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Hydrochemical Characteristics and Water Quality of the Euphrates River in the Middle Reach of Iraq

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ABSTRACT

This study investigates the hydrochemistry and water quality of the Euphrates River in central Iraq, focusing on the Musayab area and the lower (downstream) Babil reach during 2021–2022. Fifteen physicochemical parameters were measured at three sampling sites (ST.1–ST.3), including pH, total dissolved solids (TDS), electrical conductivity (EC), major ions (Ca, Mg, Na, K, Cl^-, SO_4^{-2}, HCO^{3-}), nutrient ions (PO_4^{-3} and NO_3), turbidity, dissolved oxygen (DO_2) and total hardness (TH). Relationships among variables and their implications for factor analysis were examined using Pearson correlation matrices. In addition, water quality indices (WQIs) were computed using the Canadian Council of Ministers of the Environment water quality index (CCME-WQI), the National Sanitation Foundation water quality index (NSF-WQI), and the weighted arithmetic WQI method. The findings demonstrate that the pH ranges are within the accepted limits, illustrating the excellent buffering capacity of Iraqi water. Nevertheless, TDS, TH, EC, SO_4, Ca, and PO_4^{-3} are greater than WSO/Iraqi Quality Standards (IQS) recommendations at ST.2, indicating that the Tharthar-Euphrates Canal water directly affects. Statistically, t-tests signified notable differences ($p < 0.05$) between ST.1 and ST.2, specifically for TDS, EC, Ca^{2+}, HCO^{3-}, and TH, indicating substantial impact from the Tharthar-Euphrates Canal and local pollution sources. In contrast, nutrient parameters (PO_4^{3-} and NO_3^-) showed a different trend, with PO_4^{3-} levels reaching an abnormally high peak of 9.13 ppm at ST.3, suggesting localized industrial or agricultural pressure in addition to industrial discharges from these facilities, especially the Al-Furat State Company, which is a known point source of chemical pollutants in the middle reach of the Euphrates. WQI results classified ST.1 and ST.3 as 'Fair to Good' (CCME scores ranging from 67.20 to 80.7), whereas ST.2 exhibited 'Poor' quality with a WQI reaching 57.85. These findings highlight the vital need for integrated water management to lessen the ongoing degradation of the river's middle reach.

1. INTRODUCTION

The Euphrates River in Iraq faces escalating hydrological stress due to upstream damming, reduced discharge, and climate change, which have collectively diminished its natural dilution capacity and increased salinity [1-3]. While these regional challenges are well-documented, the middle reach of the Euphrates extending from Musayab to the Babil presents a critical yet under-monitored zone [4, 5]. This area is subject to complex anthropogenic pressures from Babylon and Karbala Governorates, including industrial effluents from the Al-Furat State Company and significant agricultural runoff [6-9].

Despite previous studies on the Euphrates, there is a substantial deficiency in integrated hydrochemical monitoring specifically for this reach, particularly regarding the spatial-temporal dynamics under current low-flow regimes. Most existing research lacks a comparative evaluation of different water quality assessment tools. This study addresses this gap by employing a triple-index approach using the Canadian Council of Ministers of the Environment water quality index (CCME-WQI), the National Sanitation Foundation Water Quality Index (NSF-WQI), and the weighted arithmetic WQI.

The integration of these three distinct WQI models, combined with Multivariate Statistical Analysis (Principal Component Analysis (PCA) and t-tests), allows for a more robust detection of pollution hotspots and a clearer understanding of how various indices respond to specific contaminants like high phosphate levels. Therefore, the current evaluation is directed to convey the results of fifteen physicochemical characteristics for the period between 2021 and 2022 to specify the suitability of the water for drinking purposes and to offer precise data for decision-makers to implement localized pollution control strategies.

2. MATERIALS AND METHODS

2.1 Study area

With a total length of almost 2,800 kilometers, the Euphrates River is one of the most important rivers in Southwest Asia. It rises in Turkey and passes through Syria and Iraq on the way southward. The Euphrates River's study reach in this study stretches from Musayab to the downstream of the Babil. Table 1 summarises the upstream distances of each cross-section that coordinates, and station locations were determined based on field survey and GPS measurements conducted during the present study. Babil is one of the first built barrages in Iraq; it was constructed to reduce water depletion in the Al-Billa Branch [10, 11]. In 2021, the Euphrates River's mean annual flow at the Babil was 151.8 m^3/s [12]. Figure 1 depicts the general architecture of the examined river reach.

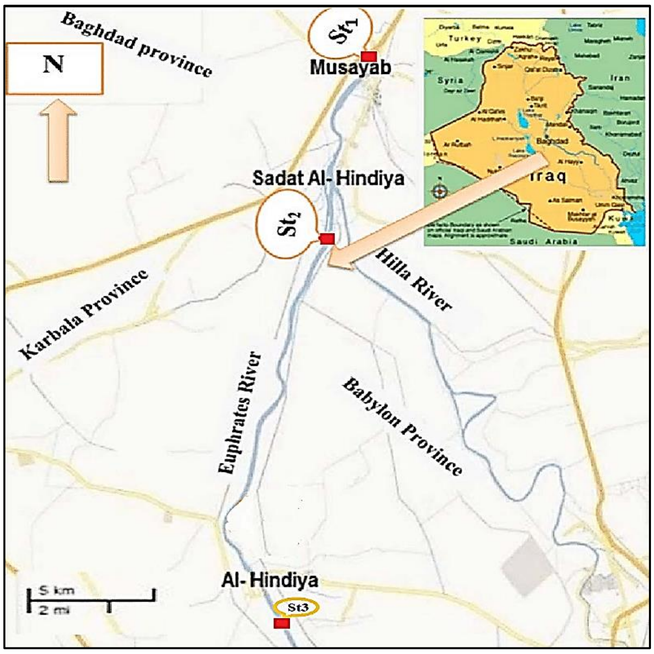

Figure 1. The Euphrates River reaches the studied area between Musayab City and Babil's downstream [13]

Table 1. Coordinates and station locations were determined based on a field survey in the study area

Site Name	Longitude (E)	Latitude (N)	Station
Musayab	44°17′24.7″	32°47′44.0″	ST.1
Babil	44°16′32.5″	32°42′42.6″	ST.2
Third Bridge of Babil	44°13′02.85″	32°33′05.14″	ST.3

The Euphrates River traverses many geological units in the study area. Recorded in the Babylon Governorate, its stratum comprises silt to marl, mostly surrounded by flood plain deposits, and recorded in Karbala Governorate, it was found dominating with sand deposits of the Al-Dibdiba Formation. The geology of the area under investigation consists mainly of 1. Quaternary deposits (clay), 2. limestone and dolomitic limestones, 3. carbonate rocks, 4. an impervious cemented sandy layer, relatively [14, 15].

2.2 Collected data

Three sampling locations along the Euphrates River were strategically selected during the period 2021–2022, as detailed in the methodology depicted in Figure 2. The water quality dataset was obtained from the Technical Direction of the Water Monitoring and Evaluation Section at the Ministry of Environment (2022), as presented in Table 2. All physicochemical characteristics were determined according to the standard methods described by research [16]. The parameters analysed included major cations, Nutrient ions (PO_4^{-3} and NO_3, electrical conductivity (EC), total dissolved solids (TDS), total hardness (TH), dissolved oxygen (DO_2), and pH. To assess the appropriateness of the water for drinking, the analytical findings were contrasted against the World Health Organization (WHO) and Iraqi quality standards (IQS) standards [17, 18].

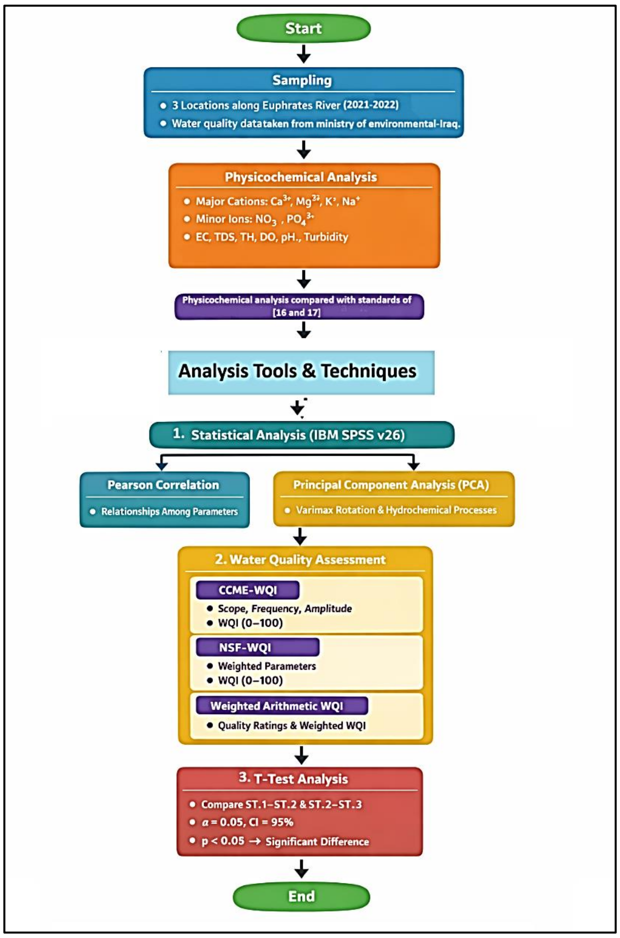

Figure 2. Research methodology of the current study

2.3 Statistical analysis methods

2.3.1 Pearson correlation

Statistical analysis was performed using IBM SPSS Statistics (Version 26). Pearson correlation matrices were computed to inspect the interrelationships between variables and to evaluate the factorability of the dataset. This helps in identifying the common sources of ions and their geochemical interactions.

Table 2. Euphrates River's water quality characteristics during 2021-2022

Parameter	2022 ST.1	2022 ST.2	2022 ST.3	2021 ST.1	2021 ST.2	2021 ST.3	Average	Ref. [17]	Ref. [18]
pH	7.3	7.5	7.53	7.39	7.48	7.39	7.43	8.5	7–8.5
TDS (ppm)	814.1	900.25	819.78	779.38	844	788.68	824.37	500	500
EC (μS/cm)	1274.75	1379.25	1268.75	1231.63	1306	1233.88	1282.38	1000	2000
Turbidity (NTU)	2.35	7.8	3	2.5	6.6	2.78	4.17	4	25
NO_3^- (ppm)	4.24	2.23	4.75	4.41	3.47	4.41	3.92	10	50
Ca^{2+} (ppm)	120.1	134.25	119.65	117.16	128.25	117.35	122.79	200	50
Mg^{2+} (ppm)	36.52	40.5	37.45	43.58	42.38	41.83	40.38	200	50
K^+ (ppm)	3.95	4.28	4.1	4.01	4.88	4.05	4.21	10	10
Na^+ (ppm)	93	90	92.95	92.23	99.5	96.3	94	200	200
HCO_3^- (ppm)	105.5	124.5	106.5	108.5	125.25	108.75	113.17	126	200
SO_4^{2-} (ppm)	363.95	358.5	348.25	349.09	349.93	356.65	354.4	250	250
Cl^- (ppm)	145.4	140.25	148.85	147.16	154.68	148.34	147.45	200	250
TH (ppm)	446.57	503	458.23	469.6	496.05	470.48	473.99	200	500
PO_4^{3-} (ppm)	0.24	0.01	9.13	0.24	0.07	7.96	2.94	0.1	0.4

2.3.2 Principal Component Analysis

The PCA was employed to signify the main parameters controlling water quality and to interpret the dominant hydrochemical processes and potential water sources of the Euphrates River [19, 20]. This method enables the identification of latent factors (principal components) governing water quality variations. Prior to PCA, the suitability of the dataset was appraised utilising the Kaiser–Meyer–Olkin (KMO) measure and Bartlett's test of sphericity. Components with eigenvalues higher than 1 were preserved based on the Kaiser criterion and subsequently subjected to Varimax rotation [20].

2.3.3 Water quality methods

Canadian Council of Ministers of the Environment Water Quality Index

The Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI) was applied to assess surface water quality by combining multiple water quality factors into a single numerical index [21]. This index is based on three essential components: scope (F1), which ascertains the percentage of variables that fail to fit water quality standards; frequency (F2), which indicates the proportion of individual tests that do not adhere to the standards; and amplitude (F3), which quantifies the extent to which failed test values deviate from their respective objectives [21].

$$\text{F1 (Scope)} = \frac{\text{Number of failed variables}}{\text{Total number of variables}} \times 100 \quad (1)$$

$$\text{F2 (Frequency)} = \frac{\text{Number of failed tests}}{\text{Total number of tests}} \times 100 \quad (2)$$

First, the excursion is calculated as:

$$\text{Excursion} = \frac{\text{Failed value}}{\text{Objective}} - 1 \quad (3)$$

Then the normalized sum of excursions (NSE) is depicted in the counter of Eq. (4):

$$\text{NSE} = \frac{\text{Sum of excursions}}{\text{Number of tests}} \quad (4)$$

Finally:

$$\text{F3 (Amplitude)} = \frac{\text{NSE N}}{(0.01\times NSE+0.01)} \quad (5)$$

The WQI is then measured by:

$$\text{WQI} = 100 - \frac{\sqrt{F1^2+F2^2+F3^2}}{1.732} \quad (6)$$

The index generates a score from 0, which identifies the poorest water quality, and 100, which identifies the excellent water quality, representing the CCME-WQI classification for aquatic environments depicted in Table 3.

Table 3. A representation of the Canadian Council of Ministers of the Environment water quality index (CCME-WQI) categorization for aquatic and irrigation purposes [21]

WQI Value	Description
95–100	**(E): Excellent:** Water quality is preserved with virtually no chance of risk or degradation, i.e., conditions are approximately near natural.
80–94	**(G): Good:** Water quality is maintained with a slight chance of risk or degradation, i.e., conditions seldom deviate from natural.
65–79	**(F): Fair:** Water quality is usually protected but occasionally threatened or impaired; conditions sometimes depart from natural or desirable levels
45–64	**(M): Marginal:** Water quality is commonly at a chance of risk or degraded, i.e., occasionally deviates from natural.
0–44	**(P): Poor:** Water quality is totally compromised or at a fixed risk of degradation, i.e., conditions usually far from natural.

National Sanitation Foundation Water Quality Index

The NSF-WQI was deployed to appraise surface water quality utilising key physicochemical factors of pH, TDS, turbidity, phosphates (PO_4^{-3}), nitrates (NO_3^-), and DO_2. Indeed, these factors have a specific contribution to the overall NSF-WQI index with a precise weight imitating its comparative significance in affecting water quality.

The NSF-WQI combines these weighted factors into a single index value varying between 0 and 100 (Table 4). The higher values signpost better water quality compared to the lower ones. The resulting index values were categorized into five classes (excellent, good, moderate, poor, and very poor) subsequent to the original NSF procedure, as presented in Table 5. Detailed weighting factors and computational procedures were delivered by studies [22-25]. This index is measured using the following correlation:

$$\text{NSF-WQI} = \sum W_i Q_i \quad (7)$$

Each parameter value (Q_i) was obtained from the standard NSF-WQI rating curves, which convert the measured concentrations into a unit less scale ranging from 0 to 100 based on water quality classification.

Table 4. Parameters of the National Sanitation Foundation water quality index (NSF-WQI) and their weight scores

Parameters	Weight
TDS	0.08
Turbidity	0.08
NO_3	0.1
PH	0.12
DO_2	0.17
PO_4	0.1

Table 5. Scores of National Sanitation Foundation water quality index (NSF-WQI) [17]

Score Range	Water Quality Category
100-91	Excellent Quality
90-71	Good Quality
70-51	Moderate Quality
50-26	Poor Quality
25-0	Very Poor Quality

Weighted Arithmetic Water Quality Index

This index combines numerous parameters of water quality into a single index value by assigning a particular weight to each parameter associated with its competent significance to impact the water quality [26, 27].

The weighted arithmetic WQI technique was deployed in the WQI evaluation as represented in Eq. (8):

$$\mathrm{WQI} = \frac{\sum Q_i W_i}{\sum W_i} \tag{8}$$

For each metric, the quality Rating (Q_i) scale was calculated using Eq. (9):

$$Q_i = \frac{V_n - V_i}{V_s - V_i} \times 100 \tag{9}$$

where, V_n is the estimated value of the parameter in the sample, while V_s is the suggested standard value of the parameter in pure water. Referring to the current study, V_i was considered the ideal value according to standard WHO guidelines for each parameter. Each water quality parameter's unit weight (W_i) is calculated using Eq. (10):

$$W_i = \frac{K}{S_i} \tag{10}$$

Eq. (10) can be utilised to estimate K. The WQI categorization scheme for water quality is depicted in Table 6.

Table 6. Water quality value according to water quality index (WQI)

WQI	Water Quality
0-25	Excellent Quality
26-50	Good Quality
51-75	Poor Quality
76-100	Very Poor Quality
> 100	Unfit for consumption

2.3.4 Statistical analysis (t-test)

A t-test (two-sample) was utilized to contrast the statistical significance of differences in water quality between selected sampling areas along the Euphrates River. The statistical analysis was achieved by IBM SPSS Statistics version 26 (α = 0.05, confidence interval of 95%). Two combinations of stations were used: ST.1–ST. 2 and ST.2–ST.3. Mean values of the stations for each physicochemical parameter were compared between pairs by the t-test approach.

The alternative hypothesis (H_1), presence of a difference, and null hypothesis (H_0) were that there were no significant differences in the mean of each water quality parameter between the stations compared. Then determined statistical significance using p-values resulting from the t-test, less than 0.05 indicating a significant difference.

3. RESULTS AND DISCUSSION

The limitation of water quality constituents during 2021–2022, the parameters investigated presented clear patterns of spatial variation across the river. TDS levels were in the range of 779.38 ppm to 900.25 ppm, higher than the WHO and Iraqi Quality Standards (IQS) standards limits [17, 18]. Range of EC was 1231.63–1379.25 µS/cm with values higher than the WHO limit, though within the IQS standard. pH values varied between 7.30 and 7.53, which were within the acceptable limits according to WHO [6.5-8.5] and IQS [7.0-8.5].

The turbidity values varied from 2.35 to 7.80 NTU, being within the IQS standard limits, except at ST.2, where the WHO guideline was surpassed. The level of nitrate (NO_3^-) varied between 2.23 and 4.75 ppm and was within the accepted limits. Levels of Ca^{2+} (117.16-134.25 ppm) and Mg^{2+} (36.52-43.58 ppm) were observed in the studied waters. Calcium exceeded the IQS standard and was less than that of the WHO, while magnesium was within both standards. Sodium (Na^+) and potassium (K^+) were normal at all stations. Sulfate (SO_4^{-2}) and TH surpassed the WHO guideline levels, and occasionally IQS standard values. Bicarbonate (HCO_3^-) concentrations showed the concentration range of 105.5-125.25 ppm, the higher alkalinity values were found in ST.1 and ST.2, and lower values at ST.3, which is affected by dilution that is performed by the Tharthar Euphrates Canal receiving water from the Tigris River with high chloride [2]. Phosphate (PO_4^{-3}) levels varied between 0.01 ppm at ST.1 to 9.13 ppm at ST.3, that has been higher than both the WHO and IQS standard limits. The abnormally high concentration of PO_4^{-3} at ST.3 (9.13 ppm) is identified as a consequence of point-source pollution rather than a data entry error. This location is directly impacted by industrial effluents from the Al-Furat State Company for Chemical Industries and Pesticides [28], where phosphorus-based compounds are utilized in production. This localized chemical loading, combined with the river's reduced flow, which limits its dilution capacity, explains the extreme nutrient spike. The moderate to high values of TDS, EC, TH, $SO_4^{-2,}$ Ca^{2+}, and PO_4^{-3} contents may be because of natural hydro-chemical processes as well as anthropogenic interferences.

Correlated analysis and PCA were employed to investigate the interrelationship of water quality variables. The scree plot of eigenvalues and the Kaiser criterion (eigenvalues greater than 1) indicated that the 15 physico-chemical variables could be reduced to five principal components, which define most of the total variance (Figure 3). The rotated component matrix (Table 7) demonstrates the loading values of each variable on the extracted principal components, facilitating the interpretation of pollution sources. Analysis of loadings due to the presence of Quaternary deposits, carbonate rocks, and limestone dolomite materials, the first principal component (the eigenvalue = 4.567), which accounted for 30.45% of the total variance, had high positive loadings for Ca^{2+}, EC, and TDS. These were indicative of geological formations associated with salinity and hardness. Nitrate (NO_3^-) showed a strong negative loading on F1 (-0.745), suggesting a distinct source relative to the salinity–hardness group.

Table 7. Component Matrix of the physicochemical characteristics between 2021 and 2022

Rotated Component Matrix[a]					
Parameters	**F1**	**F2**	**F3**	**F4**	**F5**
pH	.172	.630	-.088	-.329	-.116
NO_3	-.745	.172	-.317	-.226	-.282
Ca	.866	.150	-.212	.170	.152
Mg	.016	.035	.102	.024	.902
TH	.699	.166	-.126	.039	.655
K	.298	.620	.368	.074	-.168
Na	.363	.341	-.614	-.071	.376
HCO_3	.013	.017	.832	.130	.321
SO_4	.318	-.740	-.049	.078	-.144
CL	-.260	.773	-.127	.131	.248
TDS	.938	-.114	.215	-.005	-.100
EC	.970	-.157	.071	.067	-.073
Turbidity	.241	.108	.828	.118	-.069
DO_2	.136	-.095	.118	.947	-.103
PO_4	-.139	.009	-.131	-.960	-.141

Extraction Method: PCA.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 8 iterations.

The second factor that reflects the geochemical fluctuation of dissolved salts has a negative relationship with SO_4^{-2} and a significant association with Cl^- (eigenvalue = 2.644; 17.63% variance). A positive loading for HCO_3^- and turbidity has been identified in the third component (eigenvalue = 2.182; 14.55% variance), which has been proposed to represent soil erosion and washout from the calcareous during storm occurrences. The fourth factor (eigenvalue = 1·645; 10·97% variance), which had a poor correlation with phosphate and positively correlated with DO_2, should be associated with the local anthropogenic consequences of industrial effluents, urban discharges, and agricultural runoff. Total hardness and magnesium considerably weighted the fifth component (eigenvalue = 1.283; 8.55% variance), indicating that water–rock interaction is important in influencing element levels.

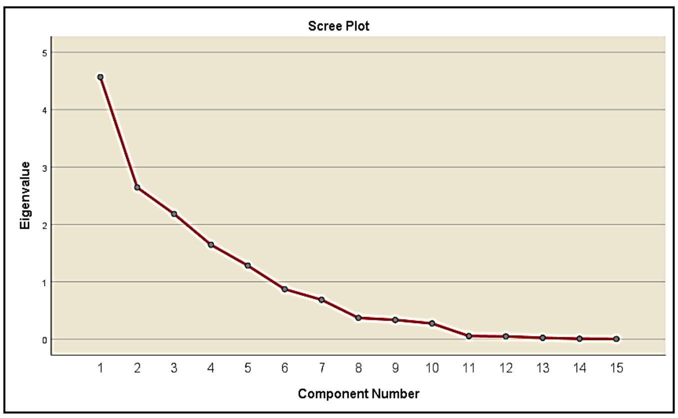

Figure 3. Scree plot diagrams

These statistical findings are in good agreement with the spatial distributions (Figure 4); ST.2 (site Babil) with the highest concentrations is affected by both QA for municipal effluents and industrial wastewater, and agriculture run-off, as well as a reduction in river flow. Station ST.3, however, presented partial dilution due to inflow from the Tharthar Canal. Seasonal effects, in particular during the fall, also led to an additional increase in alkalinity that resulted from rainwater-driven soil erosion. Overall, the PCA and correlation analyses indicate that the hydro-chemical parameters of the Euphrates water at our investigated reach are primarily affected by both natural and human activities [2, 6].

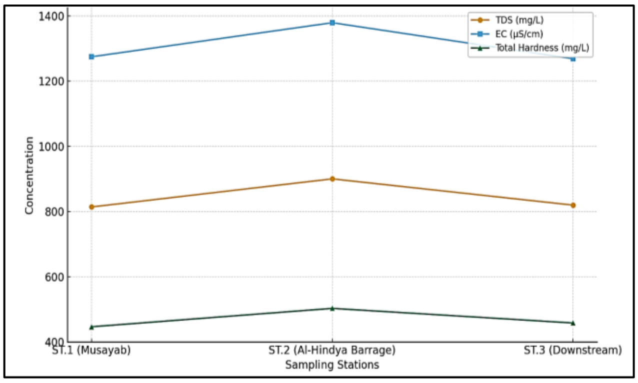

Figure 4. Spatial variation of TDS, EC, and TH throughout the studied area

TDS: total dissolved solids, EC: electrical conductivity, TH: total hardness.

Three approaches (CCME, NSF-WQI, and WQI) were utilized to evaluate the Euphrates River water quality (Table 8). The results revealed noticeable variations, which are attributed to both the inherent mathematical architectures and the distinct weight-assignment sensitivities of each model. The CCME-WQI provides a stabilized administrative overview because it evaluates the overall frequency and scope of failures, making it less sensitive to isolated extreme outliers. On the other hand, the WAI indicated a clearer spatial variation, especially at ST.3, where it reaches a 'Very Poor' status (95.79). This is due to the WAI relying on 'unit weights' (Wi) derived from the inverse of standard limits. Therefore, it disproportionately increases the final score when PO_4^{3-} surpasses the standard by a large margin (9.13 ppm). Accordingly, NSF-WQI generated 'Poor' results as a result of its sensitivity to turbidity and DO_2. In other words, CCME-WQI generates a more conservative management-oriented evaluation, while WAI acts as a high-sensitivity indicator for capturing pollution hotspots and extreme contamination scenarios.

The river flows through more densely populated areas further downstream, especially in the Al-Musayyib District. Al-Musayyib, a town in the Babylon Governorate with a population of over 390,000, is located about 30 kilometers south of Hillah. Before the river reaches the railway station ST.2, which is about 7 km away, there are several small communities and isolated human activity. The decline in water quality in downstream areas is mostly caused by these practices as well as the construction of a few facilities, such as the Saddat Hindiyah Cement factory on the left side of the river and Al-Furat State Company for chemical industries and pesticides. In order to stop pollution sources from destroying aquatic life, irrigation, drinking water, and other uses, the river in this area needs constant control and treatment. In particular, the localized spike in PO_4^{3-} concentration at ST.3 can be directly linked to industrial discharges from these facilities, especially the Al-Furat State Company, which is a known point source of chemical pollutants in the middle reach of the Euphrates. Previous study [29] has reported that industrial activities near Al-Musayyib significantly elevate nutrient levels due to the absence of advanced wastewater treatment systems. Moreover, the production of pesticides and chemical agents inherently involves phosphorus compounds, which are often discharged into the river, particularly during low-flow periods when the river's dilution capacity is limited [30].

Table 8. The annual mean WQI in the different stations from Musayab to Babil for the years 2021-2022, by scale of CCME, NSF-WQI, and weighted arithmetic average

Method Type	Standard	Year	ST.1	ST.2	ST.3
CCME-WQI	[16]	2022	F (68.6)	M (64.0)	F (71.32)
		2021	F (72.8)	F (65.8)	F (68.48)
	[17]	2022	G (79.7)	G (80.6)	F (67.20)
		2021	G (80.7)	F (79.1)	M (64.48)
NSF-WQI	—	2022	P (40.02)	P (31.22)	P (39.19)
		2021	P (37.56)	P (27.8)	P (28.8)
WQI	—	2022	G (48.61)	P (57.57)	VP (95.79)
		2021	P (51.3)	P (56.69)	VP (97.18)

WQI: water quality index, CCME-WQI: Council of Ministers of the Environment water quality index, NSF-WQI: National Sanitation Foundation water quality index

To estimate statistically significant differences between the two groups of measurement stations 1−2 vs. 2 and 2 vs. 3 for each water quality parameter, a t-test (95% confidence limit) was performed using SPSS software. A p-value was also generated to measure the mean values for each parameter between stations. Three measurements and a section for each parameter at a 95% confidence level were not significantly different between the two stations, as determined by statistical tests. Table 9 shows summary data of water quality properties at several station pairs (ST.1-ST.2 and ST.2-ST.3). Since the t-test p-values for eight parameters were higher than 0.05, demonstrating that variations in the mean values of such parameters were not meaningfully different, the null hypothesis cannot be eliminated. Table 9 indicates that this is not the case (dark-shaded columns correspond to seven factors displaying differences in the behavior between the two stations). The t-test demonstrates that the TDS, EC, Ca, HCO_3, and TH-values at station ST.2 are more significant than those in ST.1 and ST.3, but the tendency was the opposite for NO_3 and PO_4.

Statistical comparison of water quality between upstream (ST.1) and downstream (ST.3) stations revealed notable differences for specific parameters. Among the measured variables, nitrate (NO_3^-) and turbidity exhibited significant spatial variation, indicating higher concentrations at ST.3 compared to ST.1. For all other parameters, no statistically significant differences were observed between the two stations. These findings suggest that while most water quality characteristics remain relatively stable along the studied reach, localized increases in nutrients and suspended solids occur downstream, likely influenced by agricultural runoff and other anthropogenic activities. The difference can be ascribed to the features of the Euphrates River and the site of the sample collection. After passing a great distance from the area with a smaller population density and less human activity, the river passes Station ST.1 at the head of the Al-Musayyib area.

Table 9. t-test results from water quality parameters between ST.1 and ST.2, and ST.2 and ST.3 for the period between 2021 and 2022

Quality Parameter	Reach (ST.1–ST.2) t value (DF = 14)	p value	Reach (ST.2–ST.3) t value (DF = 14)	p value
TDS	−2.988	0.01	2.579	0.022
pH	−1.009	0.33	0.227	0.824
Turbidity	−2.158	0.05	1.97	0.07
EC	−2.826	0.013	2.637	0.019
NO_3^-	3.405	0.004	−3.944	0.001
Mg^{2+}	−0.654	0.524	0.99	0.339
Ca^{2+}	−2.541	0.024	2.385	0.032
K^+	−1.748	0.102	1.637	0.124
Na^+	−0.319	0.754	0.02	0.985
HCO_3^-	−3.282	0.005	3.183	0.007
SO_4^{2-}	0.312	0.76	0.203	0.842
Cl^-	−0.215	0.833	−0.211	0.836
TH	−2.737	0.016	2.24	0.042
PO_4^{3-}	7.15	0	−7.627	0
DO_2 (ppm)	1.407	0.181	−1.421	0.177

DF: degrees of freedom

To improve the interpretation of the statistical analysis, bar charts were developed for selected key factors, comprising TDS, EC, TH, SO_4^{2-}, and PO_4^{3-} (Figure 5). These figures indicate the spatial change among the stations (ST.1, ST.2, and ST.3) and demonstrate statistically significant differences based on t-test results ($p < 0.05$). The graphical representation assures that TDS, EC, Ca^{2+}, HCO_3^-, and TH parameters indicate greater values meaningfully at ST.2, contrasted to ST.1 and ST.3, whereas nutrients such as NO_3^- and PO_4^{3-} state an opposite trend.

By contrast, for station ST.3, the bore location does not overlap with that of ST.2, with AM ratios located around 15 km south of this station. These distances allow the river not only to self-purify and recover from some of its pollutants, but also to reduce concentration levels of most of the water quality parameters. Moreover, the land use ST.3 is predominantly agricultural and makes it less polluted by industrial effluents as compared to ST.2. Concerning the variation difference of stations in parameters, similarly for both 2021 and 2022, Mg concentration is very different between the Lagoon in both years at ST.1 (Table 10). The other parameters did not differ distinctly at stations ST.2 and ST.3 during the period of sampling. Behavior in ST1 could indicate a variation of (Mg) species during the passage of this river stretch before being supplied from an agricultural field.

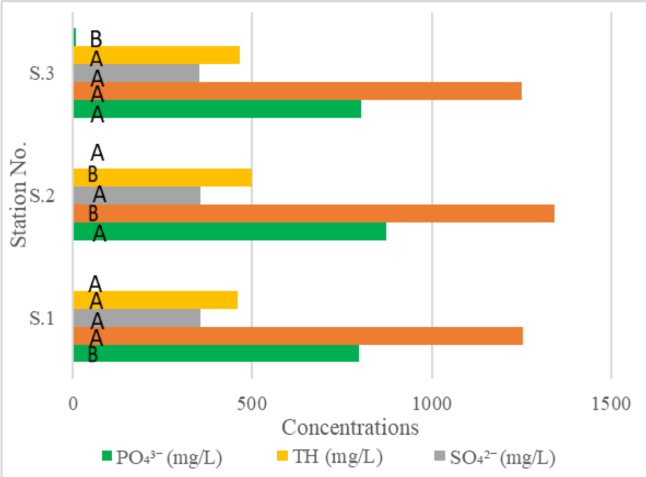

Figure 5. Spatial variation of water quality parameters (TDS, EC, SO_4^{2-}, TH, and PO_4^{3-}) across the ST.1, ST.2, and ST.3
Different letters above bars signify a significant statistical difference ($p < 0.05$), as defined by the t-test

Table 10. The Mg in ST1 t-test findings showed that there were significant variations between 2021 and 2022 ($p < 0.05$)

Water Quality Parameter	ST.1	
	t Value	p Value
Mg	3.125-	0.02

4. CONCLUSIONS

Due to hydrological exchanges and anthropogenic pressures, the current research signified that the Euphrates River between Musayab and Babil experiences notable spatial variations in water quality. Specifically, upstream and midstream stations (ST.1 and ST.2) elaborated high-mineral loading signified by increased levels of TDS, EC, and Hardness. Furthermore, the downstream reach at ST.3 stated a significant localized spike in Phosphate PO_4^{3-} of 9.13 ppm, which is attributed to canal irrigation effects. This valuable nutrient enrichment can be signified as point-source pollution from the Al-Furat State Company, which ascertains a nonfulfillment of the employed protocols of industrial discharge. Thus, this research recommends concrete technical interventions, particularly the compulsory deployment of a phosphorus-removal pre-treatment unit near Musayab. Also, the high sensitivity of the WQI suggested its adoption as a real-time early-warning tool at the ST.3 hotspot. Indeed, combining these specific treatment practices with the upgrading of municipal sewage infrastructure in Al-Hilla and Al-Musayyib is important to refine the river's ecological integrity and guarantee its use for drinking and irrigation purposes.

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