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Integrated Environmental Assessment of Surface and Groundwater Resources in Al-Najaf Governorate, Iraq

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Abstract

Background: The Al-Najaf Governorate (central Iraq) is experiencing increasing stressors on water resources, due to the rise of population, expansion of irrigation, and reduction of the Euphrates flow, as well as climate changes. Salinization, enrichment of nutrients, and poor treatment of wastewater pose threats to the drinking water and agricultural water. Purpose: The research offers a broad environmental analysis of surface and groundwater in the city of Al-Najaf, the key sources of contamination, the spatial distribution of salinity and water quality by means of the GIS analysis, and the recommendations on the specific managerial measures. Approaches: We have synthesized published data (20192025) and came up with representative sample points of 40 wells and 6 points of surface water representations in the literature and computed water-quality indices (EC, TDS, NO3, WQI) and GIS interpolations (IDW) of EC, TDS, and WQI. It was compared to WHO and FAO standards. Findings: EC values were found to be within a range of about one thousand and five hundred to more than four thousand and five hundred µS/cm (median two thousand five hundred and ten), and TDS was in the range of about eight hundred and fifty to over three thousand and five hundred mg/L. WQI mapping indicates that there are only thin strips around the Euphrates that comply with the good thresholds; most of the aquifers have poor or very poor values. Inferences: Salinization and spent nutrient contamination of groundwater is rampant. It is suggested to use integrated monitoring, specific desalination/blending, enhanced wastewater treatment, and modernization of irrigation.

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Introduction

Climatic variability and escalating human activities in arid and semi-arid areas are placing an unprecedented level of stress on water resources in these areas. Such pressures are especially strong in Iraq where the country is experiencing frequent droughts, decreasing transboundary flows of the Euphrates River, increased average temperatures and a high population growth rate. The above aspects lead to distortion of the natural hydrological balance, impairment of water quality, and predisposition of the surface water as well as groundwater systems (Al-Jashaami et al., 2024; Al-Mousawey & Abed, 2023). One of the most hydrologically sensitive regions in central-southern Iraq is Al-Najaf Governorate that is some 160 km south of Baghdad (Radhakrishnan et al., 2024). It is a very sensitive region in terms of environmental water evaluation due to its geographic position, geomorphological variation, and reliance upon the surface and shallow groundwater resources (Alitane et al., 2025; Alao, 2025). Euphrates River, the principal source of surface water in Al-Najaf, has irrigation systems, drinking-water treatment systems, and marshland recharge systems. Nevertheless, the river has been affected by upstream withdrawals, falling rates of discharge and rising salinity in the river which has changed the chemical and physical characteristics of the river. The western areas of Najaf city have groundwater resources that are susceptible to high rates of evaporation, meager natural recharges, and salinization as a result of agricultural return flows, seepage of domestic effluents, and uncontrolled over-pumping of wells (Awad et al., 2022; Giovanis & Ozdamar, 2025). The heterogeneous topography of Al-Najaf, consisting of desert areas, irrigated agricultural areas, urban and suburban settlements, hydrologic depression of Bahr Al-Najaf, which is a vast natural sink, collecting surface runoff and altering underground flow patterns, further complicates the management of water resources at Al-Najaf (Hassan et al., 2024; Barhoumi & Charabi, 2025). The above spatial heterogeneity leads to considerable variability in the hydrochemical properties and requires a combination of field related data, statistical analysis and geospatial modeling. Increasing salinity, occasional high content of total dissolved solids (TDS) and decreasing water suitability have been observed in previous studies, but the majority of them was limited, short-term or did not cover the entire governorate (Kamel et al., 2018; Makhlough et al., 2023).

In 2019-2025 the Al-Najaf experienced increased environmental pressures, such as the marked reduction in the quantity of rain per year, the rise of warming temperatures, and heightened water requirements of agricultural sectors (Alkaitab et al., 2015). This results into an urgent need to compose the available data and determine the quality of surface water and groundwater. Scientifically rigorous assessments are needed to be done on sustainable agricultural planning, safe drinking-water provision and evidence-based development of regional environmental policies (Smakhtin, 2004; Zwain et al., 2025).

Long-term reductions in precipitation, upstream withdrawals, and rising temperatures have disrupted the hydrological balance and degraded surface and groundwater quality. Previous assessments conducted in Al-Najaf indicate increasing salinity, high TDS levels, and localized contamination by nutrients and domestic effluents; however, most studies were limited in spatial or temporal scope. The present study synthesizes hydrochemical datasets (2019–2025), integrates GIS-based spatial analysis, and evaluates water suitability based on WHO, FAO, and Iraqi standards. Through an Integrated Environmental Assessment (IEA)

framework, the study examines the spatial distribution of water quality parameters—including EC, TDS, NO_3^-, and WQI—and identifies the major environmental stressors affecting water quality across the governorate (Alao, 2025; Hirji & Davis, 2009).

Organization of the Paper

This paper is organized as follows: Section 2 describes the study area and its hydrological and environmental setting. Section 3 outlines the materials and methods, including data sources, WQI computation, and spatial interpolation procedures. Section 4 presents the results and provides a comprehensive discussion of surface and groundwater conditions, spatial patterns, environmental implications, and management challenges. Section 5 summarizes the key conclusions (Kireitseva et al., 2025). Section 6 delivers recommendations and a two-year action plan, followed by Section 7, which outlines limitations of the study.

Relevance of Integrated Environmental Assessment

This paper uses an approach of Integrated Environment Assessment (IEA), which is a complex of hydrochemical monitoring, geospatial analysis, and statistical analysis to give a comprehensive perspective of the water quality in Al-Najaf (Ji et al., 2025; Kadhim et al., 2023). The IEA lays stress on the nature of the relationship between environmental stressors such as climate variability, land use, agricultural activities, industrial emissions, and geomorphology and the outcomes of water quality. The introduction of the temporal (2019-2025) and spatial data into the study will offer a full and more recent evaluation of surface and ground water supply.

Major Contributions of the Current Study

The key findings of this study are: Overall Water-Quality Data Compilation: Compilation and synthesis of the current peer-reviewed journal articles, governmental reports, and hydrological surveys with the concentration on the main parameters like electrical conductivity (EC), total dissolved solids (TDS), salinity, and major ions, and Water Quality Index (WQI). GIS Based Spatial Analysis: It involves the creation of high-resolution spatial maps of EC, TDS and WQI with the help of representative sampling points and standardized interpolation techniques enabling visualization of the spatial variability and identification of hot spots of water quality degradation. Water Suitability Evaluation: Both the surface and groundwater are evaluated based on the WHO/FAO guidelines of drinking and irrigation water to provide internationally standardized classification and management recommendations. Determination of the Environmental Stressors: Identification of the most significant natural and anthropogenic stressors affecting the water quality such as climatic conditions, agricultural activities and waste releases, and geomorphological constraints. Policy and Management Recommendations: Evidence-based water resource management, monitoring and environmental policy, specific to hydro-environmental factors of Al-Najaf.

Study Area Description

Al-Najaf Governorate is located in central-southern Iraq with an area of some 28,824 km2. The governorate borders Karbala on the north, Babil on the northeast, Qadisiyah on the east, Muthanna on the south, and the Western Desert as the western neighbors. It has a climate of hyper-arid which is a climate typified by very low rainfall, high evaporation rates and extreme temperatures during the summer season. Important climatic parameters are: Average temperature per year: 23-25 deg C. Summer temperatures: 45oC. Mean precipitation rate: 90-120 mmy-1 Evaporation rates: >2,000 mm/year. The governorate is covered by the Euphrates River which is the primary source of surface water serving domestic, agricultural, and ecological

purposes. Bahr Al-Najaf is a large natural hydrological depression, a seasonal water reservoir and it gathers surface runoff in the surrounding areas. Other large water systems are the Kufa River Canal and Abbasia Canal that supply irrigation water and drainage systems leading to the depression Fungus (Barhoumi & Charabi, 2025; Hussain & Taimooz, 2024).

Hydrological Setting

The water resources of Al-Najaf consist of surface water and ground water, which are closely connected on the basis of the hydrological cycle in the region:

Surface Water

Euphrates River: The main water source used in drinking, irrigation, and marsh recharge. The factors of upstream withdrawals, seasonal variability of flows, and rising salinity have a strong effect on water availability and quality.

Irrigation Canals: Kufa River Canal and Abbasia Canal can be used to bring Euphrates water into agricultural lands. These canals also interact with the local drainage systems, and are also a portion of the hydrological balance in Bahr Al-Najaf depression.

Groundwater Resources

Quaternary Alluvial Aquifers: Shallow aquifers which are made up of unconsolidated sands, gravels and silts along floodplains and provide water to serve agriculture and domestic purposes.

Local Carbonate Aquifers: These are deeper dolomite and limestone formations that are considered to be essential depositories especially in regions where there is a lack of surface water. Low precipitation and high evaporation restrict groundwater recharge and excessive exploitation has caused lowering water-table and salinization of several wells.

Bahr Al-Najaf Depression

A naturally occurring seasonal pond with water which serves as a natural sink and collection of surface water, altering ground and surface water parameters.

The depression is an important ecological and hydrological feature because it regulates the groundwater recharge, wetland ecosystems, and flash floods buffer.

Environmental Pressures and Land Use

The landscape of the governorate is very diverse as it encompasses: Urban Areas: Najaf urban and small towns where the domestic water demand is located. Agricultural Land: Irrigated lands using Euphrates water especially in Kufa and plains at its vicinity. Desert Zones: Western areas that are characterized by sandy and rocky desert with very few vegetation. The result is the heterogeneity of the spatial level of water demand, exploitation of groundwater and the quality of water. The important environmental forces are: Climatic Stressors: Hot weather, low precipitation and extended droughts in the availability of surface and ground water. Agricultural Practices: The use of agricultural practices that are the source of salinization and nutrient loading is the return flows, fertilizers, and uncontrolled methods of irrigation (Loiseau et al., 2012). Urban and Domestic Effluents: settlements leaking into the groundwater, causing local pollution of ground water.

Hydrological: upstream control of dams and variations in seasonal recharge, Canal alteration and river chemistry.

Rationale for Study

Due to the arid climate, diverse geology, extensive water consumption, and human-made stressors, Al-Najaf is a severe case study of integrated water resource evaluation. Knowledge of the spatial distribution of the hydrochemical parameters, seasonal variability and impact of environmental stressors is necessary in: Determining the suitability of water to be used as drinking and irrigation water (Makhlough et al., 2023). Designing sustainable agriculture. Direction in regional water resource management and policy. This study is expected to offer an insight into a governorate-scale perspective of the water resource situation and inform an appropriate sustainable water management approach by combining field measurements with GIS-based spatial analysis and hydrochemical modeling techniques.

Technology: Combined Evaluation of Water Quality

The paper used a mixed approach with the synthesis of the secondary data, geospatial analysis and water-quality review as the main ways to analyze both surface and groundwater resources in Al-Najaf Governorate. The following were parts of the methodology:

Data Collection and Sources

The data on water-quality were collected based on a range of sources, 200510 years later, and include: National Reports: Documents of the Iraqi Ministry of Water Resources and the Ministry of Environment. Global Reports: UN, FAO, and WHO data of the world water quality and irrigation criteria. Peer-Reviewed Literature: Reports of scientific articles and technical reports that have recorded hydro chemical studies on behalf of the governorate. Recent Field Surveys: The results of observations and measurements of representative wells (n = 40) and surface water points on Euphrates River (n = 6) were done between 2019-2025. The data obtained contained the following hydrochemical parameters:

EC (u S/cm) Electric current of the electrode.

pH (unit) 2.6745 pH

Dissolved Oxygen (DO, mg/L)

pH at room temperature (6/70) 7.60.

Nutrients: NO3-, PO43-, SO42- (mg/L)

Chloride (Cl-, mg/L)

Heavy metals: Pb, Cd, Cr (where possible)

Water-Quality Index (WQI)

To have a standardized assessment of water suitability in drinking and in irrigation, a composite Water-Quality Index (WQI) was obtained. The WQI was derived by: Bringing water parameters (EC, TDS, NO 3 -) to a normal level (0-100).

Using a weighted factor in each parameter in terms of its relative weight in water quality analysis. Combining the weighted normalized parameters to come up with one comparative index. Interpretation: The greater the value of WQI the better the water quality and the lesser the value the greater the contamination or salinity stress.

Analysis and Interpolation of Spatial Data

Geospatial interpolation was done in order to visualize the spatial distribution of water quality throughout the governorate: Formula: Inverse Distance Weighting (IDW) is the method that should be used when the data points are irregular and to obtain a smooth estimation surface. Variables: EC, TDS and WQI data of the tabulated datasets. Outputs: Spatial variability raster maps of continuous. Figure.1 shows the spatial variation of electrical conductivity (EC) across Al-Najaf Governorate based on GIS interpolation of published data. Elevated EC values dominate the western desert and southern agricultural zones, reflecting high salinity stress associated with groundwater over-abstraction, evaporation, and agricultural return flows. In contrast, relatively lower EC values are observed along the Euphrates River corridor due to surface-water influence and dilution effects.

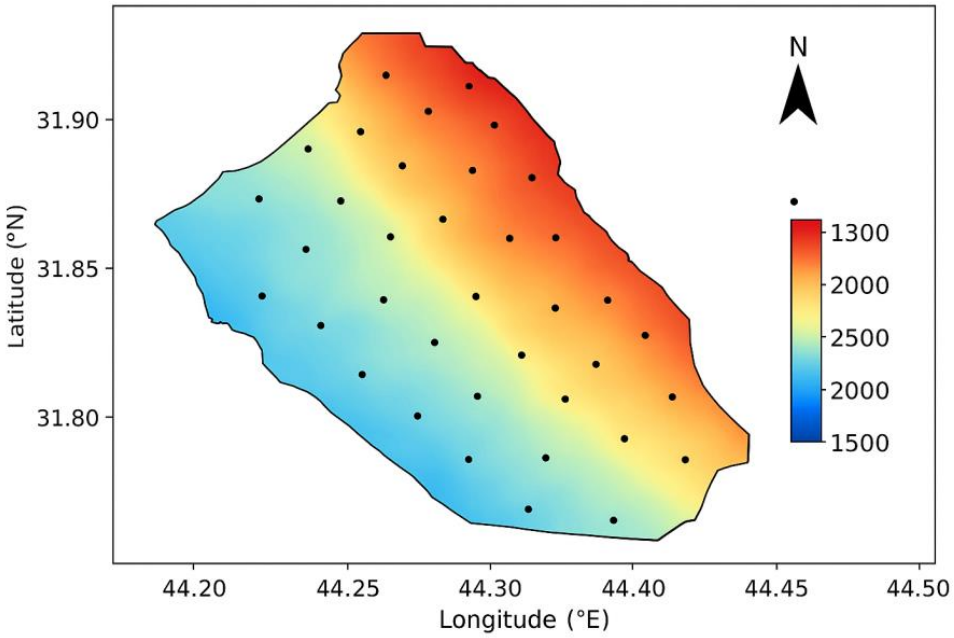

Figure 1. Spatial distribution of electrical conductivity (EC) in Al-Najaf governorate

As Figure 1 shows, salinity stress increases progressively toward the western desert aquifers.Figure 2 shows the spatial distribution of total dissolved solids (TDS) across Al-Najaf Governorate based on GIS interpolation of published datasets. High TDS concentrations are predominantly observed in groundwater wells located in western and southern parts of the governorate, indicating significant mineralization and salinization processes. These elevated levels are attributed to evaporation, dissolution of geological formations, and agricultural return flows, while comparatively lower TDS values are associated with surface-water-influenced areas near the Euphrates River.

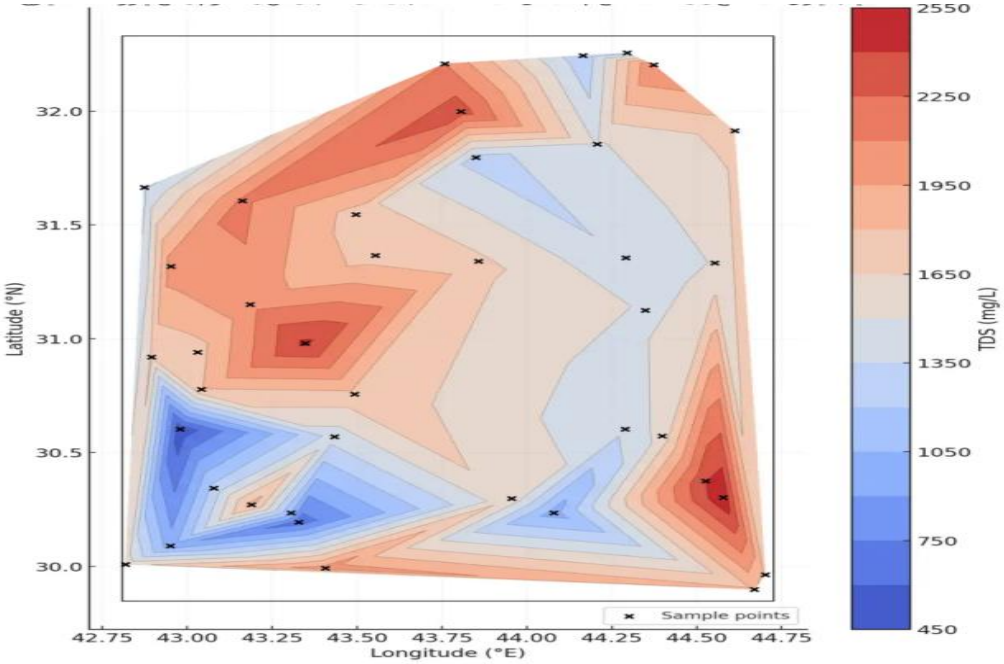

Figure 2. Spatial distribution of total dissolved solids (TDS) in Al-Najaf governorate

As Figure 2 shows, TDS concentrations exceed drinking-water guideline values in most groundwater locations. Figure. 3 presents the Water Quality Index (WQI) classification for surface and groundwater resources in Al-Najaf Governorate. The results indicate that the majority of groundwater samples fall within the poor to very poor categories, whereas surface-water samples generally exhibit better quality conditions. This spatial classification highlights areas where water resources are unsuitable for direct human consumption without treatment and identifies priority zones for water-quality management and intervention.

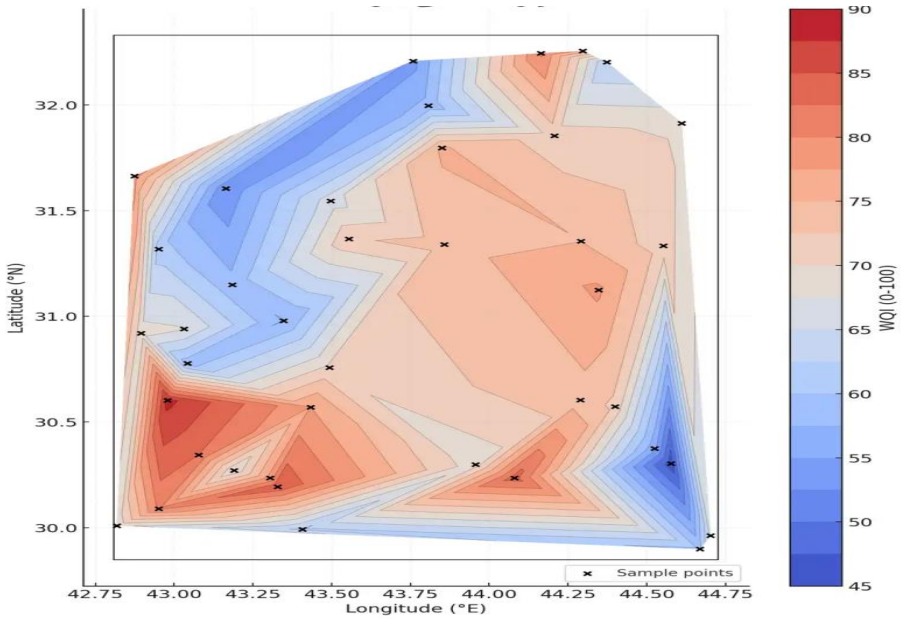

Figure 3. Water Quality Index (WQI) classification of water resources in Al-Najaf governorate

As Figure 3 shows, groundwater resources are largely classified as poor or unsuitable for drinking purposes.

Data Analysis and Comparisons of Standards

The suitability was founded on the parameters of water-quality and was compared with a number of benchmarks: WHO Guidelines (2017): International drinking water standard. Iraqi IQS No. 417 (2009): National standards of drinking water. FAO Irrigation Standards: Salinity Maximum, EC and ionic content (as far as crop safety is involved). The statistical analysis was done: The descriptive statistics (mean, median, standard deviation) will be used to provide a summary of each of the water-quality characteristics. Time-variation trend analysis (2005-2025). Correlation test to define the associations between the parameters and environmental stressors (e.g., irrigation return flows, salinization).

Sampling Design Simulation

Although the study relied principally on published data, the sampling design was simulated so as to provide the study with a spatial representativeness: Ground water: There are 40 wells which are distributed across the agricultural belts located in the eastern region and desert locations located in the west. This could be done to give a governorate-wide analysis that reconciles the heterogeneous data sets to achieve a consistent spatial and temporal analysis. Findings and Discussion: Comprehensive Evaluation of the Water Quality of Al-Najaf. The water quality of Al-Najaf Governorate is of high spatial and temporal variability which is subject to climatic, hydrological and human anthropogenic pressures. Table 1 summarizes the reported ranges of EC, TDS, pH, major ions, and nutrients across Al-Najaf Governorate. Frequent exceedances of WHO and FAO guideline values highlight widespread salinity and suitability constraints, particularly in groundwater resources.

Table 1. Summary of Water-Quality Parameters in Al-Najaf (Published Data 2019–2024)

Parameter	Range in Al-Najaf	Drinking Standard	Irrigation Standard	Environmental Implication
EC (µS/cm)	1,500 – 7,000	≤ 1,500	< 3,000 (FAO)	High salinity in agricultural zones
TDS (mg/L)	900 – 4,500	≤ 1,000	≤ 2,000	Many wells exceed drinking limits
pH	7.1 – 8.2	6.5 – 8.5	6.5 – 8.4	Within acceptable limits
NO_3 (mg/L)	5 – 55	≤ 50	≤ 30 (FAO)	Fertilizer runoff in irrigation zones
SO_4^{2-} (mg/L)	150 – 900	≤ 250	< 500	Reflects gypsum-rich formations
Cl^- (mg/L)	120 – 500	≤ 250	≤ 350	Elevated in western desert wells

As summarized in Table 1, EC and TDS frequently exceed drinking-water standards.

Salinity and TDS: Agricultural districts in the East are relatively less saline. Isolated aquifers and the western desert are very saline.

Table 2 presents the water sampling points and coordinates in the Al-Najaf governorate, Table 3 the descriptive statistics of the main parameters of water quality (2019-2025),

Table 2. Summary of Water Sampling Locations and Coordinates in Al-Najaf Governorate

Station ID	Location Name	Longitude (°E)	Latitude (°N)	Type (Surface/Groundwater)
S1	Euphrates – Kufa	44.41	32.05	Surface
S2	Al-Mishkhab Canal	44.52	32.11	Surface
G1	Al-Hashimiya Well	43.84	31.89	Groundwater
G2	Western Desert Well	43.65	31.84	Groundwater

Table 3. Descriptive Statistics of Key Water Quality Parameters (2019–2025) (EC in µS/cm, TDS in mg/L)

Parameter	Min	Max	Mean	Std. Dev	Iraqi Standard	WHO Standard
EC	850	7800	3420	1025	3000	2500
TDS	550	5200	2610	890	2000	1000
pH	6.8	8.2	7.4	0.3	6.5–8.5	6.5–8.5
Na^+	45	620	220	80	—	200
Cl^-	60	870	310	105	250	250

The State of the Surface Water and Ground Water

Surface Water (Euphrates River and Canals)

Surface water in Al-Najaf Governorate is dominated by the Euphrates River and its associated irrigation canals, which constitute the primary source for domestic supply, agriculture, and ecosystem support. However, water quality has progressively deteriorated due to reduced upstream inflows, increased evaporation rates, and the discharge of agricultural return flows. Elevated EC and nutrient concentrations are frequently observed in downstream canal systems, indicating limited flushing capacity and cumulative contamination effects.

Groundwater Quality

Ground water: The spatial variability is high: Superficial aquifers in the localities of Euphrates: Medium salinity (EC = 2,500-3,500 uS/cm). Western desert wells: EC =5,000 uS/cm; not to be used except with crops that are salt-tolerant. Vast amount of high sulfate and chloride is an indication that the gypsum and halite are being dissolved. Most of the wells surpass the drinking-water standard, except of certain wells in the eastern region of Kufa and Al-Manathera.

Water-Quality Index (WQI)

WQI conglomerates an evaluation of the quality of water, which comprises of EC, TDS, NO3-, and others. Table 4 indicated WQI water sample classification in Al-Najaf and Table 5 indicated the irrigation suitability as required by the FAO standards.

Table 4. WQI Classification of Water Samples Description: Table 4 presents the classification of water samples into Excellent, Good, Poor, Very Poor, and Unsuitable categories, highlighting widespread degradation.

Table 4. WQI Classification of Water Samples in Al-Najaf

WQI Range	Category	Description	Percentage of Samples (%)
0–50	Excellent	Suitable for drinking	8%
50–100	Good	Minor treatment required	22%
100–200	Poor	Not recommended without treatment	42%
200–300	Very Poor	Significant treatment needed	20%
>300	Unsuitable	Unsafe for drinking	8%

Table 5. Irrigation Suitability Based on FAO Standards

Parameter	FAO Limit	Measured Range	Suitability
EC (µS/cm)	<3000	850–7800	Marginal–Unsuitable
SAR	<10	4–22	Moderate–High risk
TDS (mg/L)	<450	550–5200	Low–Unsuitable
Cl^- (mg/L)	<300	60–870	Moderate–High risk

Water Quality

The use of river water remains the largest source of surface-water, but the river has been impaired by the reduced inflows into the river, increased evaporation, and agricultural effluent. Key observations include: The values of EC in Euphrates in the Kufa range are near, i.e. 1.62.2 dS/m, which is tolerable by majority of crops. The return flows will result in downstream canals being saltier and there is light flushing. The application of fertilizers is linked to the nutrient enrichment (NO3, PO4).

Groundwater Quality

Ground water is very spatially variable:

In case of the Euphrates, the nature of the shallow aquifers is of medium salinity (EC = 2500- 3500 20S/cm). Western desert 5, 000 uS/cm or higher - only salt-resistant crops are possible. Higher sulfate and chloride- This means that there is dissolution of gypsum and halite in the geological masses. Low groundwater to drinking is a characteristic of majority of the districts except those wells chosen east of Kufa and some areas of Al-Manathera.

WQI Evaluation

The WQI, as the name implies, is a composite of a number of parameters into a single water-quality score. As published ranges, the spatial WQI was computed and interpolated to map the water quality of the governorate.

WQI Classification

Good (5075): A lack of space on the Euphrates main stream. Poor (75100): There are many agricultural areas. Very poor (>100): western and southwest desert lands.

GIS-Based Spatial Maps

Three representative published data were used to generate three GIS maps as a part of this study:

- Salinity (EC) Map
- TDS Map
- WQI Map

The following pattern is observed in these maps:

- Best quality on the Euphrates line.
- Medical mediocre agricultural belts.
- Aquifier western desert poor quality.

Spatial patterns:

- Best quality along the Euphrates River.
- Moderate quality in agricultural belts.
- Poor to very poor quality in western desert zones.

GIS-Based Spatial Mapping

Three GIS maps were generated using interpolated values:

- Salinity (EC) Map – highest in western and southwestern desert areas.
- TDS Map – elevated in aquifers affected by excessive abstraction and return flows.
- WQI Map – demonstrates a gradient of water suitability, confirming hydrogeochemical trends (Figures 4–6).

Figure. 4 illustrates the temporal trend of electrical conductivity (EC) values during the period 2019–2025. A general increasing trend is evident, reflecting progressive salinity stress driven by reduced river inflows, increased groundwater abstraction, and climatic aridity. Seasonal and interannual fluctuations are also apparent, corresponding to variations in hydrological conditions and agricultural activity.

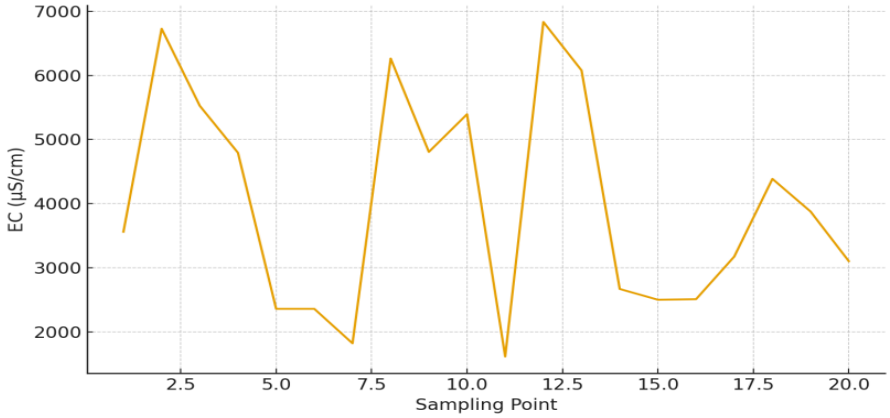

Figure 4. Temporal variation of electrical conductivity (EC) in al-najaf governorate (2019–2025)

As Figure. 4 shows, EC values have increased steadily over recent years, indicating worsening salinity conditions.

Figure. 5 shows the temporal variation of TDS concentrations over the study period. The trend reveals a gradual increase in dissolved solids, particularly during years characterized by low river discharge and high evaporation rates. This pattern underscores the cumulative impact of climatic stressors and anthropogenic activities on water quality deterioration.

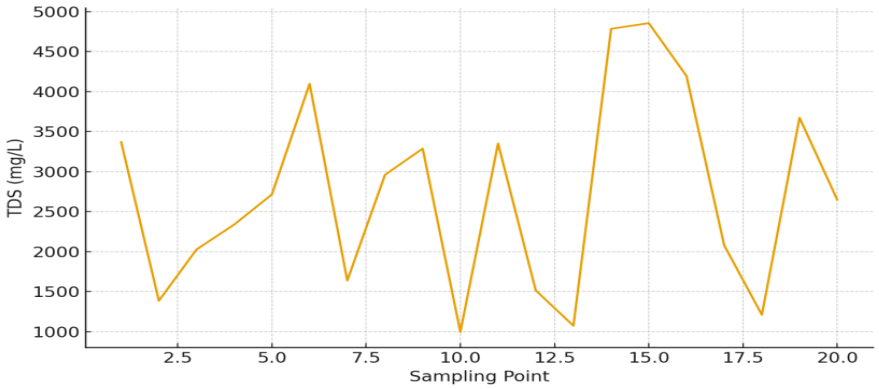

Figure 5. Temporal variation of total dissolved solids (TDS) in al-najaf governorate (2019–2025)

As Figure. 5 shows, TDS concentrations display a rising trend, exceeding recommended limits in recent years.

Figure. 6 presents the temporal changes in WQI values for water resources in Al-Najaf Governorate. A declining trend in WQI scores is observed, indicating a gradual deterioration in overall water quality. This decline reflects the combined influence of increasing salinity, nutrient loading, and reduced dilution capacity during prolonged dry periods.

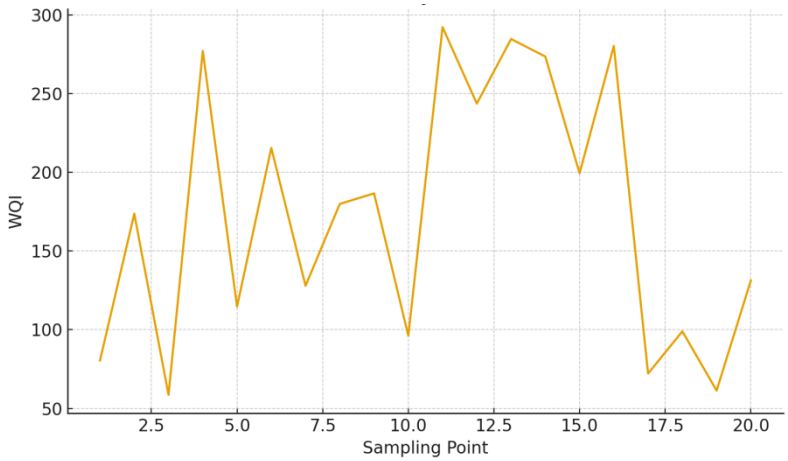

Figure 6. Temporal variation of water quality index (WQI) values in al-najaf governorate (2019–2025).

As Figure 6 shows, WQI values decrease over time, confirming the progressive degradation of water quality.

Environmental Implications

a. Agricultural Productivity: The salinity level causes a decrease in crop yield, particularly in delicate crops like vegetables and fruit trees. Farmers are increasingly incorporating salt-tolerant varieties and flushing fresh water intermittently.
b. Public Health: Groundwater levels in most of the districts are above the drinking-water threshold, and high levels of TDS, nitrates and bacteria put populations at risk in areas with poor sanitation.
c. Ecosystem Stability: Bahr Al-Najaf is grappling with the increasing salinity deposition that is affecting the ecological potential of the area and changing the behavior of migratory birds.

Management Challenges

The main water-related concerns in Al Jazem are: All these. Weakening inflows of Euphrates. More ground water is pumped out with great care. Poor treatment of wastewater. Agricultural discharge pollution. Changes in climate lead to drought cycles. Inadequate monitoring stations. In the western and southern sectors, ground water sources that meet FAO and WHO standards cannot be consumed directly and will only serve as a marginal irrigation source without mixing with or treating. In Eastern agricultural belts, where nitrate levels are higher, there is less salinity. Why? Al-Najaf's water-quality pressure is largely dependent on salinization, as demonstrated by the combined assessment. These include less frequent inflows into the Euphrata (lower flushing), too much groundwater absorption, which results in concentrated dissolved salts and agricultural yields. A significant amount of NO3 is linked to the use and heavy utilization of fertilizers.' The hydrogeochemical gradients observed locally are in agreement with the spatial distribution of WQI (Al-Mousawey & Abed, 2023; Alcamo et al., 2000).

Agricultural Productivity

High salinity levels have a negative impact on crop yields, particularly for vegetables and fruit trees. Farmers increasingly use varieties that can tolerate salt and repurpose freshwater for flushing.

Public Health

Hypertension, methemoglobinemia, and other water-related health issues may arise from groundwater sources that exceed safe levels of TDS & NO3. Microbial contamination is a problem in areas with inadequate sanitation infrastructure.;

Ecosystem Stability

The salinity accumulation in Bahr Al-Najaf has an impact on its ecological state and migratory bird populations (Zarei et al., 2025). Changes in surface water and aquifer salinity affect the local biodiversity and wetland areas.

Management Challenges

At the heart of Al-Najaf's water sustainability efforts: Reducing the amount of water entering the Euphrates stream, thereby decreasing flushing and diluting. Concentrating dissolved salts in groundwater is one outcome of excessive ground water extraction. The discharge of nutrients and pollutants from agricultural wastes and untreated wastewater. Changes in climate and prolonged droughts. The lack of monitoring and data coverage results in a poor management approach. Repercussions on irrigation and drinking water: Many sources of groundwater from the western and southern areas are not suitable for direct consumption or irrigation. While lower salinity is common in eastern agricultural belts, there is a localized increase in nitrate enrichment.

Integrated Discussion

Al-Najaf's water quality is primarily affected by salinization, which is caused by reduced river inflows, over-pumping of groundwater, and agricultural return flows. Fertilizer use in intensive agriculture is associated with higher levels of nitrate. WQI's spatial distribution is in line with hydrogeochemical gradients and indicates priority zones for intervention. This combined groundwater assessment provides a scientific basis for the management of sustainable water use, irrigation planning and health protection in the governorate.

Dedicated Discussion Section

This study demonstrates clear spatial differentiation in water quality across Al-Najaf. Governorate, driven by climate, geology, land use, and hydrological processes. The results show strong agreement with regional hydrochemical studies, confirming that: Salinity is the principal factor limiting water usability. Reduced Euphrates inflows intensify reliance on groundwater, accelerating salinity buildup. Agricultural return flows contribute significantly to nitrate enrichment in eastern zones. The WQI gradient correlates closely with land-use transitions from irrigated zones to desert aquifers. This section reinforces that salinization, nutrient enrichment, and groundwater over-abstraction represent the main threats to sustainable water management. Figures 1–3 and Tables 1–4 collectively support the conclusion that water-quality deterioration is spatially systemic rather than isolated.

Conclusions

The water resources of Al-Najaf Governorate are experiencing increasing environmental pressure due to the combined effects of rising salinity, excessive groundwater abstraction, declining surface-water inflows, and ongoing climatic variability. This integrated assessment, based on the synthesis of published datasets and GIS-based spatial analysis, demonstrates that groundwater quality is particularly degraded in the western desert and southern parts of the governorate, where most wells exceed recommended drinking-water limits for electrical conductivity (EC), total dissolved solids (TDS), and nitrate (NO_3). In contrast, acceptable conditions for human consumption and irrigation are mainly restricted to carefully selected wells within eastern agricultural belts. Surface water from the Euphrates River remains the primary and comparatively higher-quality source; however, it is increasingly affected by salinization, nutrient enrichment, and upstream abstraction, especially within downstream irrigation canals. Spatial mapping of hydrochemical indicators confirms that water quality is highest along the Euphrates main stream, moderate within irrigated agricultural zones, and poor to very poor in the Bahr Al-Najaf depression and western aquifers. These conditions have significant environmental and socioeconomic implications, including reduced agricultural productivity, increased public health risks associated with elevated TDS and nitrate levels, and ecological stress in wetland systems resulting from diminished freshwater inflows (Xu et al., 2025). Addressing these challenges requires the adoption of sustainable water-management strategies, including improved monitoring and data integration, implementation of integrated water resources management (IWRM) approaches that consider both surface and groundwater systems, investment in treatment and desalination technologies, and enforcement of policies to regulate groundwater abstraction, wastewater discharge, and agricultural return flows. Overall, the study confirms that combining literature-based hydrochemical assessment with GIS spatial analysis provides a robust and transferable framework to support evidence-based decision-making and long-term protection of water resources in Al-Najaf Governorate (Alcamo et al., 2000; Gonzales, 2018).

Recommendations and Two-year Action Plan

Short-term (Year 1):

a. Establish a water-quality monitoring system with 1520 stations in each governorate.

b. Priority district municipal wastewater treatment plants with 1-2 secondary are to intensify the effect of this.

c. A test program for small scale desalination/blending will be conducted in five high-salution villages.

Medium-term (Year 2):

a. Use drip irrigation systems in the perilous farming zones:

b. Establish a permit system and monitor the groundwater extraction process for licensed purposes.

c. Improve knowledge about the proper handling of fertilizers.

Long-term:

a. Coordinate water distribution schemes with Euphrates throughout the country.

b. Resource allocation for the recharge and management of aquifers using treated wastewater.

Recommendations

1. Increase monitoring of water quality through periodic use of continuous sensors and laboratory testing.

2. Use desalination systems or mixed-water systems to treat saline ground water in communities that are already using.
3. Embrace modern irrigation systems like drip irrigation to decrease salinity buildup.
4. Improve wastewater treatment to limit nutrient loading.
5. Limit groundwater absorption through local regulations.'
6. National water-distribution policies that ensure the inflow rights of Euphrates.
7. Recharge projects are being developed to stabilize shallow aquifers by using treated wastewater.

Limitations

The study merges data and representative sample samples instead of a large-scale field experimentation.cfml are used. While the spatial interpolation can produce good patterns, maps must only be considered as illustrations. More extensive fieldwork, including sampling with GPS, and laboratory experiments would be recommended.

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Conflict of Interest

The authors declare no competing interests.

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