasonal fluctuations and human activities cause irregular contamination patterns. In contrast, CCME-WQI offered more consistent results, aligned with field observations and chemical parameter trends, especially in wells 4 and 5, where EC, chloride, and sodium were persistently elevated. The AWQI method, based on arithmetic mean calculations, may underestimate risks in scenarios where parameter exceedances are frequent but mild, as it does not account for the magnitude or frequency of violations. This makes it less sensitive to parameters that fluctuate seasonally or exceed thresholds repetitively. In contrast, the CCME-WQI model considers both the frequency and amplitude of standard violations, which allows for a more conservative and realistic assessment—especially in semi-arid regions with intermittent contamination patterns and irregular groundwater recharge. Therefore, despite both indices offering useful insights, CCME-WQI proved to be more appropriate for evaluating groundwater quality under variable hydrogeological and anthropogenic pressures.

Table 5. Monthly AWQI values for all wells (December to June)

Month	Dec	Feb	Apr	May	June
Well 1	11.01	9.14	8.92	5.46	6.77
Well 2	15.77	10.94	7.2	12.76	8.87
Well 3	21.4	7.99	8.81	10.12	9.21
Well 4	62.36	8.89	11.79	44.2	30.74
Well 5	52	84.77	39.3	20.13	24.03
Well 6	77.63	9.32	6.04	9.34	10.92

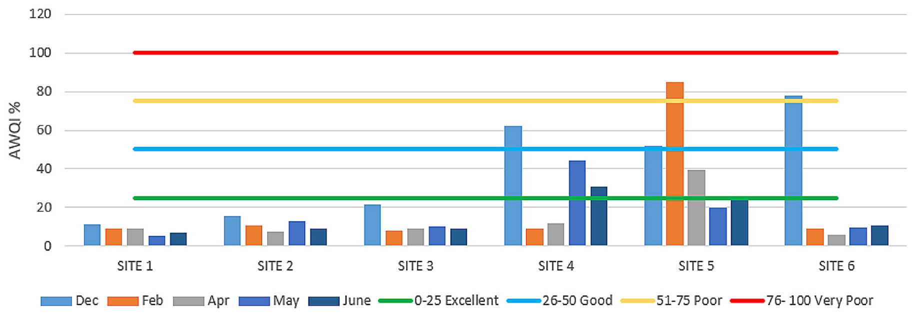

Figure 5. Monthly variation of AWQI scores across six groundwater wells in Zurbatiyah

Table 6. Canadian water quality index (CCME-WQI) scores and classifications for groundwater wells

SITE	CCME WQI	Classification
SITE 1	58.668	Marginal
SITE 2	54.299	Marginal
SITE 3	56.332	Marginal
SITE 4	49.803	Marginal
SITE 5	49.585	Marginal
SITE 6	52.788	Marginal

DISCUSSION

The results of this study highlight significant spatial and seasonal variability in groundwater quality across the Zurbatiyah sub-district. Parameters such as TDS, EC, chloride, sulfate, sodium, and hardness frequently exceeded the Iraqi drinking standards, reflecting the geochemical nature of the aquifer system and the effects of intensive groundwater abstraction during the irrigation season (Al-Sheikh and AL-Shamma'a, 2019; Al-Sudani, 2024). According to scientific studies, sulfates are linked to gastrointestinal disorders (Al-Khatib et al., 2023), while excess chloride alters the sensory characteristics of water, reducing its desirability (Todd, 2024).The consistent exceedance of key parameters, particularly in Wells 4 and 5, suggests strong lithological influence from gypsum- and halite-bearing formations, compounded by anthropogenic factors such as fertilizer application and return flows from agricultural fields (Hassan et al., 1977; Muslim et al., 2024). Seasonal patterns – marked by higher concentrations from December to April – align with periods of intense groundwater withdrawal and reduced recharge. The use of both AWQI and CCME-WQI provided complementary insights. AWQI offered a quick general classification, while CCME-WQI more accurately captured the real limitations of water quality, especially where multiple parameters exceeded permissible thresholds. This supports the argument that index-based assessments must be tailored to regional hydrogeological contexts (Chidiac et al., 2023). Furthermore, while calcium, magnesium, and total hardness were directly measured, the relationship between these parameters was consistent with theoretical models, reinforcing the reliability of

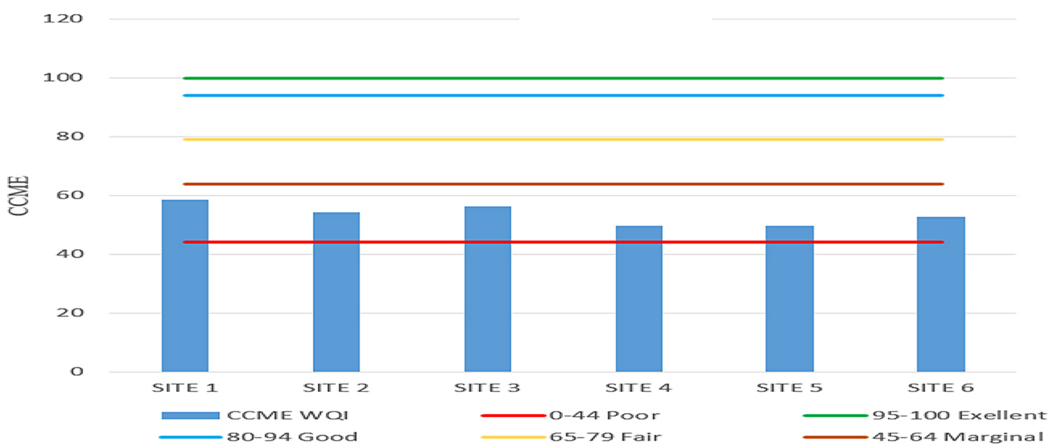

Figure 6. CCME-WQI scores for groundwater wells in Zurbatiyah sub-district

field measurements. Minor variations may arise from methodological differences in laboratory testing across different institutions. The results highlight the necessity for routine groundwater monitoring and localized water treatment or blending practices for health and agricultural risk mitigation. Potential future work includes predictive modeling of quality trends or incorporating land use and recharge to allow for more dynamic assessments. AWQI and CCME-WQI are widely used and offer valuable insights into overall water quality, both models have certain limitations. AWQI assigns equal weight to all parameters without accounting for interactions between contaminants, which may lead to risk underestimation in complex hydrochemical environments. On the other hand, CCME-WQI is more sensitive to frequency and magnitude of exceedance but does not differentiate between parameters with high or low health impacts. Additionally, both indices rely heavily on the availability and accuracy of reference standards, which may vary between regions and water use types. These constraints highlight the importance of complementing index-based assessments with detailed hydrochemical and risk-specific analyses in future studies.

The results of this study provide actionable insights for local communities and decision-makers. Understanding seasonal fluctuations and the spatial variability of groundwater quality enables farmers to optimize irrigation practices and minimize crop damage from salinity and ion toxicity. Additionally, the findings underscore the importance of treating or blending groundwater before domestic use in several locations, particularly where EC, chloride, and sodium levels exceed permissible limits. Such information can guide water allocation policies, infrastructure planning, and public health strategies in semi-arid zones like Zurbatiyah.

CONCLUSIONS

This study combined physico-chemical groundwater analysis with two water quality indices – AWQI and CCME-WQI to comprehensively evaluate groundwater quality in the Zurbatiyah sub-district, eastern Iraq. Results showed moderate to high salinity, elevated concentrations of chloride, sulfate, hardness, and sodium, and occasional nitrate peaks. These issues varied both spatially and seasonally, influenced by aquifer lithology, agricultural return flows, and groundwater over-extraction during irrigation periods. Specifically, groundwater abstraction intensified between December and April—corresponding to peak irrigation demand leading to the concentration of dissolved ions. From April to June, water withdrawal typically ceased due to the harvest season, allowing partial aquifer recovery and slight reductions in salinity.

While AWQI mostly classified water quality as "good" to "excellent," it did not adequately capture the recurrent exceedances of critical parameters. Conversely, CCME-WQI offered a more realistic assessment, categorizing all wells as "marginal" due to its sensitivity to both the frequency and magnitude of parameter violations.

This makes CCME-WQI a more suitable tool for evaluating water quality in arid and semi-arid settings like Zurbatiyah, where seasonal stress and anthropogenic impacts are significant. Based on the results of both the CCME-WQI and the AWQI, groundwater in all six wells is unsuitable for drinking. Most samples exceeded Iraqi standards for EC, TDS, chloride, sulphate, calcium, and sodium. According to FAO irrigation guidelines and individual parameter analysis, Wells 1 and 2 are relatively more suitable for irrigation, while Wells 3 to 6 are marginal to unsuitable due to high salinity and sodium hazards. The findings emphasize the importance of continuous groundwater monitoring, sustainable extraction practices, and pre-treatment or blending strategies for safe domestic and agricultural use. Future research should incorporate microbiological assessments, trace elements, and predictive modeling to support long-term groundwater resource management in Iraq and similar environments.

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