

Multivariate analysis of seasonal variability in surface water quality for irrigation in Western Iraq

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ABSTRACT

This study provides a multivariate seasonal assessment of surface water quality for irrigation in western Iraq. Water samples were collected during winter and summer of 2024 from three primary sources—Euphrates River, Lake Habbaniyah, and Lake Tharthar. Key physicochemical parameters were analyzed, including EC, TDS, TH, Na⁺, Ca²⁺, Mg²⁺, Cl⁻, SO₄²⁻, and pH. Multivariate statistical analyses, including Principal Component Analysis (PCA), were conducted to investigate seasonal patterns, assess irrigation suitability, and identify dominant hydrochemical parameters. One-way ANOVA revealed no significant seasonal differences ($p > 0.05$); however, EC and TDS values showed an increasing trend during summer, particularly in stagnant lakes. Subsequent multivariate analyses, including Pearson correlation and Principal Component Analysis (PCA), identified EC, Na⁺, and TH as the principal hydrochemical drivers, collectively accounting for over 95% of the total variance. The Sodium Adsorption Ratio (SAR) was calculated to quantify the risk of sodicity in irrigation practices. SAR values remained acceptable for Euphrates water (~4.5), but exceeded 5.0 in lake sources, indicating moderate sodicity hazards. A comparative analysis revealed that water from the Euphrates River is the most suitable for irrigation. In contrast, water from the lakes requires dilution or treatment due to elevated salinity and sodium levels. The findings underscore the need for source-specific water management, seasonal monitoring, and SAR-based risk evaluation to maintain soil health and irrigation sustainability in semi-arid regions.

Keywords: surface water quality, seasonal variation, SAR, salinity, PCA, Western Iraq, irrigation suitability, multivariate analysis

INTRODUCTION

In arid and semi-arid landscapes, agriculture is critically dependent on surface water from sources such as rivers and lakes, particularly as these regions face significant challenges to water availability and quality due to scarce precipitation and climate shifts. For western Iraq, the Euphrates River represents the cornerstone of this system, acting as the primary lifeline for regional farming, local communities, and the essential services provided by the ecosystem (Al-Quraishi & Kaplan, 2021; Rasul & Al-Jaleel, 2022). Adjacent lakes—namely Lake Habbaniyah and Lake Tharthar—function as seasonal reservoirs, regulating water flow and providing buffer capacity during dry spells (Abdullah et al., 2019; Eryigit et al., 2023).

The quality of surface water in these systems undergoes pronounced seasonal fluctuations, influenced by climatic factors, geochemical processes, and anthropogenic inputs such as agricultural runoff, wastewater discharge, and reservoir operations. Key physicochemical parameters—including temperature, electrical conductivity (EC), total

dissolved solids (TDS), pH, and concentrations of central ions (Na⁺, Ca²⁺, Mg²⁺, K⁺, SO₄²⁻, Cl⁻)—exhibit pronounced seasonal variability, especially in shallow or stagnant aquatic systems (Howland et al., 2000; Khlaif & AL-Hassany, 2024; Touhami et al., 2025).

This study offers a comprehensive, seasonal assessment of water quality for Al-Anbar's three central water bodies: The Euphrates River, Lake Habbaniyah, and Lake Tharthar. By applying multivariate statistical techniques, an approach not commonly used in Western Iraq, we specifically evaluate how the suitability of these distinct water systems for irrigation changes throughout the year.

While the importance of these water bodies is recognized, a clear gap exists in the literature regarding a comprehensive, multivariate statistical assessment of their seasonal water quality variations for irrigation in Western Iraq. This research is significant as it provides empirical, data-driven insights crucial for formulating sustainable water management strategies in a region experiencing escalating water scarcity.

This study tests the central hypothesis that the hydrological regime is the primary determinant of seasonal variations in water quality and subsequent irrigation suitability. The primary research question is:

RQ1 To what extent do key physicochemical parameters differ between the Euphrates River and adjacent lakes across distinct seasons, and what are the resulting implications for soil health and agricultural sustainability?

To answer this, the study employs multivariate statistical techniques to identify dominant hydrochemical patterns and controlling factors.

Recent studies in the Middle East and North Africa (MENA) have highlighted substantial advances and persistent challenges in irrigation water management across semi-arid regions. For instance, the 2023 Blue Peace Middle East report shows that more than 75% of available freshwater is withdrawn for agriculture, with countries such as Jordan and Lebanon increasingly adopting modern irrigation methods—like sprinkler and drip systems—to improve water use efficiency, in contrast to the dominance of surface irrigation in Iraq and Syria. Additionally, ongoing research emphasizes the need for integrated management of groundwater and surface water, as well as the use of remote sensing and water accounting systems to handle persistent water scarcity and climate-induced variability. Reviews also emphasize the importance of adaptive policies that address increased salinity, variable water quality, and the impacts of climate change on productivity throughout the region. These regional perspectives provide a broader context and inform the development of sustainable irrigation management strategies that extend beyond the Iraqi setting (Bhattarai & Yousef, 2025; Kantanka et al., 2025; Mekouar, 2023; Sulaiman et al., 2021).

Objectives

The main objectives of this study are as follows:

1. To examine seasonal variability and spatial heterogeneity in key physicochemical water quality indicators—including temperature, electrical conductivity (EC), total dissolved solids (TDS), pH, total hardness (TH), and major ions (Na^+ , Ca^{2+} , Mg^{2+} , K^+ , Cl^- , SO_4^{2-})—across dynamic riverine and stagnant lacustrine systems.
2. To assess the irrigation suitability of surface water sources through FAO classification criteria and Wilcox diagrammatic interpretation.
3. To identify the primary geochemical and anthropogenic determinants influencing water quality variability.
4. To employ multivariate statistical techniques—including ANOVA, Pearson correlation, and Principal Component Analysis (PCA)—to discern dominant patterns and underlying hydrochemical controls.
5. To formulate region-specific recommendations for sustainable irrigation practices and integrated water resource management in arid and semi-arid environments.

MATERIALS AND METHODS

Study Area

This study was carried out in Al-Anbar Province—the largest governorate in western Iraq—spanning approximately 137,808 km² (Noon et al., 2022). The province is characterized by an arid to semi-arid climate, defined by minimal annual precipitation (< 150 mm), high evapotranspiration rates, and pronounced seasonal thermal variations. Agriculture in the region is highly dependent on surface water sources, particularly the Euphrates River and a network of artificial lakes (Dagher & Obead, 2023; Jabbar & Ibraheem, 2022).

The water quality assessment focused on three major surface water bodies:

- The Euphrates River – a perennial and hydrologically dynamic river flowing through central Al-Anbar, specifically near Ramadi City (approx. 33.43°N, 43.31°E). It represents the primary source of flowing water for irrigation in the province.
- Lake Habbaniyah – a shallow, artificial reservoir located southeast of Ramadi (approx. 33.27°N, 43.57°E), receiving diverted water from the Euphrates via the Warrar Canal. The lake is hydrologically stagnant and vulnerable to evaporation-induced concentration.
- Lake Tharthar – one of Iraq's largest artificial water bodies, situated northeast of Ramadi (approx. 33.84°N, 43.30°E). The study targeted the southern portion of the lake within Al-Anbar's administrative boundary, where water exchange is partially regulated through controlled inputs from the Tigris-Euphrates transfer system.

Geologically, the study area lies within the Mesopotamian Foredeep Basin (**Figure 1**), which is underlain by carbonate and gypsum-rich formations that significantly influence water chemistry, particularly in terms of hardness and salinity levels (Abdulhameed et al., 2022; Gharib et al., 2024).

Data Sources

Water quality data for the year 2024 were sourced from two official agencies:

- Euphrates River: Central Laboratory of the Ramadi Water Project, affiliated with the Ministry of Municipalities.
- Lakes Habbaniyah and Tharthar: Environmental Directorate of Al-Anbar Province, Ramadi Office.

All measurements were taken in accordance with national water quality protocols and collected by qualified technical staff using standardized procedures.

Sampling Period and Parameters

Water samples were collected during two distinct seasonal intervals in 2024:

- Winter (December–January)
- Summer (July–August)

The following water quality parameters were analyzed:

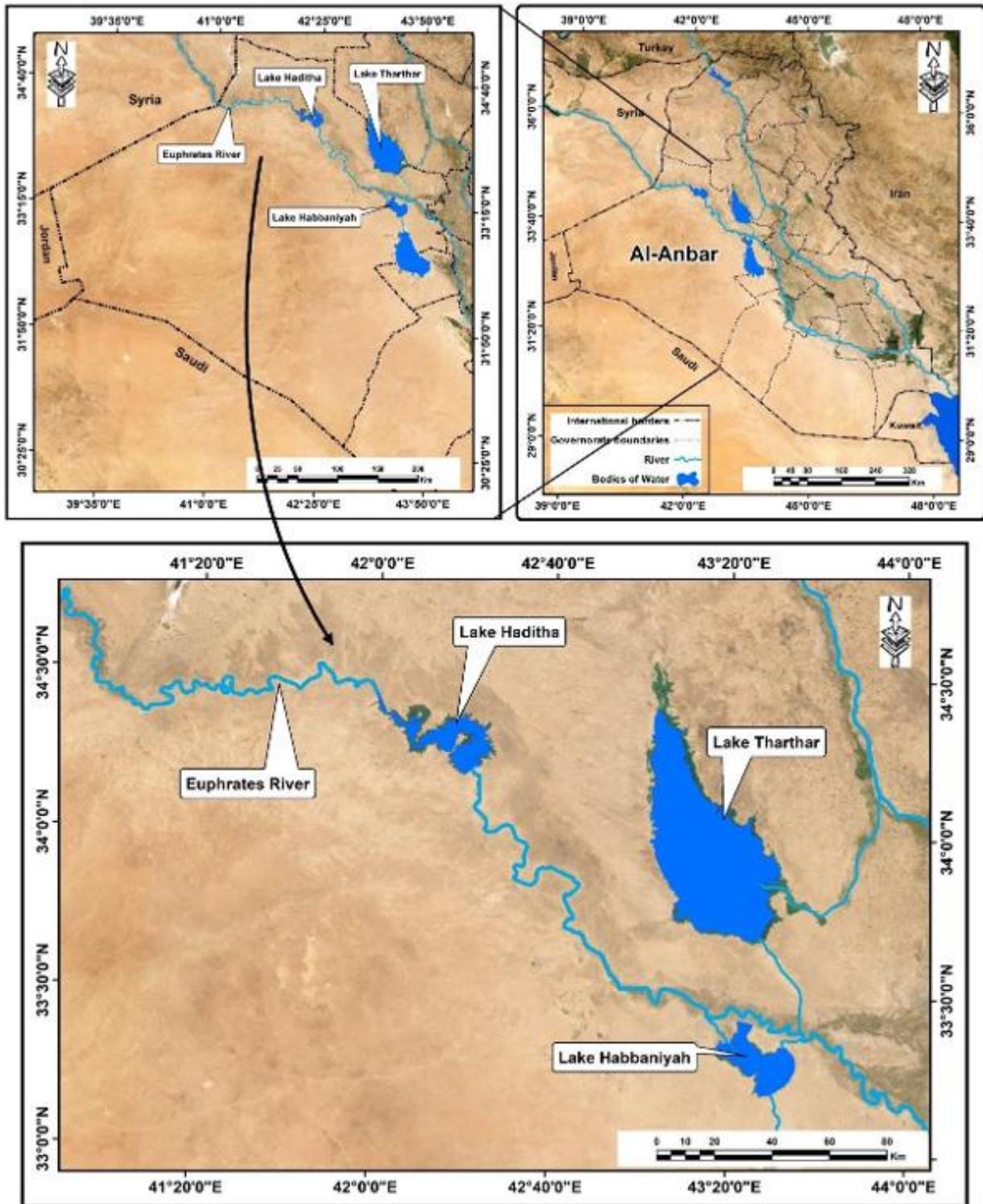


Figure 1. Study area map indicating the Euphrates River, Lake Habbaniyah, and Lake Tharthar in Al-Anbar Governorate (Source: Authors' own elaboration)

Physical parameters: Temperature, Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Total Hardness (TH), and pH.

Major ions: Sodium (Na^+), Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), Chloride (Cl^-), and Sulfate (SO_4^{2-}).

Sampling and analytical procedures adhered to national environmental monitoring standards.

Analytical and Statistical Methods

Descriptive statistical methods were employed to calculate seasonal averages and evaluate spatial variability across sampling locations.

Irrigation suitability was evaluated using the FAO Irrigation Classification System. Furthermore, Wilcoxon diagrams are based on EC and sodium concentrations (Ayers &

Table 1. Seasonal water quality parameters of the Euphrates River (2024)

Parameter	Dec	Jan	Jul	Aug	Annual avg
Temperature (°C)	19	15	29	31	23.5
EC (dS/m)	1.1	1.1	1.2	1.2	1.15
pH	8.5	8.4	7.5	8.0	8.1
Total hardness (mg/L)	335	325	385	425	367.5
TSS (mg/L)	645	635	652	660	648
TDS (mg/L)	1034	1024	1146	1116	1080
Calcium (mg/L)	61	53	70	64	62.0
Sodium (mg/L)	142	152	138	151	145.75
Magnesium (mg/L)	54	58	55	59	56.5
Potassium (mg/L)	5.2	4.4	4.2	7.4	5.3
Sulfates (mg/L)	415	416	425	482	434.5
Chlorides (mg/L)	189	200	210	187	196.5

Source: Central Laboratory of the Ramadi Water Project (2024)

Westcot, 1985; Khlaif & AL-Hassany, 2024; Savva & Frenken, 2002).

The Sodium Adsorption Ratio (SAR) was calculated to assess potential soil sodicity hazards using Equation 1, where all ion concentrations are expressed in milliequivalents per liter (meq/L).

$$\frac{[Na^+]}{\sqrt{\frac{[Ca^{+2}] + [Mg^{+2}]}{2}}} = SAR \quad (1)$$

where the $[Na^+]$, $[Ca^{+2}]$, and $[Mg^{+2}]$ are the concentrations of sodium, calcium, and magnesium ions, respectively, in meq/L (Ayers & Westcot, 1985; Khapra & Singh, 2024; Khlaif & AL-Hassany, 2024).

SAR is a critical indicator for assessing the risk of soil sodicity. It measures the relative proportion of sodium ions to the beneficial divalent cations, calcium, and magnesium. A high SAR value indicates that sodium may displace calcium and magnesium in soil clay particles, leading to degradation of the soil structure, reduced water permeability, and potential harm to sensitive crops. Consequently, SAR is a vital parameter for sustainable irrigation management.

Where ion concentrations are expressed in milliequivalents per liter (meq/L).

The following statistical analyses were also performed:

- One-way ANOVA to assess seasonal differences.
- Pearson correlation to examine interrelationships among water quality parameters.
- Principal Component Analysis (PCA) to identify dominant factors influencing water chemistry.

All statistical analyses were performed using standard analytical platforms (SPSS, R, and Python), ensuring methodological rigor and reproducibility.

RESULTS AND DISCUSSION

Water Quality of the Euphrates River

The Euphrates River is the primary source of flowing surface water in Al-Anbar Province, playing a crucial role in supporting regional agriculture. Its continuous flow

contributes to relatively stable water quality conditions compared to the surrounding stagnant lakes.

Water temperature exhibited pronounced seasonal variation, ranging from 15°C in January to 31°C in August (see **Table 1**), consistent with semi-arid climatic conditions. Such variations influence water chemistry by affecting solubility and evaporation dynamics.

Electrical conductivity (EC) remained relatively stable, fluctuating modestly between 1.1 and 1.2 dS/m, indicating moderate salinity. This salinity level is suitable for irrigating moderately salt-tolerant crops (Ayers & Westcot, 1985; Costa et al., 2024; Oliveira et al., 2022).

pH values ranged from 7.5 to 8.5, indicating slightly alkaline conditions throughout the year, which is consistent with the region's carbonate-rich geology.

Total hardness (TH) ranged from 325 to 425 mg/L, classifying the water as hard to very hard according to standard classification thresholds. These elevated levels indicate high concentrations of calcium and magnesium, which can impair soil permeability when irrigation is prolonged.

Total dissolved solids (TDS) ranged between 1024 and 1146 mg/L, approaching the upper limit of acceptability for unrestricted agricultural use. The higher TDS values observed in summer suggest an increase in evapoconcentration.

Major ions—including sodium (average: 145.75 mg/L), calcium (62.0 mg/L), magnesium (56.5 mg/L), chlorides (196.5 mg/L), and sulfates (434.5 mg/L)—were present at moderate levels, with most parameters peaking during the summer season.

Based on the evaluated parameters, the water from the Euphrates River in Al-Anbar Province is generally deemed suitable for agricultural use, particularly for crops with moderate salt tolerance. The electrical conductivity and TDS levels fall within acceptable ranges for irrigation. However, the relatively high total hardness and seasonal increases in salinity and dissolved solids—especially during summer—suggest the need for careful water management and periodic soil monitoring to prevent long-term salinization or permeability issues.

Water Quality of Lake Habbaniyah

Lake Habbaniyah is a shallow lacustrine system located southeast of Ramadi and serves as a secondary reservoir for

Table 2. Seasonal water quality parameters of Lake Habbaniyah (2024)

Parameter	Dec	Jan	Jul	Aug	Annual avg
Temperature (°C)	14.0	17.8	37.6	31.7	25.3
pH	7.9	7.7	8.1	8.2	7.975
EC (dS/m)	1.5	1.3	1.9	1.8	1.625
TSS (mg/L)	818	843	960	977	899.5
TH (mg/L)	551.4	501.0	783.8	581.7	604.5
TDS (mg/L)	895	908	1058	1150	1003
Sodium (mg/L)	203	209	237	249	224.5
Potassium (mg/L)	7.1	7.2	9.3	10.5	8.525
Calcium (mg/L)	120.3	122.1	191.3	125.5	139.8
Chloride (mg/L)	224.5	216.2	338.4	290.8	267.475
Magnesium (mg/L)	56	64	80	60	65
Sulfates (mg/L)	490	500	510	680	545

Source: Environmental directorate of Al-Anbar Province (2024)

Table 3. Seasonal water quality parameters of Lake Tharthar (2024)

Parameter	Dec	Jan	Jul	Aug	Annual avg
Temperature (°C)	20.9	17.8	33.5	31.9	26.0
pH	7.8	7.6	8.1	8.0	7.875
EC (dS/m)	1.5	1.6	1.9	1.8	1.7
TSS (mg/L)	522	523	644	648	584.2
TH (mg/L)	610	640.3	665	662.4	644.4
TDS (mg/L)	760	776	785	783	776.0
Sodium (mg/L)	242	248	262	271	255.7
Potassium (mg/L)	8.8	9.0	10.2	12.0	10.0
Calcium (mg/L)	188.4	200.1	224.3	219	208.0
Chloride (mg/L)	127.6	141.0	149.1	144.2	140.5
Magnesium (mg/L)	40	45	48	46	44.8
Sulfates (mg/L)	510	519	484.2	460	493.3

Source: Environmental directorate of Al-Anbar Province (2024)

excess Euphrates River water via the Warrar Canal. Due to its stagnant hydrology and broad surface area, the lake is highly susceptible to evaporative concentration of dissolved solutes, especially during the dry season.

Water temperature ranged from 14.0°C in December to a peak of 37.6°C in July, reflecting significant seasonal thermal fluctuations (see **Table 2**). These elevated summer temperatures promote high evaporation rates, which in turn influence the chemical composition of the lake water.

Electrical conductivity (EC) increased markedly during summer, reaching 1.9 dS/m. Total dissolved solids (TDS) exceeded 1000 mg/L, peaking at 1150 mg/L in August. These values surpass the FAO thresholds for many crops, particularly those sensitive to salinity.

Total hardness (TH) reached extremely high levels, particularly in July (783.8 mg/L), due to elevated concentrations of calcium and magnesium. Prolonged use of such water for irrigation could reduce soil permeability and disrupt nutrient balance.

Total suspended solids (TSS) remained high year-round, peaking at 977 mg/L. This suggests internal sediment resuspension and limited water circulation, likely exacerbated by wind activity and surface runoff.

Major ions showed similar seasonal patterns, with sodium increasing from 203 to 249 mg/L, chloride reaching 338.4 mg/L, and sulfate peaking at 680 mg/L in August. These trends confirm substantial solute accumulation during the summer months.

In summary, Lake Habbaniyah exhibits elevated salinity, hardness, and turbidity, particularly during the summer months. Without ameliorative interventions such as dilution or pretreatment, the utility of Lake Habbaniyah's water for sustained agricultural application is severely compromised, particularly for fine-textured or poorly drained soils.

Water Quality of Lake Tharthar

Lake Tharthar, the largest artificial reservoir in Iraq, plays a pivotal role in regulating water transfers between the Tigris and Euphrates rivers. This study focuses on the southern portion of the lake within Al-Anbar Province—an area characterized by controlled water exchange and moderate evaporative stress, especially when compared to Lake Habbaniyah.

Water temperature ranged from 17.8°C in January to 33.5°C in July, indicating notable seasonal variation (see **Table 3**). However, these fluctuations were less extreme than those in Lake Habbaniyah, likely due to Tharthar's larger volume and partial hydraulic renewal.

Electrical conductivity (EC) reached 1.9 dS/m in summer, while total dissolved solids (TDS) remained relatively stable (760–785 mg/L). This suggests that periodic inflows and the lake's depth help moderate the effects of evaporation.

Total hardness (TH) averaged 644.4 mg/L, the highest among all study sites. This is attributed to elevated concentrations of calcium (up to 224.3 mg/L) and magnesium. Elevated hardness levels may lead to nutrient precipitation and progressive reduction in soil infiltration capacity.

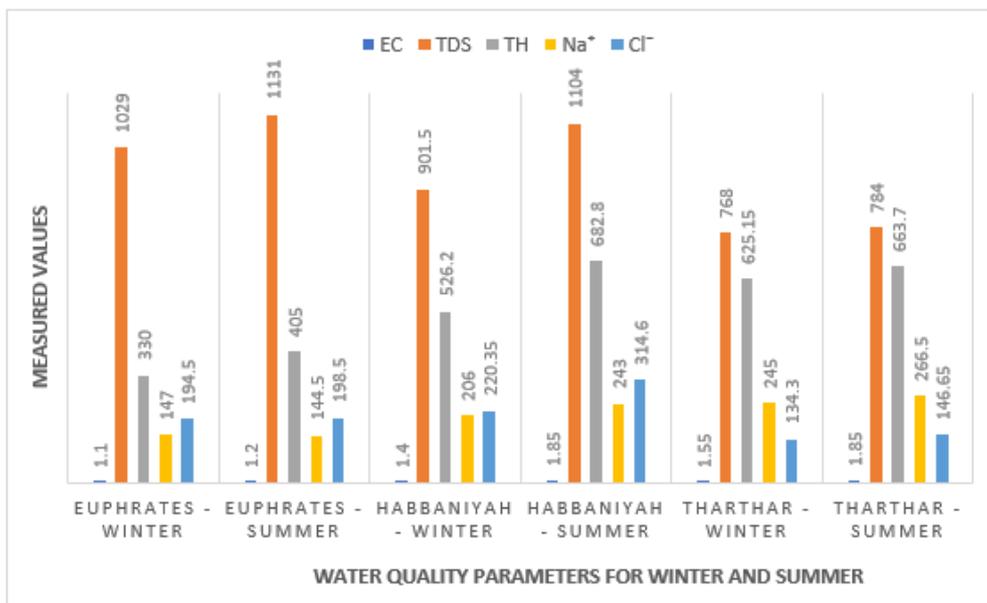


Figure 2. Seasonal comparison of key surface water quality parameters across three irrigation sources in Western Iraq (as of 2024) (Source: Authors' own elaboration)

Note: Units vary across parameters (e.g., EC in dS/m, TDS in mg/L, Na⁺ in mg/L)

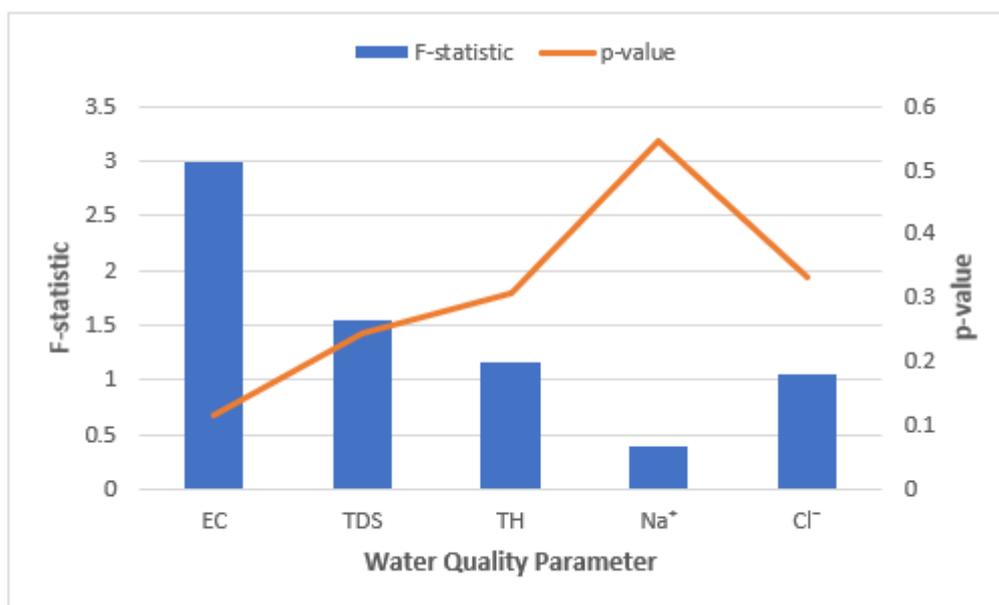


Figure 3. One-way ANOVA results for seasonal differences in water quality parameters (Source: Authors' own elaboration)

Sodium levels increase in potassium, calcium, and chloride, which peaked at 271 mg/L—the highest concentration recorded—and are driven by two concurrent processes: intensified evaporation that concentrates the salts, and geochemical inputs from the surrounding gypsum and carbonate formations.

Sulfate concentrations. By contrast, Total Suspended Solids (TSS) fluctuated moderately with the seasons, a pattern likely driven by wind mixing the water column and resuspending bottom sediments.

While Lake Tharthar's water is less saline than Lake Habbaniyah's, its overall quality is only intermediate. The high levels of hardness and sodium present a long-term threat to soil structure, meaning its use for irrigation is conditional on

careful management, which may include dilution with higher-quality water.

Statistical Analysis of Seasonal Water Quality Variations

To statistically evaluate the seasonal and spatial shifts in water quality, we constructed a unified dataset. It contained winter and summer measurements of five key physicochemical parameters—(EC), (TDS), (TH), (Na⁺), and (Cl⁻), taken from the Euphrates River, Lake Habbaniyah, and Lake Tharthar. This dataset, presented in **Figure 2**, served as the basis for one-way ANOVA and correlation analyses.

One-way ANOVA results indicated no statistically significant seasonal differences ($p > 0.05$) across the tested water quality parameters (**Figure 3**). However, EC and TDS

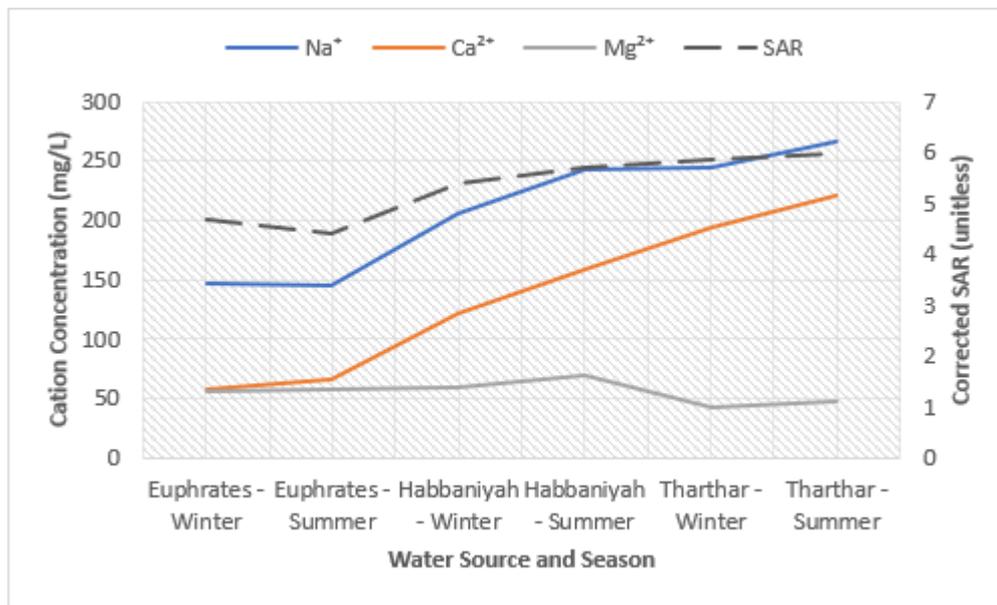


Figure 4. Corrected SAR and major cation concentrations across water sources and seasons (Source: Authors' own elaboration)

values showed a general increasing trend during the summer months—particularly in Lake Habbaniyah and Lake Tharthar. This pattern likely reflects intensified evaporation and reduced inflows, which are typical of stagnant water bodies during the hot season.

Despite the lack of statistical significance, the observed seasonal trends may carry important agronomic implications for irrigation management and soil health. Continued seasonal monitoring is recommended to detect long-term changes and emerging risks, particularly in the context of climate change.

Sodium Adsorption Ratio (SAR) Analysis

To evaluate the potential risk of soil sodicity from irrigation, the Sodium Adsorption Ratio (SAR) was calculated for each site and season using significant ion concentrations (Na^+ , Ca^{2+} , Mg^{2+}). The results are summarized in **Figure 4**.

The Euphrates River exhibited the lowest SAR values (4.43–4.68), indicating moderate sodicity risk. In contrast, Lake Habbaniyah and Lake Tharthar exhibited elevated SAR levels (5.4–5.9), indicating a higher potential for soil sodicity due to prolonged irrigation. However, all values remained below the FAO threshold of 9.0.

These findings support earlier results from PCA and correlation analysis, which identified sodium and hardness as key contributors to water quality variability and irrigation constraints.

Correlation Analysis of Water Quality Parameters

To investigate the interrelationships among key water quality parameters, a Pearson correlation matrix was generated using all available data collected from the three water bodies across both seasons. The results are presented in **Table 4** and **Figure 5**.

The correlation analysis revealed several noteworthy relationships:

- Electrical conductivity (EC) showed strong positive correlations with total hardness (TH) ($r = 0.94$) and

Table 4. Pearson correlation matrix of selected water quality parameters

	EC	TDS	TH	Na ⁺	Cl ⁻
EC	1.000	-0.373	0.936	0.908	0.197
TDS	-0.373	1.000	-0.485	-0.642	0.682
TH	0.936	-0.485	1.000	0.899	0.152
Na ⁺	0.908	-0.642	0.899	1.000	-0.078
Cl ⁻	0.197	0.682	0.152	-0.078	1.000

sodium (Na^+) ($r = 0.91$), confirming their role as principal contributors to salinity levels.

- Total hardness also showed a strong correlation with sodium ($r = 0.90$), suggesting a common geochemical origin or similar behavior in aquatic systems.
- Notably, Total Dissolved Solids (TDS) exhibited a moderate negative correlation with both Sodium (Na^+) ($r = -0.64$) and Total Hardness (TH) ($r = -0.49$). This inverse correlation is hypothesized to stem from the distinct hydrochemical signatures inherent to each water body. The stagnant lakes, despite having the highest Na^+ and TH concentrations due to evaporative concentration, recorded lower average TDS values (e.g., Lake Tharthar at 776 mg/L) than the flowing Euphrates River (1080 mg/L) in this study. This suggests that the Euphrates carries a different suite of dissolved ions, including high concentrations of sulfates, which significantly contribute to its overall TDS and create an inverse statistical relationship when the datasets are combined.
- Chloride (Cl^-) demonstrated a moderate positive correlation with TDS ($r = 0.68$). At the same time, its associations with other parameters remained weak or statistically insignificant, suggesting distinct sources or geochemical processes may influence it.

By identifying electrical conductivity, total hardness, and sodium as the primary drivers of salinity and sodicity, these findings clarify the complex interactions within the water system. The strong correlation we observed between sodium

	EC	TDS	TH	Na ⁺	Cl ⁻
EC	1	-0.373	0.936	0.908	0.197
TDS	-0.373	1	-0.485	-0.642	0.682
TH	0.936	-0.485	1	0.899	0.152
Na ⁺	0.908	-0.642	0.899	1	-0.078
Cl ⁻	0.197	0.682	0.152	-0.078	1

Figure 5. Corrected SAR and major cation concentrations across water sources and seasons (Source: Authors' own elaboration)

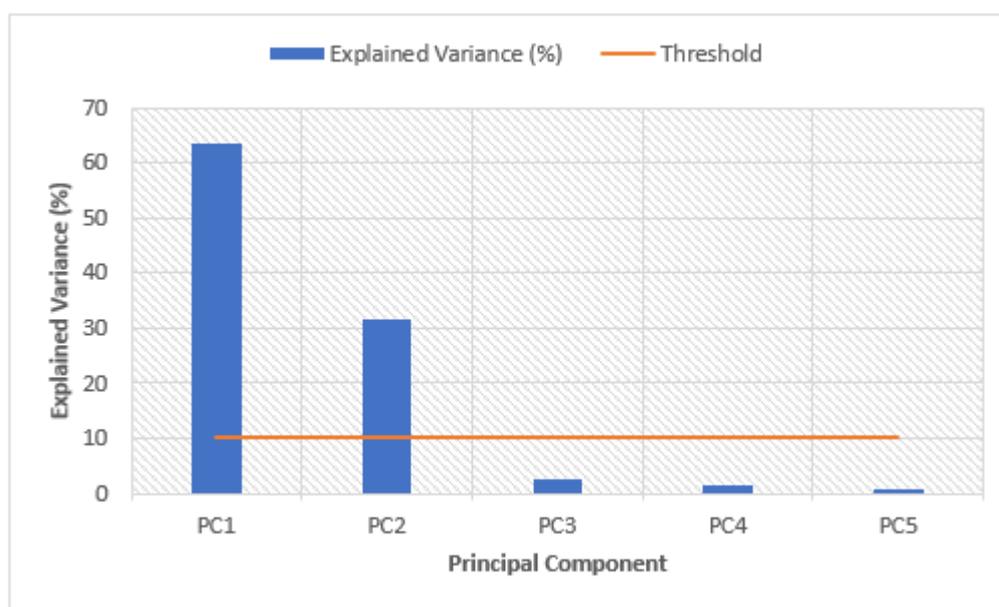


Figure 6. Scree plot displaying the explained variance by principal components with 10% threshold (Source: Authors' own elaboration)

and hardness, in particular, reinforces the previously discussed SAR trends and signals a long-term risk of cumulative damage to soil structure. This knowledge is crucial for designing targeted monitoring and effective water treatment plans, which are essential for sustainable irrigation in this context.

Principal Component Analysis (PCA)

To identify the key factors controlling water quality variation and to reduce dataset dimensionality, a Principal Component Analysis (PCA) was performed using standardized values of five core parameters: Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Hardness (TH), Sodium (Na⁺), and Chloride (Cl⁻).

The results revealed that the first two principal components (PC1 and PC2) account for 95.32% of the total variance, with PC1 accounting for 63.61% and PC2 accounting for 31.71%, as shown in **Figure 6**. This suggests that a significant portion of the variability in water chemistry can be attributed to just two dimensions.

PC1 exhibited strong positive loadings for EC, TH, and Na⁺, indicating their dominant influence on salinity and sodicity potential in surface water sources. PC2 was more associated

with TDS and Cl⁻, possibly reflecting seasonal or geochemical influences that differ from those driving PC1.

These findings are in agreement with the Pearson correlation matrix and SAR analysis, which also highlighted sodium and hardness as dominant contributors to water quality variability and soil-related irrigation risks.

From a water resource management standpoint, PCA findings advocate for a streamlined monitoring framework centered on EC, Na⁺, and TH as key hydrochemical indicators for irrigation suitability assessment in semi-arid environments. This reduces analytical complexity while maintaining sensitivity to key hydrochemical changes.

Comparative Analysis of Water Quality Among All Sources

The comparative assessment of annual average water quality parameters across the three studied sources—Euphrates River, Lake Habbaniyah, and Lake Tharthar—revealed marked differences shaped by hydrological regime, evaporation intensity, and surrounding geology. A summary of key indicators is presented in **Figure 7**.

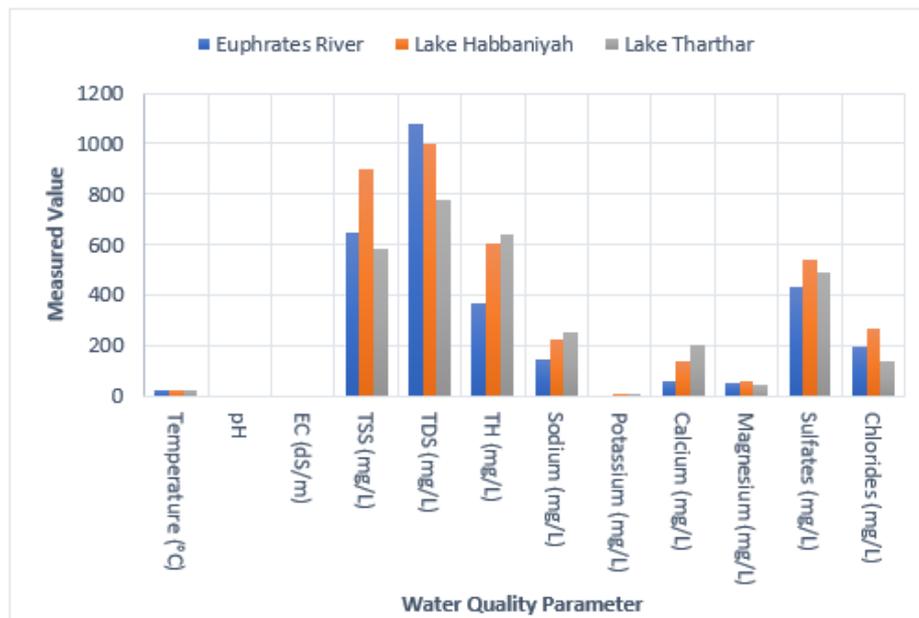


Figure 7. Comparison of average water quality parameters (2024) (Source: Authors' own elaboration)

Note: Units vary across parameters (e.g., EC in dS/m, TDS in mg/L, Na⁺ in mg/L)

The Euphrates River, as a flowing system, exhibited the most stable and favorable quality for irrigation, with the lowest average EC (1.15 dS/m), Na⁺ (145.75 mg/L), and TH (367.5 mg/L). These values indicate moderate salinity and hardness, making it suitable for a wide range of crops, especially during cooler months.

Lake Habbaniyah, being shallow and hydrologically stagnant, showed signs of water quality degradation due to evaporation and limited flushing. It recorded the highest TSS (899.5 mg/L), elevated TH (604.5 mg/L), and Cl⁻ (267.5 mg/L), posing clear risks for soil permeability and salt accumulation.

Lake Tharthar exhibited intermediate behavior. While its TDS value (776 mg/L) was relatively moderate, it had one of the highest SAR values (averaging over 5.5) and the highest sodium levels (255.7 mg/L), reflecting geochemical interactions with gypsum- and carbonate-rich sediments and limited exchange dynamics.

These comparative results align with the multivariate statistical findings from PCA, which identified EC, Na⁺, and TH as dominant contributors to water quality variability. Additionally, SAR values confirm that both lakes, particularly Tharthar, carry higher sodicity risks, reinforcing the need for blending, treatment, or source-specific irrigation strategies.

Discussion

The integrated seasonal and multivariate analysis conducted in this study revealed substantial spatial and temporal variations in surface water quality across the three major water bodies in western Iraq. These spatial and temporal disparities are fundamentally governed by a combination of factors: the prevailing hydrological regime, evaporation intensity, and the geochemical composition of regional lithology.

The Euphrates River, with continuous flow and relatively cooler microclimatic conditions, maintained more favorable water quality. Its moderate EC and TH values, along with lower

SAR levels, indicate their suitability for a broad range of crops, especially during the winter season.

In contrast, Lake Habbaniyah and Lake Tharthar, both stagnant or semi-regulated reservoirs, showed clear signs of evapoconcentration, particularly during summer. These effects were evident in the higher EC, TDS, and Na⁺ levels, which can pose significant sodicity risks, as confirmed by SAR values exceeding 5.0. Prolonged irrigation with such water can lead to degradation of soil structure, reduced permeability, and nutrient imbalances.

Although the calculated SAR values for all water sources remain below the high-hazard threshold of 9.0, it is crucial to consider the potential for long-term cumulative risk. Continuous application of irrigation water with moderate sodicity, especially in the fine-textured soils common to semi-arid regions, can lead to a gradual accumulation of sodium in the soil profile. Over several growing seasons, this buildup can progressively degrade soil structure, reduce water infiltration and aeration, and ultimately impair crop productivity. Therefore, even 'acceptable' SAR levels warrant a proactive management strategy, including periodic soil monitoring and potential amendments, to prevent irreversible soil degradation.

The strong correlation between Na⁺ and TH ($r \approx 0.90$), as well as their dominant influence in PCA, underscores their shared geochemical origin, most likely from carbonate and gypsum-rich formations. This is consistent with the elevated calcium, sodium, and sulfate concentrations in lake systems.

From an agronomic standpoint, the synergistic effect of alkaline pH and elevated sodium concentrations exacerbates the sodicity hazard, necessitating the use of mitigation strategies such as gypsum amendments, periodic soil monitoring, or blending with higher-quality water (e.g., Euphrates River).

The results underscore the importance of tailoring irrigation strategies to specific water sources, coupled with

systematic seasonal monitoring and adaptive management practices that reflect the dynamic nature of surface water chemistry in arid and semi-arid regions. This is a critical component for ensuring long-term sustainable development in such water-stressed environments.

Beyond their statistical significance, these findings have direct practical implications for regional stakeholders. For instance, water resource managers can use this data to implement a dynamic water allocation strategy; during the low-risk winter season, water from Lakes Habbaniyah and Tharthar could supplement the Euphrates for agricultural expansion. Conversely, in the high-risk summer months, releases from the Euphrates should be prioritized, and blending with lake water must be carefully managed to maintain an acceptable SAR level below 5.0. For farmers and agricultural engineers, the study provides a clear directive: crops sensitive to salinity and sodicity should be irrigated exclusively with Euphrates water, while more tolerant crops could be sustained with blended water. This source-specific approach is crucial for preventing long-term soil degradation, which is a significant threat given the prevalence of fine-textured soils in the region.

It is essential to recognize that these findings represent a snapshot of current conditions. Future climate variability, such as prolonged droughts or altered precipitation patterns, could significantly influence these results. For instance, reduced rainfall and higher temperatures would likely intensify evapoconcentration in the lakes, further elevating salinity and sodicity risks. Conversely, changes in the Euphrates River's flow regime due to upstream dam operations or increased regional water demand for agriculture could diminish its dilution capacity, potentially degrading its quality over time. These factors underscore the need for continuous, adaptive management strategies that can accommodate future environmental and anthropogenic pressures.

CONCLUSIONS

This study presents a comprehensive, multivariate analysis of seasonal water quality shifts across western Iraq's three primary water bodies: The Euphrates River, Lake Habbaniyah, and Lake Tharthar. Our work, which integrated physicochemical data with a suite of statistical techniques, identified key spatial and temporal trends with direct implications for regional irrigation practices.

The findings reveal a sharp contrast in water quality between the river and the stagnant lake systems. The Euphrates River consistently emerged as the most suitable source for agriculture, a status attributed to its comparatively moderate salinity, lower sodium content, and acceptable SAR levels, particularly during the winter. Conversely, Lakes Habbaniyah and Tharthar pose a significant and seasonally variable risk to long-term soil health. This is driven by evapoconcentration and regional geology, which elevate EC, TH, and Na⁺ concentrations, thereby heightening the threat of sodicity. This risk is quantified by corrected Sodium Adsorption Ratio (SAR) values, which increase from a manageable 4.4 in the river to a concerning 5.9 in Lake Tharthar.

Given these divergent profiles, our analysis confirms that a "one-size-fits-all" approach to water management in this region is untenable. The statistical models identify EC, Na⁺, and TH as the most critical hydrochemical drivers, solidifying their status as the top priority for routine monitoring. Therefore, ensuring the long-term sustainability of agriculture under increasing water stress demands a highly adaptive strategy. This must be both source-specific and seasonal, incorporating targeted mitigation tactics—such as water blending or gypsum application—to preserve the integrity of vital soil resources.

Ultimately, these findings highlight not only the urgent need for adaptive, source-specific water management but also position continuous monitoring as an essential safeguard for sustaining agriculture in western Iraq under accelerating climate and hydrological pressures.

RECOMMENDATIONS

Based on the outcomes of this study, the following specific recommendations are proposed for key stakeholders to support sustainable water resource management in western Iraq:

1. For governmental bodies (e.g., Ministry of Water Resources, Ministry of Agriculture, Al-Anbar Environmental Directorate):
 - Implement a source-specific allocation policy: Prioritize the allocation of Euphrates River water for irrigating sensitive crops and during dry seasons, leveraging its superior quality. Lake water should be officially designated for blending or for irrigating salt-tolerant crops.
 - Establish a coordinated monitoring program: Create a joint task force to conduct routine monitoring (at least twice annually) focused on the key risk indicators identified in this study: EC, TH, Na⁺, and SAR. Data should be centralized and made publicly accessible.
 - Promote inter-agency coordination: Develop a formal framework for collaboration between water authorities, environmental regulators, and agricultural stakeholders to ensure that water management decisions are integrated and data-driven.
2. For the agricultural sector (e.g., Farmers, Agricultural Extension Services, Farmers' Cooperatives):
 - Adopt on-farm water blending strategies: Where possible, farmers should be trained and equipped to blend high-salinity lake water with higher-quality Euphrates water to mitigate sodium accumulation and preserve soil integrity.
 - Conduct regular soil health assessments: Agricultural extension services should assist farmers in assessing SAR levels in their soils periodically to detect and mitigate sodicity-related impacts before they become severe.

- Promote best management practices (BMPs): Encourage the adoption of practices such as selecting salt-tolerant crop varieties and improving soil drainage in areas irrigated with lake water.
3. For the academic and research community:
- Expand research scope: Future investigations should assess the long-term impact of these water sources on different soil types and crop yields through field-based studies.
 - Incorporate socio-economic Analysis: Future research should assess the cost-effectiveness of different water management strategies (e.g., blending, treatment) and the policy implications for regional water security to create more holistic and implementable management plans.

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