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Analysis and assessment of surface water quality in Al-Habbaniyah, Iraq

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ABSTRACT

Water quality is a crucial factor affecting human health in arid and semi-arid regions. The Al-Habbaniyah area includes two important sources of surface water: Lake Habbaniyah and the Euphrates River. To assess water quality, surface-water samples were collected and analyzed. Relative precision and deviation (E%, T%) were adopted for interpretation. Physical properties that significantly influence water quality, including color, odor, taste, temperature, pH, total dissolved solids, and electrical conductivity, were analyzed. Most water samples (R1, R2, R3, L1, L2, L3, Ch1, Ch2) were grouped into three categories according to the USDA irrigation water-quality assessment diagrams. The results demonstrated that most natural water sources contain cations and anions in chemical equilibrium. The study concludes that surface water is suitable for irrigation and drinking, provided that drinking water is treated to remove naturally occurring iron and manganese ions. Irrigation water requires management to control sodium and salinity risks. Integrated management of surface water for drinking and irrigation purposes is recommended to address water problems. Additionally, the Piper diagram indicated that all samples belong to Class I, Category V.

Keywords: *Al-Habbaniyah District, Hydrochemical characteristics, Laboratory analysis, Surface water*

1 INTRODUCTION

Water is one of the most important natural resources on Earth and is essential for sustaining life. Comprehensive management of water resources is a crucial prerequisite for sustainable development planning. With the increasing global population, demand for drinking water, agriculture, industry, and livestock has risen significantly. Hence, managing water resources in arid and semi-arid environments is critical because of their inherent dryness and limited water availability. Climate change and increasing water demands have compounded these challenges, necessitating sustainable strategies for resource management [1,2].

The growing need for water, driven by expanded energy production, rapid industrial growth, intensified agriculture, urbanization, and improved living standards, has dramatically increased water consumption. This expansion poses challenges in meeting increasing demands within the limits of available water resources [3,4]. One of the primary global challenges today is inadequate water availability to meet the needs of a growing population and to ensure optimal utilization of surface- and groundwater resources for various human activities, including agriculture, livestock, and industry. It is crucial to continually evaluate water quality for practical uses, as early identification of water conditions supports better decision-making, ensuring sustainability and safety for users [5].

Water quality assessment is fundamental and depends on its intended purpose. Drinking water requires precise, high standards, whereas agricultural irrigation water has comparatively lower standards. Water for livestock, such as sheep, cattle, fish, and poultry, requires standards closer to drinking water quality. Climate change can significantly disrupt water-resource balances, negatively affecting water quality and spatial–temporal distribution and further exacerbating management challenges in many areas [6].

Several approaches can enhance Iraq's water-resource management, such as developing knowledge, expanding rainwater-harvesting applications, and continually monitoring and evaluating water quality [5]. Studies indicate that contemporary water issues will be central challenges in the future, with analysts predicting water-related conflicts due to rising temperatures and climate change. Countries controlling river sources have begun constructing dams and reservoirs, diverting river courses to serve their interests, and using water as leverage against neighboring countries. Iraq faces severe water scarcity and water-quality deterioration, exacerbated by upstream countries' projects controlling the Tigris, Euphrates, and their tributaries, intensifying environmental and human impacts [7].

Variations in Iraqi river discharges, notably in the Euphrates River, the main water supplier to Lake Habbaniyah, have led to fluctuations in the lake's surface area, causing environmental problems. Hence, attention to lakes and water storage projects is vital for providing the necessary water quantities and reducing the impacts of water scarcity. Access to potable water is a fundamental human right [8].

Water, a critical component of the biosphere, is essential for humans and other organisms and is naturally renewed through the hydrological cycle. However, expanding human populations and activities disrupt ecosystems, leading to significant changes in water quality [9]. Thus, studying water quality, both chemical and physical, is vital because it is sensitive to rapid changes that affect humans and their activities. Recently, water quality in Iraq has deteriorated due to climate change and reduced Euphrates water levels, combined with rising water demands from increasing populations [10]. Following an initial assessment of the study area's natural characteristics, this study examines the physical and chemical properties, hydrochemical formula, water quality, hydrochemical indicators, groundwater origin, and classification to determine water properties and their suitability for various purposes in the eastern part of central Iraq [11].

The purpose of this research is to investigate whether surface-water quality has changed due to pressures from direct and indirect agricultural, industrial, household, and medical waste disposal in Al-Habbaniyah. Based on this purpose, this research hypothesizes that water resources in the study area are chemically affected by pollutants from various sectors, causing changes in water quality and rendering them unsuitable for all uses. Therefore, the objective of this research is to identify the qualitative properties and indicators of surface water in the study area.

2 MATERIALS AND METHODS

2.1 Geographic location of the study area

The study area is located in central Iraq, specifically in the eastern part of Al-Anbar Province. It is bordered by Fallujah to the east, Ramadi to the west and north, and the Ameriyat Al-Fallujah District to the south and southeast. The area is approximately 90 km from Baghdad, 20 km from Ramadi, and 25 km from Fallujah, and it is centrally positioned between Ramadi and Fallujah. Al-Habbaniyah District covers an area of 802 km2, as illustrated in Figure 1. Geographically, it lies between latitudes 33°19' and 33°29' N and longitudes 43°11' and 43°25' E. The population was 157,680 in 2023. The temporal scope for data analysis was from 1990 to 2020.

Surface water in the study area includes the Euphrates River, the region's lifeline and primary source of surface water (Figure 2). It also includes Lake Habbaniyah, located on the right side of the Euphrates River. This low-lying reservoir borders the study area on its southeastern side and is surrounded by highlands on all sides except the northwest. The reservoir is used to store excess water from the Euphrates River during flood seasons via the Warar Regulator. During the rainy season, the water is then returned to the Euphrates River via the Dhaban Regulator.

Overall, groundwater levels in the study area can be affected by several factors, including annual rainfall, which significantly influences aquifer recharge. Rainfall in the study area totaled 113.2 mm between 1990 and 2020. Agricultural use can also reduce groundwater levels because many farmers rely on groundwater for irrigation, especially when abstraction exceeds recharge. Climate change also affects rainfall and temperature patterns, which in turn influence groundwater levels.

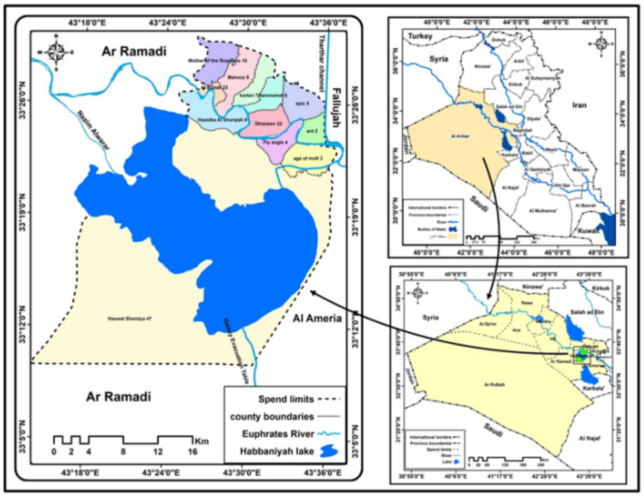

Fig. 1 Location of the study area

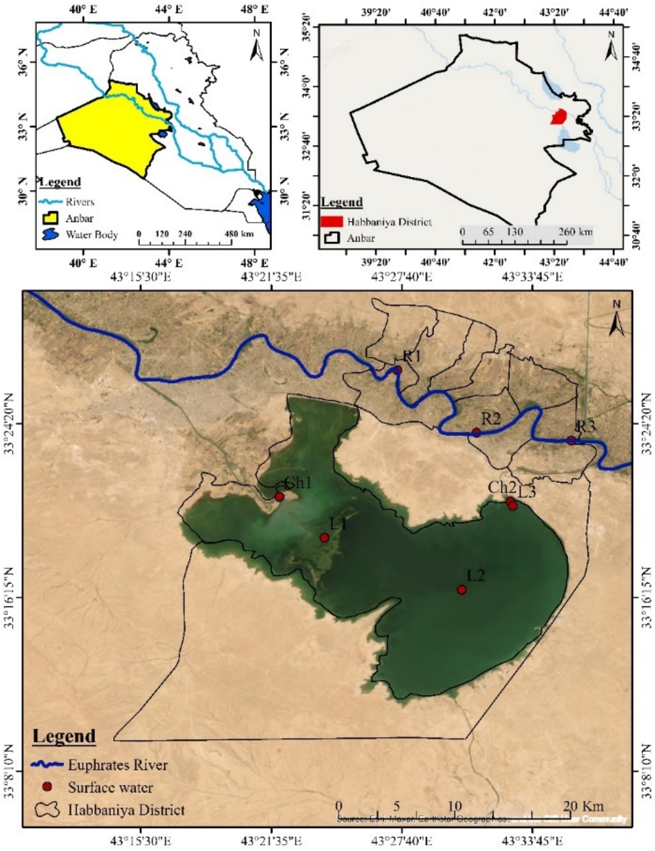

Fig. 2 Location of Surface water (Euphrates River and Habbaniyah Lake) and sampling location in the study area

2.2 Methodology

The research process included four stages:

2.2.1 Office work stage

Information was gathered from Arabic and foreign books, theses, dissertations, research articles, and scientific reports related to water resources. Official reports and data on climate and water resources were also used.

2.2.2 Field work stage

Surface water was sampled at nine locations along the Euphrates River (R1, R2, and R3), Lake Habbaniyah (L1, L2, and L3), and channels connected to the lake (Ch1 and Ch2) during November (Figure 2). Samples were collected in 500 mL screw-cap polyethylene bottles. Before use, each bottle was washed with 1 M HCl, then rinsed repeatedly with deionized water. The samples were labeled with sample numbers and collection dates, stored in an ice container, and transported to the laboratory for further analysis. Furthermore, other necessary data were obtained from different government departments.

2.2.3 Laboratory work stage

Physical properties that influence water quality, including color, odor, taste, temperature (°C) , pH, total dissolved solids (TDS), electrical conductivity (EC), and the TDS-EC relationship, were measured during field work and laboratory analysis. The pH was measured in situ using a digital pH meter (SensoDirect 150). Electrical conductivity and temperature were measured using a conductivity meter (SensoDirect 150). Color and odor were visually identified and evaluated by sensory analysis, respectively, during fieldwork. TDS was also measured in the field using a conductivity meter (SensoDirect 150). All instruments were previously calibrated.

The major ions in the water samples were chemically treated and analyzed at the Central Laboratory of the College of Agriculture, University of Anbar. Cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) were quantified using inductively coupled plasma optical emission spectrometry (ICP-OES) (PerkinElmer Optima 5300 DV, USA). Major anions ($Cl^{-}, HCO_3^{-}, NO_3^{-}$, and SO_4^{2-}) were determined by ion chromatography (IC) (150443). Heavy metals (Fe, Cu, Pb, and Cd) were also analyzed via ICP-OES. The detection limits for ICPOES and IC were both 1mg/L. Analytical precision for major ions was maintained within 1%, and the ion balance error (IBE) for all samples was below 5%.

2.2.4 Statistical analysis stage

The water-sample results were analyzed using general statistics to support evaluations, conclusions, and recommendations.

2.2.5 Analytical precision

Analytical precision measures how closely the results match actual values. It was evaluated based on the ionic balance of negative and positive ions, assuming minimal secondary-ion concentrations. The equation used for this analysis is [12]:

$$E\% = \frac{\sum Cat - \sum Ani}{\sum Cat + \sum Ani} \times 100 \tag{1}$$

Where, E% = Percentage error, Σ^{C2t} = Total positive ion concentrations, Σ^{Ani} = Total negative ion concentrations. Relative differences of less than 5% indicate high reliability of hydrochemical interpretations. Differences of 5% – 10% require cautious interpretation, while differences of 10% or more are unreliable [13]. Another precision testing method is the T% test (difference percentage between calculated and measured Total Dissolved Solids (TDS), calculated as [14]:

$$T\% = \frac{TDSm - TDSc}{TDSm} \times 100 \tag{2}$$

Where, T% = Test percentage, TDSm = Measured TDS in laboratory (ppm), TDSc = Total Dissolved Solids (Calculated), acceptable limit: 0-5 (confirmed), limit 5-10 (probable-confirmed), and limit above 10 (unconfirmed) (Table 1).

Table 1 Classification of accuracy and relative deviation

Acceptability	T%	E%
Confirmed	A ≥ 95%	E% ≤ 5%
Probable	90% ≤ A ≤ 95%	5% ≤ E% ≤ 10%
Uncertain	A < 90%	E% > 10%

It is expected that the calculated total dissolved solids (TDS) values will be slightly lower than the laboratory-measured values. This discrepancy can be explained by factors like organic matter, carbonates, and bicarbonates. Organic matter and high-molecular-weight heavy elements were excluded from analyses used to calculate total dissolved solids by the computational method [15]. The effects of carbonates and bicarbonates were accounted for in the calculation method; however, during drying, bicarbonate ions convert to carbonate ions, releasing CO2 and precipitating CaCO3. This affects the concentration determined by the evaporation method [16]. In both methods, when the reaction error value is less than 5%, the results can be accepted for interpretation. If the error value is between 5% and 10%, the results are acceptable but carry some risk. However, if the error value exceeds 10%, the results cannot be relied upon for hydrochemical interpretations [17]. Applying both methods to water samples produced results (Table 2) within the acceptable confirmed range (less than 5%), suitable for hydrochemical interpretations.

Table 2 Analytical precision of surface water samples

Samples	E%	T%
R1	3.97	1.45
R2	4.82	3.91
R3	4.01	2.29
L1	4.09	0.23
L2	3.28	0.46
L3	4.58	1.24
Ch1	3.29	4.68
Ch2	5.00	3.00

3 RESULTS AND DISCUSSION

3.1 Physical properties

Physical properties that significantly influence water quality include color, odor, taste, temperature (°C), pH, total dissolved solids (TDS), electrical conductivity (EC), and the TDS–EC relationship were tested in this study.

3.1.1 Color, odor, and taste

The sources of color, odor, and taste in water originate from organic substances, minerals, and dissolved gases. Drinking water of acceptable quality is typically colorless, odorless, and tasteless. However, water containing iron tends to exhibit a greenish color. When hydrogen sulfide is present, the water may take on a bluish hue. Water rich in dissolved acids often appears yellow, while water containing manganese usually has a black coloration. Regarding odor, the primary cause is the presence of certain dissolved substances. Water containing organic materials and microorganisms often exhibits distinctive color and odor. For example, water containing hydrogen sulfide has an odor resembling rotten eggs. In general, varying concentrations of different compounds can alter the color and odor of water [18].

Regarding taste, water containing certain compounds and organic matter can be unpalatable, especially well water, which may have a salty taste due to elevated salinity. In the study area, all water samples were colorless and odorless, while some groundwater samples exhibited a salty taste. This salinity is attributed to increased total dissolved solids, which contribute to the water's saltiness.

3.1.2 **Temperature** (°C)

Temperature is a key physical property affecting water quality. It influences chemical reactions and the solubility of gases in water, thereby altering water's natural properties. Temperature also affects the metabolic (biochemical) activities of organisms in aquatic environments. Deviations from permissible temperature ranges can lead to substantial changes in the behavior and functions of these organisms. Collectively, these factors exert a strong influence on water's natural properties [19].

Additional factors affecting water temperature include ambient air temperature, water-body depth, and the presence or absence of suspended materials. During site visits, surface-water temperatures were measured in the field using water temperature meters. The observed surface-water temperatures in the study area ranged from 20.00 °C to 22.30 °C, as detailed in Table 3.

Table 3 Physical properties and total hardness values of surface water samples

Sample	**Temp.** (°C)	**pH**	**EC(μS/cm)**	**TDS (mg/L)**
R1	21.20	7.90	1053.00	737.10
R2	21.00	7.90	1090.00	763.00
R3	22.3	8.00	1060.00	742.00
L1	20.9	7.60	1186.00	830.20
L2	20	7.01	1266.00	886.20
L3	20.3	7.20	1129.00	790.30
Ch1	21.00	7.61	1160.00	812.00
Ch 2	22.10	7.78	1170.00	819.00

3.1.3 pH (**hydrogen ion concentration**)

pH is defined as the negative logarithm of hydrogen ion concentration and serves as a measure of water acidity or alkalinity under standard temperature and pressure conditions. A pH value above 7 indicates alkaline water, a value below 7 indicates acidic water, and a pH of exactly 7 indicates neutral water.

Most biological processes occur within a specific pH range, and deviations from this optimal range can disrupt normal physiological or biological functions. For example, rainwater typically exhibits slight acidity (approximately pH 6) due to dissolved carbon dioxide. Additional atmospheric pollutants can further acidify rainwater, causing "acid rain." According to laboratory analyses, pH values for surface water samples in the study area ranged from 7.01 to 8.00, as detailed in Table 3.

Both Iraqi and international standards establish a permissible pH range for water of 6.5–8.5. Based on the analytical results, pH values for surface-water samples from the study area fall within the acceptable range. Furthermore, analysis of the surface-water samples indicates that all samples are classified as alkaline saline waters [20].

3.1.4 **Total dissolved solids** (TDS)

Total dissolved solids (TDS) refer to all substances fully dissolved in water that remain after filtration. These exclude suspended solids, colloidal particles, and dissolved gases. TDS primarily consists of the sum of positive and negative ions and is influenced by the geological composition of rocks and soils in contact with water, as well as the duration of this contact. TDS are expressed in milligrams per liter (mg/L). TDS values generally indicate water salinity and the total dissolved solids content, which are crucial for assessing water suitability for various uses.

Total dissolved solids (TDS) values in surface-water samples ranged between 737.10 and 886.20 mg/L, as shown in Table 3. The lowest TDS value was recorded at the entrance of the Euphrates River (737.10 mg/L), representing the minimum concentration among the surface-water samples from the study area. Conversely, the highest TDS concentration was observed in the central region of Lake Habbaniyah (886.20 mg/L) [21].

3.1.5 **Electrical conductivity** (EC)

Electrical conductivity refers to the ability of one centimeter of water to conduct an electric current. It is measured in microsiemens per centimeter (µS/cm). Electrical conductivity is a numerical indicator of water's capacity to carry an electrical current, and it is inversely related to resistivity. Water conductivity depends primarily on three factors: dissolved solids concentration, ion valence, and water temperature. This technique is adopted as an approximate measure of dissolved salt concentration in water. Measurements were taken using an electrical conductivity meter. Pure water exhibits low electrical conductivity, whereas higher conductivity indicates higher concentrations of acids, bases, and salts. Conductivity depends on the valence and concentration of dissolved ions, as well as on water temperature at the time of measurement, because temperature directly affects ion mobility [22].

Table 3 shows that the electrical conductivity values of surface water in the study area ranged from 1,053 to 1,266 µS/cm. The lowest conductivity was recorded at the Euphrates River entry point (1,053 µS/cm), while the highest was measured in the central area of Lake Habbaniyah (1,266 µS/cm). The elevated conductivity in the surface waters of the study area is primarily attributed to pollution sources, particularly wastewater discharge and agricultural runoff.

3.2 Chemical characteristics

3.2.1 Positive ions (cations)

Calcium (Ca^{2+}): Calcium is among the most common alkaline elements and is primarily responsible for water hardness, although other elements contribute as well. Calcium is essential to plants and aquatic organisms; however, elevated calcium levels in water can lead to undesirable odors. Dolomitic limestone, limestone rocks, and fossil-bearing rocks such as gypsum, which dissolve rapidly in water, are the primary sources of calcium ions [23].

Analysis of Table 4 reveals that calcium ion $\left(Ca^{2+}\right)$ concentrations in surface-water samples from the study area range from a minimum of 77mg/L at the Euphrates River outlet to a maximum of 99mg/L in the central region of Lake Habbaniyah. The variation in calcium levels across the study area can be attributed to fluctuations in water levels. Decreased water levels enhance chemical weathering, leading to greater limestone dissolution and, consequently, higher Ca^{2+} concentrations. Conversely, elevated water discharge rates dilute calcium ion concentrations, resulting in lower levels. Upon evaluating the results, it is evident that Ca^{2+} concentrations in the surface waters of the study area fall within internationally permissible limits [24].

Magnesium $\left(Mg^{2+}\right)$: Magnesium is classified among the alkaline earth elements and is present in various rock formations and groundwater. In river water, its concentration tends to be lower, depending on its sources of input. The most significant sources of magnesium include limestone, dolomite rocks, and clay formations. Magnesium, particularly when combined with sulfates, is a primary cause of diarrhea, though humans can develop tolerance to it over time. Additionally, magnesium contributes to water hardness.

Analysis of Table 4 indicates that the highest concentration of magnesium ions recorded was 36 mg/L, observed in two locations: the central region of Lake Habbaniyah and the Nazim Sin al-Dhiban area. The lowest concentration was recorded at the entrance of the Euphrates River, measuring 28mg/L. The elevated magnesium levels can be attributed to anthropogenic factors, such as the discharge of untreated sewage into the Euphrates River and the release of agricultural wastewater, both of which increase Mg^{2+} concentrations. Natural factors related to the region's geological composition also contribute to magnesium levels. Upon analyzing the results, it is evident that Mg^{2+} concentrations in the surface waters of the study area do not exceed internationally permissible standards.

Sodium (Na^{+}): Sodium is a widely distributed element in the Earth's crustal rocks. The primary source of sodium ions is halite, which dissolves rapidly and is especially found in the rock formations of the Fatha, Euphrates, and Quaternary periods. Sodium plays a vital role due to its diverse applications across human activities, including industry and agriculture. It is also an essential component of human nutrition, primarily in the form of sodium chloride, commonly known as table salt.

Sodium ions hold significant importance in assessing water quality because of their implications for public health; elevated sodium concentrations can contribute to hypertension. Additionally, high sodium levels in irrigation water negatively affect soil and plants.

Analysis of the surface-water samples from the study area, as presented in Table 4, shows that the lowest sodium ion concentration was 114 mg/L, recorded at the Euphrates River outlet within the study boundaries. The highest sodium concentration was 138 mg/L, observed in the central region of Lake Habbaniyah. The elevated sodium levels are attributable either to anthropogenic factors arising from various human activities or to natural factors related to the region's geological characteristics. Upon evaluating the sodium ion concentrations in the surface waters of the study area, it is evident that these levels fall within internationally permissible limits [25].

Potassium (K^{+}): Potassium ions in freshwater typically occur at low concentrations despite their presence in all components of the natural environment and the high solubility of potassium in water, as this ion tends strongly to remain dissolved. Potassium is an essential nutrient for humans, playing a vital role in numerous cellular functions, including metabolism, regulation of body volume and growth, and cellular electrical properties. Elevated potassium levels in the blood can lead to serious health effects, particularly for individuals suffering from heart disease, kidney disorders, hypertension, diabetes, or those taking medications that interfere with potassium balance in the body [26].

Analysis of surface-water samples from the study area, as detailed in Table 4, shows that the lowest potassium ion concentration of 2.00 mg/L was recorded at two locations: the Euphrates River outlet within the study area and the Nazim Al-Warar region. The highest potassium concentration, 4.00 mg/L, was recorded at the inlet of Lake Habbaniyah. One cause of elevated potassium levels is the discharge of water containing chemical fertilizers. Compared with internationally acceptable limits, all potassium ion concentrations in the surface-water samples fall within acceptable ranges.

Table 4 Positive ions of surface water samples

Samples	Calcium mg/L	Magnesium mg/L	Sodium mg/L	Potassium mg/L
R1	80	28	118	2.10
R2	82	29	119	2.40
R3	77	32	114	2.00
L1	92	35	130	4.00
L2	99	36	138	3.30
L3	86	34	123	3.10
Ch1	84	32	122	2.00
Ch2	88	36	125	3.40
Total	688	262	989	22.30
Mean	86.00	32.75	123.62	2.78

3.2.2 Total hardness (TH)

Total hardness is one of the key characteristics of water and results from the presence of magnesium and calcium ions, expressed as calcium carbonate. Measuring water hardness is important because it helps determine the suitability of water for various uses. Hardness refers to water's tendency to precipitate insoluble solids when reacting with soap or to form deposits on the walls of boilers and water-distribution systems [27].

There are two types of hardness: permanent hardness (non-carbonate hardness) and temporary hardness (carbonate hardness). Permanent hardness arises from the association of chlorides, sulfates, and nitrates with calcium and magnesium ions. This type of hardness does not precipitate upon boiling and can be reduced by adding chemicals such as sodium carbonate, which precipitates calcium and magnesium ions. Temporary hardness, also known as carbonate hardness, is termed "temporary" because it decreases upon boiling as calcium and magnesium carbonates precipitate.

Referring to Table 5, the lowest recorded total hardness was 348 mg/L at the Euphrates River outlet within the study area, while the highest was 651 mg/L in the central region of Lake Habbaniyah. The average total hardness for all surface-water samples in the study area was 401.8 mg/L. According to the World Health Organization, the permissible limit for total hardness is 500 mg/L. Comparing the analytical results shows that the inlet, center, and outlet regions of Lake Habbaniyah, as well as the Nazim Al-Warar area, exceed the internationally accepted total-hardness limit.

Table 5 Total hardness of surface water samples

Sample	Total Hardness mg/L
R1	353
R2	361
R3	348
L1	572
L2	651
L3	521
Ch1	560
Ch2	370
Total	3.215
Mean	401.8

3.2.3 Negative ions (anions)

Chloride (Cl-): Chloride ions are important negatively charged ions that are commonly found in natural waters. When combined with sodium ions, they impart a salty taste to the water by forming sodium chloride. Chloride salts are characterized by their high solubility in water and are abundantly present in limestone and gypsum rocks found worldwide. However, elevated chloride ion concentrations can be toxic to plants, particularly when they exceed internationally permissible limits. The global permissible limit for chloride ion concentration in water is set at 250mg/L.

According to surface-water sample results from the study area, presented in Table 6, the lowest chloride ion concentration was 114mg/L at the Euphrates River outlet within the study boundaries, while the highest was 173mg/L in the central part of Lake Habbaniyah. Elevated chloride levels are primarily attributed to anthropogenic activities in cities located near the Euphrates River. When comparing chloride ion concentrations in the surface-water samples with World Health Organization standards, all results fall within the internationally accepted limits [28].

Sulfates (SO42-): Sulfate ions occur in water due to the dissolution of evaporite minerals such as gypsum and anhydrite, as well as through the oxidation of marcasite and pyrite minerals in shale and clay formations. Additionally, organic matter and chemical fertilizers used in agriculture serve as significant sources of sulfate ions. Sulfates contribute to permanent hardness in water, especially when present as calcium or magnesium sulfates. They are also a primary cause of salinity and play an important role in determining water suitability for irrigation purposes.

Analysis of sample results, as shown in Table 6, indicates that the average sulfate ion concentration is 240.5mg/L. The lowest recorded concentration was 230mg/L in the midsection of the Euphrates River within the study area, while the highest was 250mg/L in the central part of the lake. The maximum permissible sulfate concentration is 250mg/L, indicating that all sulfate ion measurements meet internationally accepted standards [29].

Bicarbonate (HCO3-) and Carbonate (CO32-): The bicarbonate ion is the primary indicator of water alkalinity, as bicarbonate and carbonate ions collectively influence the pH level. Bicarbonate ions are generally present in water at concentrations ranging from 50 to 400mg/L. The main source of bicarbonate and carbonate ions in water is the dissolution of carbonate rocks, namely calcium and magnesium carbonates, in water containing dissolved carbon dioxide (CO2), along with hydrogen ions produced from the dissociation of carbonic acid.

When using groundwater, bicarbonate is essential for irrigation. However, excessive bicarbonate levels can cause soil aggregation, thereby increasing sodium levels. Moreover, elevated bicarbonate levels reduce nutrient absorption and mobility, thereby impeding plant growth [30].

Analysis of surface-water samples from the study area, as detailed in Table 6, indicates that bicarbonate (HCO3-) concentrations range from 151.00 to 182.80 mg/L. The lowest concentration was recorded at the Euphrates River outlet within the study boundaries, while the highest was observed in the central region of Lake Habbaniyah.

Carbonate ions (CO32-) are also significant negatively charged ions, showing a positive correlation with dissolved carbon dioxide (CO2) in water. These ions enhance the ability of groundwater to dissolve rock formations such as limestone and dolomite, thereby increasing the mineral content in groundwater. When the pH is below 8.2, hydrogen ions combine with carbonate ions to form dissolved bicarbonate (HCO_3-). However, at pH values above 8.2, the conversion of bicarbonate (HCO3-) to carbonate ions (CO32-) becomes significant, with carbonate ions predominating at pH 10.3. Conversely, at a pH of 6.3, dissolved carbon dioxide is the dominant species.

Consequently, analysis of the samples shows that carbonate ions are entirely absent in the surface waters of the study area, as indicated in Table 6.

Minor Compounds (Nitrates NO3-): Nitrate is one of the forms of nitrogen present in water and generally occurs in organic materials. Nitrates in water originate from multiple sources, including rainwater that carries nitrogen compounds from the atmosphere, polluted industrial wastewater, domestic sewage, and agricultural runoff from lands where nitrogen-based fertilizers are applied. The contamination of groundwater by nitrates is a significant concern because pollution of aquifers with this compound renders the water unsuitable for drinking or household use for extended periods. This is due to the limited natural purification capacity of groundwater-bearing strata [31].

Analysis of surface-water samples from the Habbaniyah District shows that secondary compounds (nitrates, NO_3-) range from 0.12 to 11 mg/L, as detailed in Table 6. The lowest nitrate concentration recorded was 0.12 mg/L at the Euphrates River outlet within the study area, while the highest concentration of 11 mg/L was found at the Euphrates River inlet within the study boundaries. The internationally permissible limit for nitrate concentration in water is 50 mg/L. Comparing these analytical results indicates that all surface-water samples from the study area fall within globally accepted limits.

Table 6 Negative ions of surface water samples

Sample	**Nitrate mg/L**	**Carbonate mg/L**	**Bicarbonate mg/L**	**Sulfate mg/L**	**Chloride mg/L**
R1	11.00	0	146.30	235	117
R2	9.40	0	152.80	230	118
R3	0.12	0	151.00	235	114
L1	2.10	0	174.30	240	153
L2	0.60	0	182.80	250	173
L3	3.20	0	157.40	245	132
Ch1	2.70	0	159.00	243	132
Ch2	2.90	0	161.00	246	135
Total	32.02	0	1284.60	1924	957
Mean	4.00	0	160.57	240.50	119.62

3.3 Heavy metals

Heavy metals are defined as metallic elements with atomic weights exceeding 20. Their concentrations in water systems depend on factors such as pH, clay minerals, and surface adsorption. Natural sources include erosion, weathering, dust storms, and decaying organisms, while anthropogenic sources include industrial waste, petroleum products, fertilizers, and sewage. Due to their toxicity and non-degradability, heavy metals pose significant health and environmental risks.

Five heavy metals (iron (Fe), copper (Cu), lead (Pb), cadmium (Cd), and zinc (Zn)) were analyzed in surface-water samples from the study area, as summarized in Table 7.

Iron (Fe): Iron is a common element in the Earth's crust but generally occurs at low concentrations in natural water systems. It is essential for human health, primarily because it facilitates oxygen transport in the blood. Iron in drinking water originates from natural processes such as rock weathering and soil erosion, or from corrosion of water pipes in treatment plants that are over one hundred years old. Deposited iron can impart an orange color to surfaces such as washing equipment and cooking utensils, and it may render water unsuitable for household use when concentrations exceed 0.3 mg/L. Iron compounds are also widely used in water treatment. The World Health Organization (1984) recommended a guideline value of 0.3 mg/L for iron in drinking water [32].

Analysis of surface-water samples from the study area shows iron concentrations ranging from 0.0600 to 0.1300 mg/L (see Table 7 and Figure 4). The lowest iron concentration was recorded at the Euphrates River outlet within the study boundaries and at the Nazim Sin al-Dhiban area. The highest concentration was observed at the beginning of Lake Habbaniyah, measuring 0.1300 mg/L. Both the 2022 WHO guidelines and the 2009 Iraqi standards set the permissible iron concentration in water at 0.3 mg/L. Hence, all surface-water samples in the study area comply with international standards.

Copper (Cu): Copper is a relatively rare metal because most copper minerals are not highly soluble. Due to its affinity for the solid phase, copper occurs at low concentrations in natural waters. Copper is an essential micronutrient for plants, animals, and humans, playing vital roles including photosynthesis. However, elevated copper concentrations are toxic to living organisms, with varying sensitivity among species. Algae and mollusks are particularly sensitive, with safe copper concentrations in water around 10 mg/L. Although copper is not generally considered harmful to human health, high copper levels can interfere with water use. Copper in water increases corrosion of iron and steel fittings when concentrations exceed 4 mg/L. Copper concentrations tend to rise with increasing temperature and acidity (lower pH). Typical copper levels in groundwater are around 1.5 mg/L, but concentrations above 2 mg/L render water toxic, causing diarrhea, vomiting, and potentially fatal diseases in humans [33].

Analysis of surface-water samples from the Habbaniyah District (Figure 3 and Table 7) reveals copper concentrations ranging from 0.0900 mg/L at mid-Euphrates to 0.5400 mg/L at the Euphrates River outlet. All copper levels in the surface-water samples fall within permissible limits.

Lead (Pb): Lead is found in most rock types and exists at low concentrations in groundwater and surface water due to the low solubility of its compounds. Lead is concentrated in granite, limestone, basalt, and sandstone formations. It is one of the most critical and abundant environmental pollutants and is highly toxic to humans because the body cannot efficiently eliminate it. Accumulation of lead in the body at high levels causes severe health issues such as general weakness, fainting, and paralysis. In women, lead exposure is linked to infertility, fetal malformations, and miscarriage [34].

Surface-water analyses (Table 7, Figure 3) indicate lead concentrations ranging from 0.0080 mg/L at the Euphrates River outlet to 0.1100 mg/L at the inlet of Lake Habbaniyah. The elevated lead levels are attributed to high temperatures and a lack of rainfall, with concentrations decreasing when temperatures drop and rainfall occurs.

Cadmium (Cd): Cadmium is a relatively rare element in nature and is often associated with zinc due to their similar chemical properties. Cadmium is highly toxic and complex, with safe drinking-water limits set at no more than 0.003 mg/L. It tends to accumulate in human tissues, particularly in the kidneys, liver, digestive system, and lungs. Recent studies have established a strong link between cadmium exposure and cancers of the kidney, liver, and lungs. The primary environmental sources of cadmium are chemical fertilizers and heavy industrial wastewater. Cadmium ions are environmental pollutants often found combined with lead and zinc ores and, like zinc, have a strong affinity for sulfur [35].

Surface-water sample analyses from the study area (Table 7, Figure 3) show cadmium concentrations ranging from 0.0001 mg/L at the Euphrates River inlet and Lake Habbaniyah inlet to 0.0004 mg/L at the lake outlet and Nazim Sin al-Dhiban. The 2022 WHO guidelines and 2009 Iraqi standards permit cadmium concentrations up to 0.003 mg/L, indicating that all sample results fall within internationally accepted limits.

3.4 Hydrochemical formulae and water type

The hydrochemical formula of water is represented by the major positive and negative ions, expressed in equivalents per million (epm). Only ions with concentrations exceeding 15% are included, and the ions are arranged in descending order. Negative ions are placed in the numerator and positive ions in the denominator. Total dissolved solids (TDS) in mg/L and pH are also included, as in the Kurlov formula, as follows [36]:

$$\text{TDS} = \frac{\text{Negative Ions (emp)}}{\text{Positive Ions}} pH \tag{3}$$

$$TDS = 791.46$$

$$\frac{\text{SO}_4^{2-}(43.82)\text{HCO}_3^{-}(43.82)\text{Cl}^{-}(33.07)}{\text{Ca2} + (34.60)\text{Mg}_{\square}^{2} + (21.37)\text{Na}(43.43)\text{K}(0.57)} \tag{4}$$

$$\text{pH}(7.60)$$

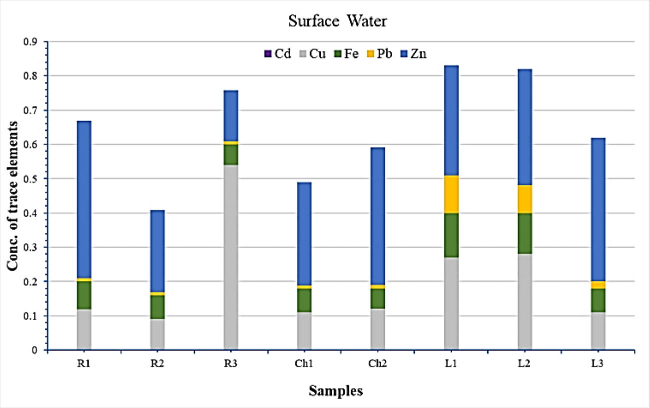

Fig. 3 Change in concentration of heavy metals in surface water samples of the study area

Table 7 Heavy metals in surface water samples

Sample	Fe(mg/L)	Cu(mg/L)	Pb (mg/L)	Cd (mg/L)	Zn(mg/L)
R1	0.0800	0.1200	0.0100	0.0001	0.4600
R2	0.0700	0.0900	0.0090	0.0002	0.2400
R3	0.0600	0.5400	0.0080	0.0002	0.1500
L1	0.1300	0.2700	0.1100	0.0001	0.3200
L2	0.1200	0.2800	0.0100	0.0001	0.4600
L3	0.0700	0.1100	0.0090	0.0002	0.2400
Ch1	0.0700	0.1100	0.0080	0.0002	0.1500
Ch2	0.0600	0.1200	0.1100	0.0001	0.3200
Total	0.66	1.64	0.0800	0.0003	0.3400
Mean	0.0825	0.205	0.0200	0.0004	0.4200

3.5 Water classification

For water classification, Piper's classification will be used. In 1944, Piper proposed a trilinear diagram for water classification consisting of two trilinear graphs and a diamond-shaped plot. The analyses are plotted as percentages of each cation and anion, calculated in milliequivalents per liter (meq/L). The right trilinear graph shows the relative concentrations of anions, and the left graph shows the relative concentrations of cations.

This tool was developed by Arthur M. Piper in 1944 and enhanced in 1994. It is an analytical graphical method used to understand the sources of dissolved constituents in water. It assumes that most natural waters contain cations and anions in chemical equilibrium (Table 8).

To describe the hydrochemical characteristics of surface-water samples from Al-Habbaniyah district, Piper's classification and diagram were applied to the samples collected on 16th November 2024. Piper's diagram shows that all eight samples belong to Class I $\left(\text{Ca}^{2+} - \text{Mg}^{2+} - \text{Cl}^{-} - \text{SO}_4{}^{2-}\right)$ and Category V($\text{Ca}^{2+} - \text{Mg}^{2+} - \text{HCO}_3^{-}$), as illustrated in Figure 4.

Table 8 Classification of water samples according to Piper's trilinear diagram

Category	Water Type	Class	Hydrochemical
I	Permanent hardness: $\text{Ca}^{2+} - \text{Mg}^{2+}$ and $\text{SO}_4{}^{2-}, \text{Cl}^{-}$(Non-carbonate hardness > 50%) Chloride calcium type	1	$\text{Ca}^{2+} - \text{Mg}^{2+} - \text{Cl}^{-} - \text{SO}_4{}^{2-}$
II	Saline solution: $\text{SO}_4{}^{2-}, \text{Cl}^{-}, \text{Na}^{+}, \text{K}^{+}$(Non-carbonate alkalinity > 50%) Sodium chloride type	2	$\text{Na}^{+} - \text{K}^{+} - \text{Cl}^{-} - \text{SO}_4{}^{2-}$
III	Alkaline carbonates: $\text{HCO}_3{}^{-}, \text{CO}_3{}^{2-}, \text{Na}^{+}, \text{K}^{+}$(Alkaline carbonates > 50%) Sodium bicarbonate type	3	$\text{Na}^{+} - \text{K}^{+} - \text{HCO}_3{}^{-}$
IV	Temporary hardness: $\text{HCO}_3{}^{-}, \text{CO}_3{}^{2-}, \text{Ca}^{2+}, \text{Mg}^{2+}$ (Carbonate hardness > 50%) Magnesium bicarbonate type	4	$\text{Ca}^{2+} - \text{Mg}^{2+} - \text{HCO}_3{}^{-}$
V	Mixing zone (Ion concentrations of cations and anions do not exceed 50%)		

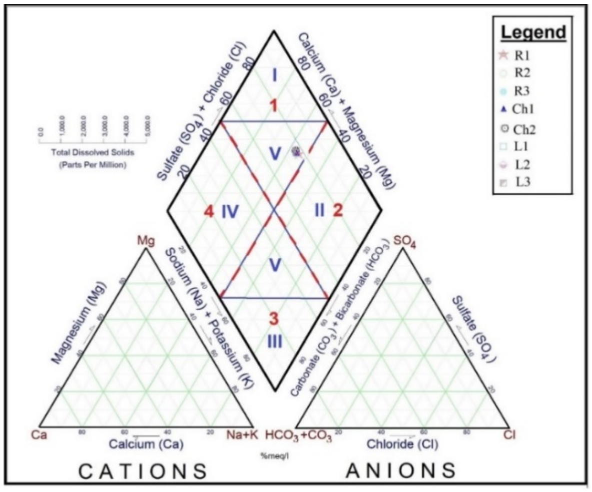

Fig. 4 Piper's diagram for surface water samples

4 CONCLUSION

Chemical and physical analyses indicated that surface-water samples from Lake Habbaniyah and the Euphrates River fall within acceptable limits for drinking and irrigation, with minimal treatment needed for some components. Based on the U.S. Department of Agriculture water-quality classification, most samples are suitable for irrigation, with caution regarding sodium and salinity; therefore, appropriate irrigation management practices are required. Physical characteristics (color, odor, taste, temperature, pH, TDS, EC) showed relatively stable water quality in the study area and met initial water-quality criteria. A clear relationship between TDS and EC supports their use as rapid assessment indicators. Ion analysis confirmed chemical equilibrium between cations and anions, indicating hydrochemical stability of the studied water sources. Piper's diagram showed that all eight samples belong to Class I (Ca2+-Mg2+-Cl$^-$-SO$_4$2-) and Category V (mixing zone, where no single ion exceeds 50%) represented by (Ca2+-Mg2+-HCO3$^-$), reflecting a distinctive hydrochemical pattern for the region. Removal of iron and manganese from drinking water is recommended to reduce potential long-term health effects. The study emphasizes the importance of integrated surface-water management to balance drinking and irrigation needs and to ensure sustainable environmental water-resource management.

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