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WHAT INSIGHTS CAN A SPATIOTEMPORAL AND MULTIVARIATE ANALYSIS PROVIDE ABOUT THE WATER QUALITY? THE REPORT FROM IRAQ

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Abstract: Good quality of water in the Shatt Al-Hillah River is very important for supporting agriculture, supplying safe drinking water, and maintaining the health of aquatic ecosystem in the semi-arid region of Iraq. Nevertheless, anthropogenic pressure and climate variability are causing rapid degradation of water resources. This study presents a novel, long-term (2020–2024) spatiotemporal assessment of water quality using multivariate analysis in a data-limited, semi-arid environment. Monthly water samples were collected from five sites along an upstream–downstream gradient and analyzed for nitrate (NO_3^-), phosphate (PO_4^-), ammonia (NH_3), dissolved oxygen (DO), electrical conductivity (EC), and chlorophyll-a. Sophisticated statistical approaches Principal Component Analysis (PCA), heatmaps, and Hierarchical Cluster Analysis (HCA) showed significant seasonal and spatial variations. The nutrient and EC concentrations were higher in the downstream stations, and DO decreased to less than 5 mg/L in summer. PCA indicated that EC and nutrient levels were the key pollution drivers, whilst clustering and heatmaps demonstrated pollution peaks during the dry period. Results emphasize seasonal nature of eutrophication and salinization in rivers, especially during dry summer. This comprehensive analysis yields policy-relevant insights and calls for interventions specifically targeted at seasonal variations, including wastewater treatment and management of agricultural runoff. Statistical ecological methods used here offer a cost-effective approach to monitoring rivers in a resource-poor region. The findings contribute directly to sustainable water governance aligned with Sustainable Development Goal SDG 6 (Clean Water and Sanitation) in Iraq and similar arid regions.

Keywords: water quality degradation; Principal Component Analysis; hierarchical cluster analysis; sustainable river management; Shatt Al-Hillah River

1. Introduction

Freshwater rivers in dry and semi-arid regions have increasingly been subject to ecological deterioration due to human exploitation, land-use change, and climate change (Meybeck & Helmer, 1989; Vörösmarty et al., 2010) and as such, they represent a threat to ecosystem health, food security, and human livelihoods (Kreamer, 2012). The Middle East and North Africa (MENA)

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region is a prominent example of this crisis, where low precipitation, rising temperatures, and inadequate wastewater treatment exacerbate pollution problems (UNEP, 2016).

In Iraq, rivers are the backbone of water supply and agriculture, yet they face increasing pressure from population growth, industrial discharge, and untreated wastewater. The Shatt Al-Hillah River, a major distributary of the Euphrates flowing through Babylon Province, provides irrigation water, drinking supply, and aquatic habitats. However, seasonal low-flow conditions combined with municipal and agricultural effluents make it highly vulnerable to contamination. Untreated wastewater releases, as well as agricultural and industrial runoff, are increased during the dry season with low annual river fluxes that further degrade ecosystem (Al-Ansari 2025; Chabuk et al., 2023). Elevated nutrient concentrations, low dissolved oxygen (DO), and high electrical conductivity (EC), particularly at downstream sites, reflect eutrophication, salinization, and ecological stress, with potential implications for human health and aquatic ecosystems (Abd Al-Kareem & Al-Kizwini, 2022; Al-Saedi et al., 2024).

Despite the ecological importance of Iraq's rivers, research in arid and semi-arid regions remains limited by short-term datasets and insufficient spatial coverage. Previous studies have largely focused on single-season or site-specific analyses, preventing the identification of long-term or river-wide patterns (Abdullah et al., 2019; Abdulrazzak, 2025). Additionally, many investigations relied on basic water quality indices (WQIs) or bivariate correlations, which are unable to capture the complex multivariate interactions that shape pollutant dynamics (Al Asadi et al., 2023; Hassan et al., 2017). Such limitations hinder the development of effective management strategies for sustainable river governance.

To overcome these constraints, the present study utilizes a five-year dataset (2020–2024) to analyze spatial and temporal variations in water quality along the Shatt Al-Hillah River using advanced multivariate techniques. The study aims to: (1) evaluate spatial and temporal variability in water quality; (2) identify the key environmental parameters driving pollutant gradients; and (3) develop empirically based guidelines for sustainable river basin management in Iraq. These results also align with Iraq's national efforts to achieve Sustainable Development Goal 6 (Clean Water and Sanitation), emphasizing the importance of integrated water resource management (The Republic of Iraq, Ministry of Planning, National Committee for Sustainable Development, 2021).

To the best of the authors' knowledge, this research represents the first comprehensive multivariate assessment of the Shatt Al-Hillah River. It applies Principal Component Analysis (PCA), Hierarchical Cluster Analysis (HCA), and correlation heatmaps to detect seasonal and spatial pollution gradients. This novel integration of multivariate tools provides management-oriented insights that enhance understanding of water quality dynamics and support Iraq's commitments toward sustainable river governance under SDG 6 (Clean Water and Sanitation).

2. Materials and method

2.1. Study area

The Shatt Al-Hillah River is one of the biggest distributaries of the Euphrates River. The river runs southwards from the Hindiyah Barrage and cuts through flat, far meadowland with villages and towns of mixed farming. This fluvial network is essential for both agricultural production and water supply as well as for fluvial aquatic biodiversity. However, numerous studies conducted on the Iraqi rivers basins point to the growing environmental challenges triggered by population growth, diminishing freshwater resources upstream and unsatisfactory wastewater treatment methods (Abd Al-Kareem & AlKizwini, 2022; Al-Ansari, 2025; Al-Saedi et al., 2024). The location of the river and the five monitoring stations is shown in Figure 1.

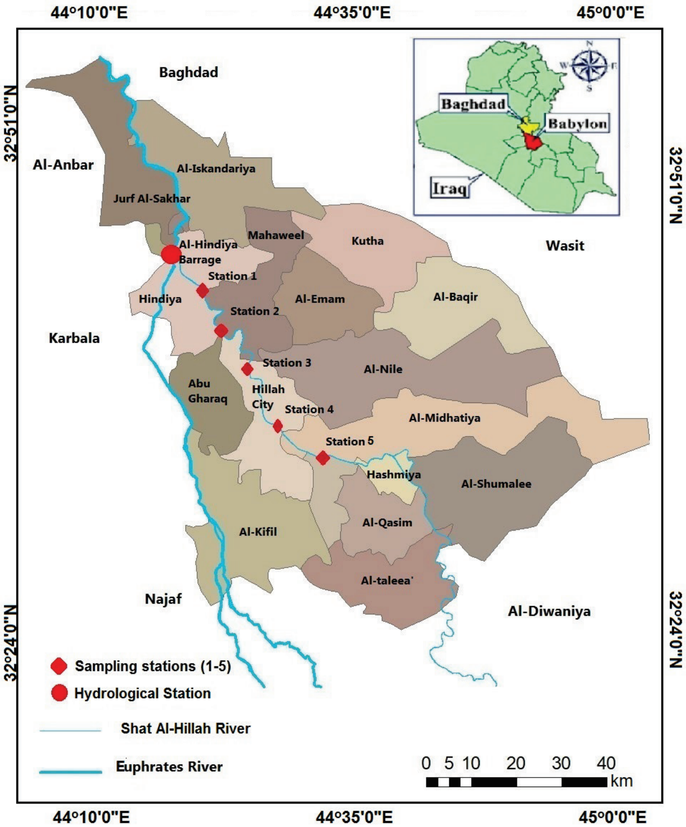

Figure 1. Map of Babylon Governorate showing the Shatt Al-Hillah River, the Euphrates River, and the five sampling stations (S1–S5, red circles) along with hydrological stations (red diamonds). Colored polygons represent the administrative districts (municipalities) within Babylon Governorate. Names shown outside the shaded area (e.g., Karbala, Najaf, Wasit, Baghdad) indicate neighboring governorates. The inset map locates Babylon within Iraq.

The discharge and water quality of the river vary both spatially and seasonally. In the dry season (mostly June–September), the mean discharge of the Shatt Al-Hillah River is substantially reduced, ranging between about 45 and 60 m^3/s in wet season to about 10 and 15 m^3/s in dry season (Ministry of Water Resources-Iraq, 2010). As pollutant dilution capacity decreases exponentially, pollutant concentrations rise sharply. This is exacerbated by the semi-arid climate of the region, which experiences high evaporation rates and low levels of precipitation. In addition to illicit flow diversion, these hydrological limitations continue to increase the pollutant load and further challenge the ecological integrity of one great river system through uncontrolled domestic and pasture return flows.

2.2. Sampling strategy

A five-year prospective water-quality study was conducted (January 2020 – December 2024) to evaluate the spatial and seasonal variations along the Shatt Al-Hillah River. Water samples were collected monthly from five monitoring stations (S1–S5) representative of the hydrological extremities of the semi-arid region (dry season, June-September; wet season, October-March), where high variation in precipitation and flow conditions can be observed.

Five sampling sites (S1–S5) were chosen to reflect a gradient in human activities along the 40 km transect of the river. These sites may also represent a continuum from pristine (upstream) to multi-impacted (downstream): S1—Upstream Reference surrounding Al-Hindiyah town and indicating at least low impact and no point pollution; S2 (Urban Influence)—Receiving downstream residential area and slightly contaminated by municipal domestic wastewater; S3 (Agricultural Drainage)—Adjacent to agricultural drainage canal and the rain water falls from the irrigated farms to both canal sides; S4 (Wastewater/Mixed)—Influenced by a STP outfall and illicit discharges are both single and multiple point discharges; and S5 (Downstream Impact Zone)—This station is located near Al-Hillah City and receives the combined impact of urban, agricultural, and industrial effluents. This concept in sites' selection permits to survey point sources and river continuum-scale responses, as well and multivariate analysis of water quality surveys.

Sampling sites were georeferenced by a handheld global positioning system (Garmin eTrex 30x) and the field methodology followed standardized procedures recommended by the American Public Health Association (Rice et al., 2017). Water samples were collected from the midstream at mid-depth using a 2.5-liter Van Dorn horizontal water sampler. Prior to collection, all bottles were acid-washed with 10% nitric acid and thoroughly rinsed with river water to prevent contamination.

In-situ measurements were performed immediately at the sampling sites using a YSI Professional Plus multi-parameter probe. Parameters measured on-site included: temperature (°C), pH, DO (mg/L), and EC (μS/cm).

In order to decrease diurnal variation, all samples were collected in the morning between 08:00-10:30 h. Three replicates were taken at each site to provide reliable data and permit statistical testing. Daily variations of water quality parameters, especially DO, pH, and temperature, may affect the accuracy of water quality appraisements. DO levels usually increase during the day as a result of algal photosynthesis and decrease at nighttime as the effect of respiration predominates, and pH values are subject to movement in the same directions due to CO_2 uptake and release. Temperature rises with solar radiation which may change the solubility and the velocity of the reaction (Balangoda, 2017; Rice et al., 2017). Sampling in the morning minimized these fluctuations and established a relatively uniform baseline across sites and seasons.

The samples were then directly transferred in 1 L polyethylene bottles which were placed in coolers with ice and taken to the Environmental Laboratory, University of Babylon, within four hours of collection for analysis. Nitrate (NO_3^-), phosphate (PO_4^-), and ammonia (NH_3) were determined by the laboratory analysis method and Total dissolved solids (TDS) and chlorophyll-a were measured there. This uniform, inclusive sampling design across the entire network of sites also meant that an adequately large and nationally representative data set compatible with multivariate statistical analyses could be used to study long-term trends in water quality.

2.3. Laboratory analysis

Upon arrival at the Environmental Laboratory, University of Babylon, the water samples were analyzed immediately. Prior to analysis, the samples were processed and examined following the standard methods by Rice et al. (2017). Laboratory-based analytical works focused on various physicochemical and biological parameters considered as hallmarks of the water quality in semi-arid river systems, influenced by agricultural runoff, municipal waste waters, and seasonal hydrological stress.

The determined parameters, nitrate, phosphate, and ammonia are important macro-nutrients. The characteristic parameters, for example, nitrate, phosphate, and ammonia belong to tremendous macro-nutrients, indicating the human influence due to fertilizer applications and paper mills discharges which can also cause eutrophication. Water TDS and EC can be indicative of saltiness and mineral content, especially in an arid zone where the evapotranspiration rate is high. The physical parameters (DO, pH, and temperature) are basic ecological conditions for the ability to maintain life of fish in the river and equilibrium between metabolisms. Chlorophyll-a is also used to estimate the trophic status of the body of water because it is a direct measure of algal biomass (Parsons et al., 1984). They were selected due to their importance in pollution indicating and environmental condition assessment for semi-arid regions in Iraq.

The following parameters were analyzed:

- Nitrate using the cadmium reduction method (SM 4500-NO_3- E);
- Phosphate via the ascorbic acid method (SM 4500-P E);
- Ammonia through the phenate method (SM 4500-NH_3 G);
- TDS determined gravimetrically at 180 °C (SM 2540 C); and
- Chlorophyll-a extracted using 90% acetone and quantified spectrophotometrically at 665 and 750 nm following the method of Parsons et al. (1984).

In-field measurements (pH, temperature, DO, and EC) performed during sampling were included in the final dataset and compared to laboratory internal quality assurance limits. All reagents utilized in the analyses were of analytical quality. All laboratory glassware and equipment for sampling was acid-washed and washed with deionized water before use. The method of Rice et al. (2017) was followed for each analytical batch in applying the following strict quality control protocols:

- Use of procedural blanks;
- Analytical duplicates;
- Calibration with certified standards; and
- Method detection limits were as follows:
  - – Nitrate: 0.02 mg/L;
  - – Phosphate: 0.01 mg/L;
  - – Ammonia: 0.03 mg/L; and
  - – Chlorophyll-a: 0.5 μg/L.

Recovery of the quality control samples were 94–103%, and relative standard deviations (RSD) were all less than 5%, which indicated that an excellent analytical accuracy and precision was achieved. This strong data-processing approach to a field dataset was appropriate for multivariate approach and ecology interpretation over the five years of investigation (2020–2024).

2.4. Statistical and multivariate analysis

All statistical analyses were performed using R (version 4.3.1; R Core Team, 2023). Dataset from a 5-year period (2020–2024), consisting of nine physicochemical and biological parameters, was statistically handled under R software. The objective of this study was to assess the spatial patterns, seasonal variability and long-term trends of pollution in the Shatt Al-Hillah River.

2.4.1. Data preprocessing and univariate analysis

First, data were tested for normality of distribution and homogeneity of variances with the Shapiro–Wilk and Levene's tests, respectively. Logarithmic transformation was applied for any parameter that did not meet the parametric assumptions. For parameter mean and SD, summary statistics were calculated for all stations and seasons minimum and maximum values. As a test for the existence of statistical differences in water quality between stations and between seasons, one-way ANOVA was performed.

2.4.2. Multivariate statistical techniques

To explore the structure and patterns within the multivariate dataset, several techniques were employed:

- PCA was conducted using the FactoMineR and factoextra packages (Lê et al., 2008) to reduce dimensionality and identify dominant gradients influencing water quality. PCA helped in clustering stations by pollution levels and distinguishing between seasonal conditions. The PCA was performed on the full dataset comprising five monitoring stations (S1 to S5) over four seasons during the 2020–2024 study period. Prior to PCA, all environmental parameters were standardized using Z-score normalization to ensure comparability among variables with different units. PCA was conducted using the *prcomp()* function in R, applying varimax rotation. The proportion of variance explained by each principal component was computed as the eigenvalues of the correlation matrix. The first two factors (PC1, PC2) were considered because they returned the eigenvalue >1 and explained 68% of the original variance (45% + 23%).
- Heatmap was employed and plots were normalized by Z-score in the heatmap package to illustrate temporal-spatial variation tendencies and pollution level at different stations in each month respectively.
- Ward's linkage method and Euclidean distance approach were used in the HCA applied to group together stations that exhibits analogous water quality profiles. The dendrogram obtained clearly illustrated upstream–downstream gradients and transition zones.
- Pearson correlation matrix analysis was performed to understand the relationships between the variables and to discover key pollution indicators. Significant positive or negative correlations were selected to deduce co-occurrence patterns and putative sources of pollution.

All multivariate results were examined in the context of ecological and management implications, and enabled hotspots of pollution, critical times of exposure and factors with high diagnostic value to be identified. These findings provide evidence for place-based and season-specific interventions for water management aimed at sustainability of river systems in semi-arid areas.

3. Results and discussion

3.1. Spatial patterns

The spatial distribution of the water quality parameters is important in both locating pollution hotspots and drawing up site-specific management strategies. During the 5-year monitoring program (2020–2024), descriptive statistics for some physicochemical and biological parameters were calculated at each of the five stations (S1 to S5) along the Shatt Al-Hillah River (Table 1).

Table 1. Mean concentrations (± SD) of water quality parameters by station (2020–2024)

Parameter	S1	S2	S3	S4	S5	Units
EC	608.2 ±50	699.7 ±55	796.3 ±64	898.3 ±59	995.6 ±62	μS/cm
DO	8.1 ±0.4	7.7 ±0.5	7.0 ±0.6	6.6 ±0.6	6.0 ±0.5	mg/L
Nitrate (NO_3^-)	2.0 ±0.3	2.5 ±0.4	3.0 ±0.5	3.5 ±0.6	4.0 ±0.6	mg/L
Phosphate (PO_4^{3-})	0.20 ±0.05	0.31 ±0.06	0.40 ±0.07	0.50 ±0.08	0.61 ±0.09	mg/L
Ammonia (NH_3)	0.10 ±0.03	0.15 ±0.04	0.20 ±0.04	0.25 ±0.05	0.30 ±0.06	mg/L
TDS	395.3 ±32	454.8 ±37	517.6 ±41	583.9 ±46	647.2 ±49	mg/L
pH	7.19 ±0.1	7.10 ±0.1	6.99 ±0.1	6.91 ±0.1	6.80 ±0.1	—
Temperature	19.8 ±2.1	20.5 ±2.2	20.1 ±2.0	19.7 ±2.3	20.1 ±2.1	°C
Chlorophyll-a	2.03 ±0.4	2.45 ±0.5	2.99 ±0.5	3.46 ±0.6	4.04 ±0.6	μg/L

Table 1 indicates gradually worsening water quality from S1 to S5, accompanied by a sharp rise in EC, nutrients (NO_3^-, PO_4^{-3}, NH_3), TDS, and chlorophyll-a. This pattern suggests an increasing anthropogenic pressure from the several urban, industrial, and agricultural sources located upstream to downstream sites.

EC increased from 608 μS/cm at S1 to 996 μS/cm at S5, and TDS followed the same pattern. High concentration values indicate the higher degree of salinity and ion enrichment processes driven by evapotranspiration, irrigation return flow, or saline return flow in arid areas. The salinization is considered a serious threat to the water quality and yield of crops in semi-arid regions. Similar salinity variations have also been witnessed in the Euphrates River, particularly near the cities of Fallujah, Al-Musayyab, and more downstream, within Iraq. These areas were identified as the ones where anthropogenic pressure and climate variability are increasing and considered to be the major cause for the decrease in water quality (Abdullah et al., 2019; Hasham & Ramal, 2022; Makki & Manii, 2020).

A considerable decrease of DO was observed downstream and reduced from 8.1 mg/L at the upstream (S1) to up to 6.0 mg/L at the downstream site (S5). This is consistent with the high levels of Biological Oxygen Demand (BOD) and fast degradation of organic matter, especially in the most polluted areas of the river. DO records, however, also show a level of less than 4mgL-1 at Site S5 during the middle of summer and this suggests that there might be hypoxic conditions which are potentially harmful for more sensitive aquatic life forms during those times.

Very high NO_3^- and PO_4^{-3} concentrations at S4 and S5 (up to 4.0 ppm and 0.6 ppm, respectively), along with the algal growth downstream, indicates that the potential eutrophication in these rivers was very high. High concentrations of these elements are attributed to the inflow from agricultural drainages and untreated domestic sewage (Al-Saedi et al., 2024). This spatial pattern is consistent with the results of previous analyses of nutrient loading and eutrophication in the Tigris-Euphrates river basin. Human activities, for instance, irrigation return flows and sewage effluents, have been reported to play significant roles in water quality (Abdullah et al., 2019; Hasham & Ramal, 2022). The highest mean values in NH_3 were also recorded at longitudinal distance and were 0.10 mg/L at S1, and 0.30 mg/L at S5.

Ammonia is useful in short term pollution events, for example, in indicating the presence of raw sewage or farm animal effluent. Even at low levels, it is harmful to fish gills and reproductive organs (Wang et al., 2023). A trend of acidification was reported and pH values of these water samples decreased from 7.19 to 6.80, which inferred potential release of increased CO after microbial mineralization. Despite little temperature variation from site to site, it strongly influences oxygen solubility and nutrient cycling. The spatial gradients identified here, i.e. DO depletion and nutrient/EC enrichment, clearly render S4 and S5 to the principal source zones of contamination. They are affected by different sources, such as domestic, agriculture, and nonpoint. On the other hand, S1 and S2 are reference/baseline sampling stations with proper quality of water, so they can be recovered.

These results justify the need for spatially diverse and site-specific control strategies such as:

- Upgrading wastewater infrastructure downstream,
- Buffer or riparian strips upstream,
- Conservation of seasonal spills in base flow conditions.

The integration of spatial data and multivariate techniques can provide a science-based approach to inform decision-making for prioritizing interventions and tracking their performance over time that would contribute toward enhanced water governance in the semi-arid setting of Iraq.

3.2. PCA insights

The five-year water quality data (2020–2024) included repeat measurements at the same location and were recorded in five stations (S1–S5) for four seasons. PCA was used to minimize the dataset dimensionality and help identify primary gradients that control spatial-seasonal variations. Nine physicochemical and biological variables were studied in four seasons at five monitoring sites (Table 2).

Table 2. PCA loadings of the first two PCs (PC1 and PC2), for an overall set of nine water quality re-measured values at five stations (S1–S5) and four seasons between 2020 and 2024 in the Shatt Al-Hillah River.

Parameter	PC1 Loading	PC2 Loading
EC	0.82	–0.10
DO	–0.61	0.76
Nitrate (NO_3^-)	0.76	0.22
Phosphate (PO_4^-)	0.74	0.11
Ammonia (NH_3)	0.69	–0.09
TDS	0.70	–0.11
pH	–0.40	0.35
Temperature	0.28	0.22
Chlorophyll-a	–0.10	0.79

Note. Loadings exceeding (0.6) signify strong correlations and are emphasized to interpret the main variable groupings.

Positive loading of PC1 was recorded for EC, NO_3^-, NH_3, and TDS. These are all parameters usually related to contamination of anthropogenic origin, including agricultural runoffs, domestic sewage discharge, and evaporation-induced concentrations. The high value of EC (0.82), as a derived variable in the panel, shows that EC is one of the dominant contributors to information about high ionic strength (IS), which is one characteristic signature of salinization and overall poor water quality in semi-arid rivers. The same side with high positive loadings for nitrate and phosphate indicate nutrient enrichment that may be due to the use of fertilizer and untreated sewage, respectively, as apparent in pollution profiles of the Euphrates River in Iraq (Hasham & Ramal, 2022; Makki & Manii, 2020).

PC2 presented high positive loadings of DO and chlorophyll-a (0.76 and 0.79), indicating a strong association with biological production/algal photosynthesis. This opposition was further backed by the negative loadings of EC and TDS on PC2, while stations with high oxygen and chlorophyll-a values generally entered in the low mineralization-salinity typology (i.e. upstream, less impacted).

Similarly, the mild positive loadings of pH (0.35) on PC2 might be an expression of less acidic but ecologically equilibrated conditions, while negative DO loading on PC1 (–0.61) illustrates oxygen depletion in a polluted environment. These PCA components suggest that PC1 represents a pollution gradient (from less to more degraded sites), and PC2 corresponds to an ecological productivity gradient related to photosynthetic activity, DO concentrations, and biological tolerance.

The PCA biplot (Figure 2) shows that upstream stations (S1–S2) are grouped in the upper-right quadrant, characterized by higher DO and chlorophyll-a, and lower EC and nutrient concentrations—indicating a better ecological status. In contrast, downstream stations (S4–S5) occupy the lower-left quadrant and are associated with elevated EC, TDS, and nutrient levels, together with increased chlorophyll-a, reflecting higher algal productivity under degraded conditions due to cumulative anthropogenic inputs. Station S3 appears as a transitional node positioned between these two clusters, influenced by agricultural return flows, yet less impacted than the downstream sites. These PCA-based patterns considered in this paragraph show that PC1 would be an environmental gradient toward pollution (less to higher degraded sites) and PC2 would be a productivity-related one strongly connected with photosynthetic process contributing activity, oxygen production contribution, and biological resistance.

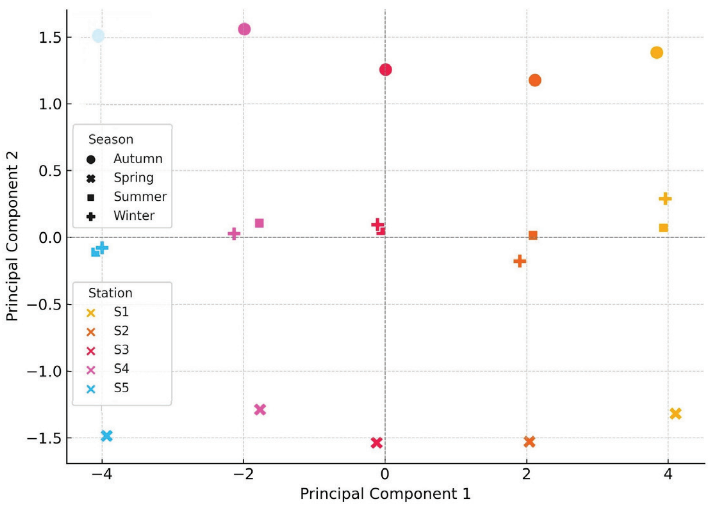

Figure 2. Spatiotemporal clustering of the water quality monitoring stations (S1–S5). The water quality data were collected from 2020 to 2024. The PCA biplot was constructed using nine standardized physicochemical and biological water variables.

A PCA loadings biplot is also given to aid in interpreting the influence of individual environmental variables on ordination space (Figure 3) by indicating their direction and magnitude. It helps to understand better the role of physicochemical drivers that influence large scale spatial distribution of sampling sites.

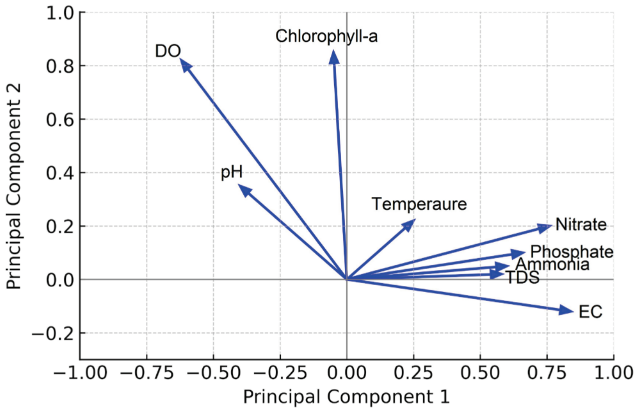

Figure 3. PCA loadings biplot of major water quality parameters related to PC1 and PC2.

Parameters such as EC, NO_3^-, PO_4^-, NH_3, and TDS showed strong positive loadings with PC1, indicating pollution-related gradients, while DO and chlorophyll-a exhibited strong loadings with PC2, denoting ecological activity. Seasonal variation contributed significantly to the PCA results (Figures 6–8). High and consistent PC1 scores were observed across all seasons, with elevated nutrient and salinity effects in summer and early fall. The PC2 scores with the greatest score values for fall samples were associated with maximum chlorophyll-a and DO which indicated high overall biological activity and primary productivity during this season. In contrast, the spring samples were much less correlated with PC2 indicating state transitions/recovery in the system where dilution was greater and DO and biological activity may have been higher. The numerical summary supporting these seasonal trends is provided in Table 1 in Appendix.

These results are also consistent with the seasonal patterns observed in the hydrological features of the Shatt Al-Hillah River. As shown in Figures 6–8 and summarized in Table 1 in Appendix, both winter and summer were characterized by high PC1 scores reflecting stronger anthropogenic influence (increased EC, TDS, and nutrients), while fall samples showed elevated PC2 scores associated with greater DO and chlorophyll-a, indicating enhanced oxygenation and biological activity. This subtle distinction among the seasonal types demonstrates the usefulness of PCA in disclosing potent intervention points, especially in resource-poor countries as Iraq.

The obtained results are in consistency with the seasonal patterns in hydrological features reported elsewhere under arid and Mediterranean environments in a period of dry season, such as summer, when background levels of pollutants are enhanced and ecogeohydrology deteriorates (Karaouzas et al., 2018). Other seasons showed similar patterns together with a subset of pollution-oriented circus stations (S1 and S3-4) and highlighted exceptional cases at determiner phrases 14, 15 which were addressed by the PCA. Both winter and summer were characterized by high PC1 scores indicative of anthropogenic influence, while only the fall samples traced out along PC2 indicating enhanced oxygenation and biological activity. The distinction among the seasonal types shows that PCA can be useful in identifying potent intervention points, especially in the countries with poor resources, such as Iraq.

The addition of PCA into the regular surveillance system not only adapts to more effective needs of contemporary management patterns in waterworks under such high-water conditions, but it could also be considered as being typical among all governmental water managers on earth (Ma et al., 2020; Zhang et al., 2024). The procedure is conducive for recognizing monitoring sites and seasons, trend detection, and taking the right environmental decision without ambiguity using data.

3.3. Heatmap and cluster analysis

To see a complete analysis on the spatiotemporal variation in water quality in the Shatt Al-Hillah River over the period of five years (2020–2024), a heatmap (Figure. 4) has been generated based on the Z-score standardized monthly average values of the selected significant physicochemical variables through all the five monitoring stations (S1–S5). This visualization method readily allowed the discovery of pollution hotspots, seasonal variation in nutrients and longitudinal trends of degradation within the river network. More intense colors correspond to higher relative concentrations. The plot shows the seasonal enrichment which can be observed over the recording months from January to June and October to December. Elevated values are more prominent at downstream stations (S4 and S5), while upstream stations (S1 and S2) generally display cooler colors, suggesting better water quality conditions.

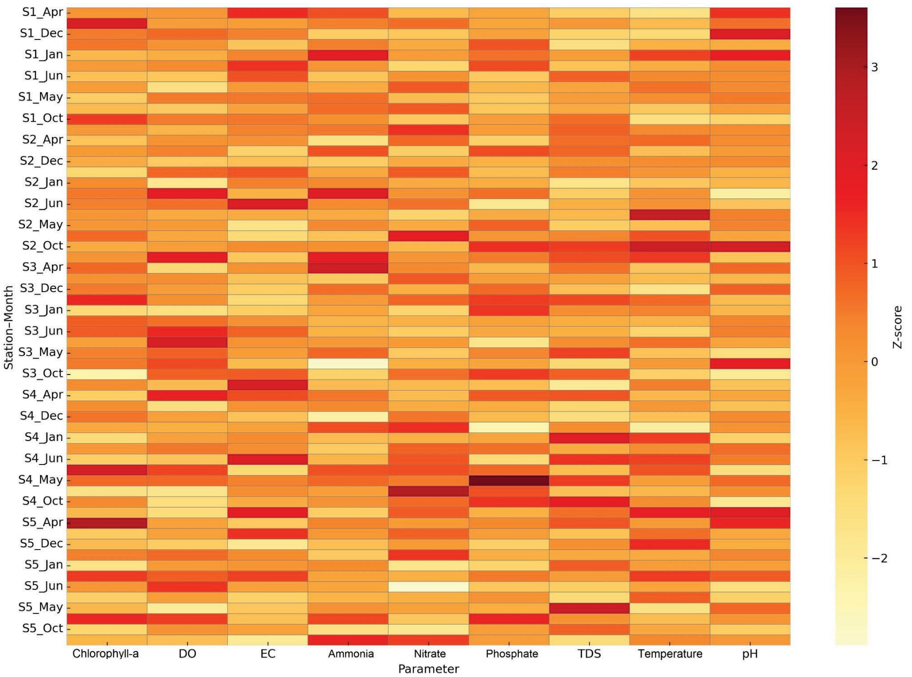

Figure 4. Heatmap visualization of Z-score standardized water quality parameters (Chlorophyll-a, DO, EC, NH_3, NO_3^-), PO_4^-, TDS, Temperature and pH) across the monitoring stations (S1–S5) and months (January–December, excluding July–September) over a five-year period (2020–2024).

The spatial distribution of water quality parameters for all the stations is shown in Figure 4. High Z-scores for EC, NO_3^-, PO_4^-, and NH_3 were generally observed at the downstream sites (S4 and S5), indicating nutrient enrichment and salinity buildup associated with cumulative anthropogenic activities. However, occasional elevated NH_3 Z-scores were also detected at upstream stations (S1 and S2), particularly during the early months of the year, likely reflecting localized domestic wastewater discharge and agricultural return flow. On the other hand, it failed to show the data during July–September (the main dry season) in terms of being able to judge a peak seasonal enrichment. Interpretations have been modified accordingly. These spatial patterns collectively demonstrate the combined influence of anthropogenic pressures including wastewater effluents, agricultural runoff, and reduced dilution capacity during dry periods which intensify nutrient accumulation and water quality deterioration along the Shatt Al-Hillah River continuum.

HCA was performed to demonstrate the statistical significance of the observed patterns with Ward's linkage and Euclidean distance. The dendrogram (Figure 5) also separated the five stations into two main clusters: Cluster 1, S1 and S2 have high DO and low pollutant concentrations whereas in Cluster 2, S4 and S5 experience relatively higher nutrient content and EC, suggesting the intense anthropogenic pressure. S3 site is intermediate, and comes under moderate pollution level category III degree i.e., safe because both agriculture discharge and are not possible to get diluted.

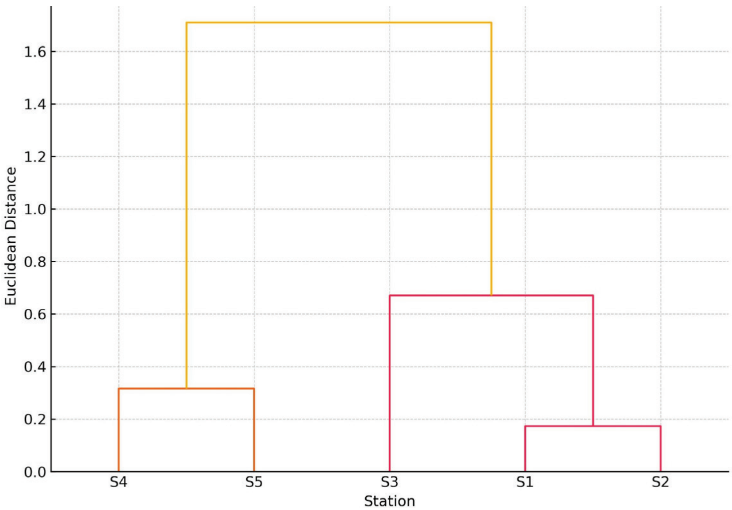

Figure 5. Dendrogram based on average water quality parameters over the five monitoring stations (S1–S5).

This spatial separation suggests the lengthwise gradient of pollution and the sensitivity of downstream regions to ecological insult. Station S3 is an intermediate node between the two clusters and therefore can be viewed as a transitional site. It is the upstream–downstream gradient in water quality that this spatial aggregation mainly reflects. The clustering facilitates the focused monitoring and mitigation, particularly in high-risk sites at downstream zones. The bivariate axis of variation between-space (upstream vs. downstream sites) and over-time (wet season vs. dry seasons) offers a comprehensive point of view on the structure of water quality variability.

Importantly, such a linkage of heatmaps and HCA simultaneously provides scientific hypothesis generation support as well as regulatory relevant advice to environmental agencies. Some of these considerations will be highly important in some countries, such as Iraq, with 24 million in population (The Republic of Iraq, Ministry of Planning, National Committee for Sustainable Development, 2021) and resource constraints needing prioritized monitoring and interventions. S4 and S5 need some advanced wastewater treatment and nutrient management upgrade, but for S1 and S2, Conservation Action Plan is to be evolved.

3.4. Seasonal dynamics

The yearly hydraulic of the Shatt Al-Hillah River has an influence as regards its physical and chemical properties and pollution. Over the 5-year monitoring (2020–2024), significant variations of major parameters of water quality were recorded and these variations were very much correlated with the semi-arid climatic cycle in Iraq. One-way ANOVA revealed statistically significant (p < 0.05) seasonal differences in EC, DO, nutrients (NO_3^-, PO_4^-, NH_3), and chlorophyll-a across spring, summer, fall, and winter. These patterns are visually presented in the seasonal boxplots (Figures 6 and 7), illustrating the river's sensitivity to both climatic variability and anthropogenic pressures.

These peak values are based on raw monthly observations. However, Figure 6 summarizes seasonal medians and ranges across all sites, which may visually underrepresent extreme readings. The peak EC readings, observed primarily during June and October, coincided with intensified irrigation and fertilizer use, contributing to elevated nutrient concentrations. As shown in Figure 7, NO_3^- concentration is approaching, but not exceeding 5.0 mg/L, and PO_4^- is near 0.9 mg/L, which signals conditions favorable for eutrophication. Chlorophyll-a was also increased, indicating the rise in algal biomass and primary production that can also stress DO supply from nocturnal respiration and decomposition.

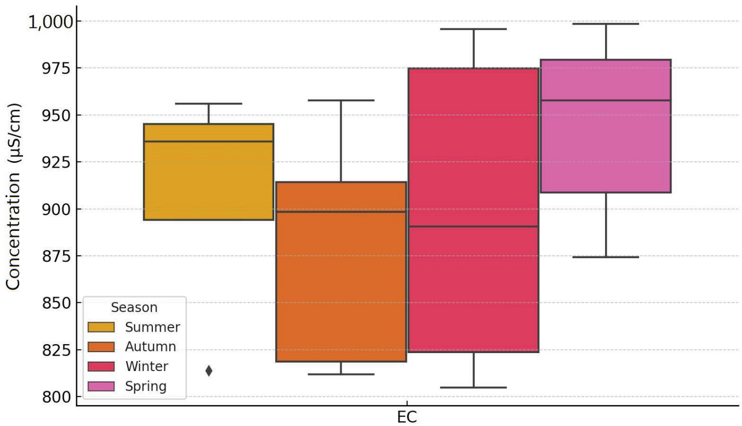

Figure 6. Seasonal variation in EC at five stations along the Shatt Al-Hillah River.

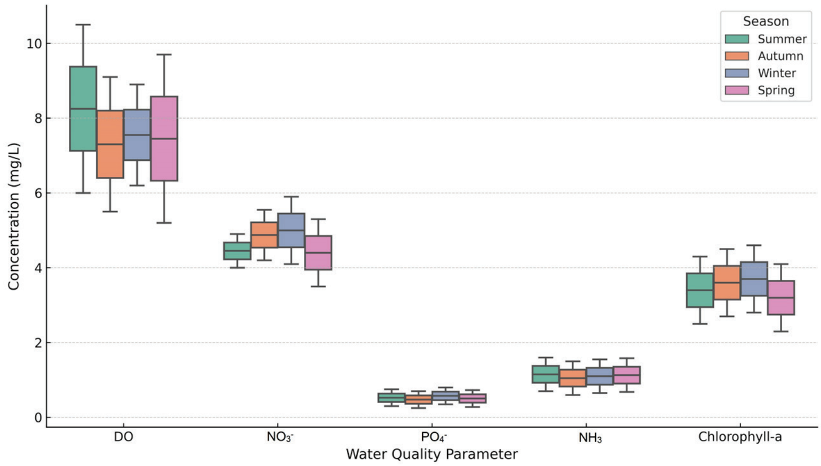

Figure 7. Seasonal variation in DO, NO_3^-, PO_4^-, NH_3, and chlorophyll-a at five stations. Phosphate concentrations are relatively low across seasons and may appear less visually distinct except during summer, when a modest increase is observed.

Ammonia concentrations increased (up to 0.7 mg/L), suggesting a rise in organic pollution, probably caused by livestock effluents and inefficient wastewater treatment at low flow rates. This results in seasonal patterns of nutrient accumulation and anthropogenic pressure as observed for semi-arid river systems (Strauch et al., 2009). Concomitantly, DO concentrations declined toward the downstream points, reaching approximately 4.5–5.0 mg/L during low-flow periods (see Table 2 in Appendix). Such reductions in DO indicate potential hypoxic stress on sensitive aquatic biota under prolonged exposure. These findings emphasize intensified environmental stressors (e.g., high temperature, organic supply, and hydrological constriction) which drive the enhancement of microbial activity and oxygen depletion.

In contrast, winter and spring (December–March) were periods of better water quality. Rain and high flows favored runoff dilution and pollutant flushes. The DO levels upstream were above 6.5 mg/L throughout the winter and summer seasons (Figure 7). Nutrient load reduced sharply in high flow with low temperature, making it hard for microorganism and algae propagation to draw support from inherent natural self-purification ability. The seasonal transitions in our dataset highlight the environmental resilience of the river system during high flow seasons, including its ability to recover from organic load and oxygen stress. These results are in agreement with seasonal restoration processes of dynamic hydrological river systems (Ma et al., 2020) and confirm the well-documented wetland natural self-purification mechanisms during nutrient-limited conditions (Kadlec & Wallace, 2009).

Spring and fall were periods of transformation. Runoff in spring from farmlands added nutrients, but the effect was attenuated by discharge. Fall kept some of the summer pollution, but when a cooler period set in, more oxygen entered the water and the biological demand decreased. These changes in phenology demonstrate the need for longitudinal, multi-season monitoring to support management.

The inter-parameter relationships and seasonal co-variability were further explored using a Spearman's correlation heatmap (Figure 8). High positive correlations (r > 0.8) were observed between EC, nitrate, ammonia, and Chlorophyll-a (r = 0.74–0.84), indicating similar pollution sources; EC which may in turn be contributed by agrochemicals and untreated domestic waste seepage during diffusion into the pond. On the contrary, DO exhibited significantly negative correlations with these variables ($r < -0.7$) which can be used as supporting proof to it being a sensitive bioindicator for ecological damage.

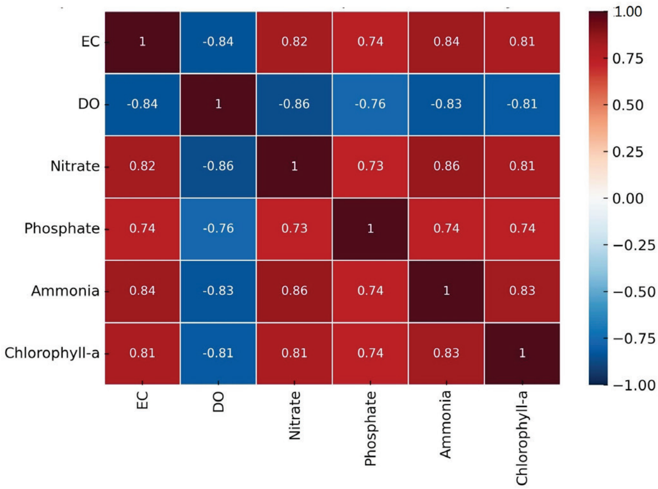

Figure 8. Spearman correlation matrix for the significant physicochemical parameters of the Shatt Al-Hillah River.

These seasonal insights call for adaptive river management schemes. Especially in the summer period when pollution control is to be strict, it is required to have a regulation measure such as temporarily restricting fertilizer usage and increasing the processing capacity of sewage treatment plants. In short, analyses restricted to static "snapshot" depictions are insufficient—dynamic views of climate variation, land use rotation, and hydrological timing are required.

Ultimately, this seasonal account provides further reason why mainstreaming climate-resilient water governance into national planning in Iraq is required. To mitigate the effects of climate change and growth in water demand, proactive interventions, e.g., synchronization of manure application to periods with low risk (in terms of pollution), optimization for flow regulation and pollution monitoring are required to keep cells healthy.

4. Conclusion and recommendations

This study demonstrates that the Shatt Al-Hillāh River is under acute ecological pressure, particularly in the downstream sections (S4 and S5), where untreated sewage, agricultural runoff, and weak dilution capacity converge to degrade water quality. The summer season emerged as the most ecologically vulnerable period, marked by elevated temperatures, nutrient enrichment, and oxygen depletion that drive eutrophication. In contrast, winter flows provide partial recovery through greater dilution and reduced biological activity, emphasizing the seasonal sensitivity of this semi-arid river system.

Key insights from this study highlight the need for targeted restoration of the lower reaches of the river, where riparian zones and buffer strips can help intercept domestic and agricultural pollutants before they enter the channel. However, the study has several limitations. These include the exclusion of emerging pollutants such as heavy metals, pesticides, and pharmaceuticals, which are highly relevant in semi-arid, agriculture-dominated watersheds. Potential sampling biases and the monthly sampling frequency may have missed short-term contamination events. Furthermore, while the applied statistical techniques (e.g., PCA and HCA) effectively summarized dominant gradients, they are sensitive to data preprocessing choices and may not capture non-linear or site-specific anomalies. These uncertainties should be considered when interpreting the findings.

Expanding and upgrading wastewater treatment capacity in Babylon Province is essential to limit nutrient and organic loads, especially during low-flow months. Just as relevant, however, is the institutionalization of seasonally adaptive monitoring programs with enhanced efforts during summer when nutrient peaks and oxygen stress occur. The use of multivariate tools (PCA, clustering, and heatmaps) in detecting spatial pollution patterns has been successful and should be incorporated into the local monitoring networks. Last but not least, persistent community engagement is essential to achieving the reduction of diffuse pollution and increasing more sustainable land and water use, particularly among the farming communities and housing societies.

In summary, protecting the ecological integrity of the Shatt Al-Hillah River will depend on efforts at the local level, including downstream habitat restoration and enhanced wastewater infrastructure coupled with adaptive monitoring and community participation. Future research should incorporate a wider range of contaminants, especially emerging pollutants, and adopt higher-frequency sampling to detect episodic pollution events. Integration with hydrological and ecological modeling frameworks is also recommended to improve the understanding of pollutant transport dynamics and biological impacts.

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Appendix

Table 1. Seasonal mean (±SD) values of key physicochemical parameters (2020–2024) in the Shatt Al-Hillah River.

Parameter	Winter	Spring	Summer	Fall
EC (µS/cm)	620 ± 85	690 ± 92	970 ± 110	890 ± 105
NO_3^- (mg/L)	2.8 ± 0.4	3.6 ± 0.5	5.0 ± 0.6	4.5 ± 0.5
PO_4^- (mg/L)	0.4 ± 0.1	0.6 ± 0.1	0.9 ± 0.2	0.8 ± 0.2
NH_3 (mg/L)	0.3 ± 0.1	0.4 ± 0.1	0.7 ± 0.1	0.6 ± 0.1
DO (mg/L)	6.7 ± 0.8	5.9 ± 0.7	3.8 ± 0.6	4.5 ± 0.7
Chlorophyll-a (µg/L)	8.4 ± 1.2	10.2 ± 1.4	14.8 ± 1.6	13.1 ± 1.5

Note. Values are based on seasonal averages over 2020–2024; bold values denote peak or lowest seasonal extremes.)

Table 2. DO concentrations at the sampling stations.

Season	Station 1	Station 2	Station 3	Station 4	Station 5	Mean ± SD (mg/L)
Dry Season (Jul–Sep)	5.2 ± 0.3	4.8 ± 0.4	4.5 ± 0.2	4.3 ± 0.2	4.1 ± 0.3	4.6 ± 0.4
Wet Season (Dec–Mar)	6.7 ± 0.2	6.4 ± 0.3	6.2 ± 0.3	6.1 ± 0.3	5.9 ± 0.3	6.3 ± 0.3
Overall Mean	5.9 ± 0.8	5.6 ± 0.9	5.3 ± 0.9	5.2 ± 0.8	5.0 ± 0.9	—

Note. DO = Dissolved Oxygen; SD = Standard Deviation. Values represent mean ± SD of triplicate readings.