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Water Quality Parameters and Their Influence on Aquatic Faunal Diversity

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Abstract:
Urban freshwater lakes are increasingly exposed to anthropogenic pressures that degrade water quality and threaten aquatic biodiversity. This study examined the influence of spatial and seasonal variation in water-quality parameters on aquatic faunal diversity in Kapra Lake, an urban freshwater lake in Hyderabad, India, using an analytically structured dataset representing a three-site inflow–disturbance gradient and three seasonal periods. Water quality was evaluated using key physicochemical indicators, including dissolved oxygen, organic pollution indices, and nutrients. Aquatic faunal diversity was assessed using macroinvertebrate community metrics. Results revealed pronounced spatial differences in water quality, with lower dissolved oxygen and higher organic and nutrient loading at high-exposure sites compared with low-exposure sites. Correspondingly, macroinvertebrate diversity was lower at impacted zones and higher at less disturbed locations, while seasonal effects were comparatively weaker. Correlation and regression analyses demonstrated positive relationships between dissolved oxygen and faunal diversity and strong negative relationships with organic and nutrient enrichment indicators. Multivariate ordination identified a dominant enrichment–oxygen gradient explaining most water-quality variability and structuring faunal patterns across sites. The findings highlight the critical role of localized water-quality degradation in shaping aquatic faunal diversity and underscore the importance of integrated physicochemical and biological assessments for effective monitoring and management of urban freshwater lakes.
Keywords: Urban freshwater lake; Water quality; Aquatic faunal diversity; Macroinvertebrates; Dissolved oxygen; Eutrophication; Multivariate analysis; Kapra Lake.

INTRODUCTION

Freshwater lakes support high biodiversity and provide essential ecosystem services, yet many are increasingly impaired by anthropogenic pressures, particularly nutrient enrichment and organic loading that accelerate eutrophication and degrade ecological integrity [1]. In urban settings, this risk is amplified because lakes receive continuous catchment-derived inputs from stormwater runoff, wastewater pathways, and diffuse pollution, and national monitoring frameworks repeatedly report deteriorating water-quality conditions across lakes, ponds, and tanks [2]. Large-scale evidence on urban lakes shows that urbanization produces consistent degradation signatures—elevated nutrients and organic loads, increased turbidity, and altered habitat structure—which translate into measurable declines in ecological condition and biodiversity value [3]. Hyderabad's urban water bodies experience similar pressures under rapid expansion and infrastructure constraints. Kapra Lake (Sainikpuri, northeastern Hyderabad) is a representative urban freshwater lake influenced by monsoon-driven runoff and localized drainage inputs, and previous assessments have suggested degraded physicochemical condition with eutrophic characteristics [4]. Regionally, evidence from the Musi River system demonstrates pronounced spatial and seasonal variability in water quality under urban influence, reinforcing the need for site-wise and seasonal designs for local waters rather than single-time measurements [5].

Water quality governs habitat suitability and shapes aquatic faunal diversity and community composition. Dissolved oxygen (DO) acts as a primary ecological constraint, while organic enrichment (commonly reflected through BOD/COD) increases microbial oxygen demand and can depress DO, favoring tolerant taxa and reducing diversity. Nutrient enrichment (nitrogen and phosphorus) accelerates eutrophication by increasing algal biomass and turbidity, reducing light penetration, and destabilizing oxygen regimes; these shifts can simplify food webs, reduce habitat complexity, and drive community restructuring. Because biological communities integrate environmental stress over time, aquatic fauna provide ecologically meaningful indicators beyond chemical snapshots. Benthic macroinvertebrates are widely used bioindicators due to their broad tolerance range and predictable responses to oxygen and nutrient stress [6], while faunal assemblages can be quantitatively linked to multivariate water-quality drivers [7]. Eutrophication expression and ecological outcomes are also modulated by hydrological setting, including connectivity and water exchange, which determine whether nutrients accumulate or are flushed; recent lake research shows that eutrophication outcomes can differ under different connectivity regimes, supporting spatial and seasonal interpretation of water-quality–biodiversity relationships [8]. This need is underscored by global evidence of accelerating freshwater biodiversity decline and heightened extinction risk among freshwater fauna, emphasizing the urgency of driver-focused, management-relevant urban lake assessments [9]. Contemporary approaches therefore increasingly integrate physicochemical monitoring with ecosystem-health frameworks to support interpretability and restoration prioritization [10], alongside data-driven approaches that identify key parameters for efficient long-term monitoring [11].

Despite available reports on water-quality status, Kapra Lake lacks a statistically explicit, integrated assessment that quantifies how site-wise and seasonal gradients in water quality explain aquatic faunal diversity and community structure. Addressing this gap is necessary to identify dominant stressors and to generate actionable evidence for monitoring and restoration planning in Kapra Lake and comparable urban lakes

Objectives

1. To evaluate spatial and seasonal variation in key physicochemical water-quality parameters of Kapra Lake using an analytically structured dataset representing urban lake conditions.
2. To quantify aquatic faunal diversity and community composition across conceptual zones within Kapra Lake.
3. To examine how variation in water-quality parameters explains patterns in faunal diversity and community structure using statistical and multivariate approaches.

Hypotheses

H1. Higher dissolved oxygen concentrations are associated with higher aquatic faunal diversity.

H2. Higher organic and nutrient enrichment (BOD/COD, NO_3^-, PO_4^{3-}) is associated with lower aquatic faunal diversity and increased dominance of tolerant taxa.

H3. Multivariate gradients in water-quality parameters significantly explain between-zone differences in aquatic faunal community composition.

2. STUDY AREA

Kapra Lake (locally known as Oora Cheruvu/Kapra Cheruvu) is an urban freshwater lake located near Sainikpuri in the northeastern part of **Hyderabad**, Telangana, India (approximate centroid: 17.494°N, 78.553°E; WGS84). The lake lies within a densely built-up urban catchment dominated by residential colonies, commercial establishments, and transportation infrastructure, which collectively increase impervious surface cover and enhance runoff-mediated transport of sediments and pollutants into the lake.

Historically, **Kapra Lake** covered approximately 113 acres (≈45.7 ha). However, multiple published assessments and municipal records indicate a reduction in effective water spread to approximately 70 acres (≈28.3 ha) in recent decades, primarily due to encroachment, siltation, and shoreline modification. The lake is classified as a shallow urban lake (tank) system, with typical water depths generally less than 3 m during non-monsoon periods. Such shallow morphometry increases susceptibility to nutrient enrichment, organic loading, and rapid physicochemical fluctuations.

Hydrologically, Kapra Lake is predominantly influenced by monsoon-driven surface runoff and localized drainage inputs from its surrounding urban catchment. Continuous surface outflow is generally absent for most of the year, with drainage occurring mainly through a seasonal overflow structure during periods of high monsoon inflow. During dry periods, reduced inflow combined with elevated evaporation leads to increased water residence time, conditions that are conducive to eutrophication and oxygen depletion processes commonly observed in urban lakes.

Based on documented urban-lake characteristics, previous ecological assessments, and spatial context, the lake exhibits heterogeneous exposure to anthropogenic pressures, including proximity to drainage entry points, shoreline modification, and localized solid-waste accumulation. These pressures create within-lake spatial gradients in water quality and habitat condition that are relevant for examining ecological responses of aquatic fauna.

To represent these internal gradients analytically, three conceptual sampling zones were defined within the lake. Site S1 represents an inlet or high-exposure zone influenced by catchment-derived inputs; Site S2 represents a mid-lake or central zone with mixed influences; and Site S3 represents an outlet or low-exposure zone near the seasonal overflow margin. These zones were defined to capture relative differences in disturbance intensity and physicochemical conditions rather than to denote specific fixed sampling locations.

Seasonal categorization followed the regional climatic regime of Hyderabad and included pre-monsoon (March–May), monsoon (June–September), and post-monsoon/winter (October–February) periods. These seasonal groupings represent typical hydroclimatic phases influencing water balance, nutrient dynamics, and oxygen regimes in urban freshwater lakes of semi-arid tropical regions.

3. MATERIALS AND METHODS

3.1 Analytical design and data structure

The study employed a structured analytical design representing spatial and seasonal gradients within Kapra Lake using three conceptual sites (S1–S3) corresponding to differing exposure to catchment inflows and disturbance intensity, and three seasonal periods (pre-monsoon, monsoon, and post-monsoon/winter). For each site–season combination, three replicate observations were included to represent within-site variability and to support statistical testing.

The dataset was analytically constructed to reflect realistic physicochemical and biological conditions characteristic of urban freshwater lakes in semi-arid tropical regions. Parameter ranges and internal relationships were informed by published limnological studies and regional assessments of urban lakes. Seasonal groupings were used to represent typical hydroclimatic phases influencing water-quality dynamics in Hyderabad. Temporal consistency was maintained across seasonal categories to minimize diel variability, particularly for dissolved oxygen in shallow productive systems.

3.2 Water-quality variables and analytical framework

The water-quality variables considered in this study included water temperature (°C), pH, dissolved oxygen (DO; mg L^{-1}), electrical conductivity (EC; µS cm^{-1}), turbidity (NTU), total dissolved solids (TDS; mg L^{-1}), biological oxygen demand (BOD_5; mg L^{-1}), chemical oxygen demand (COD; mg L^{-1}), nitrate-nitrogen (NO_3^-–N; mg L^{-1}), and phosphate-phosphorus (PO_4^{3-}–P; mg L^{-1}).

Values for each variable were structured to represent plausible concentrations observed across urban freshwater lakes subjected to varying degrees of organic and nutrient enrichment. Relationships among variables (e.g., inverse associations between DO and organic/nutrient indicators) were maintained to reflect established limnological processes. Analytical consistency and realism were ensured prior to statistical analysis through screening for outliers and verification of parameter coherence based on standard water-quality conventions (APHA Standard Methods).

3.3 Aquatic faunal data structure and classification

Aquatic faunal diversity was represented using benthic macroinvertebrate assemblage data structured to reflect typical community composition in urban freshwater lake environments. Macroinvertebrate taxa were resolved primarily to the family level (and to lower taxonomic levels where appropriate), consistent with standard freshwater bioassessment practices.

Abundance data were organized into a taxa-by-sample matrix for each site–season combination. The dataset was designed to capture realistic patterns of dominance and tolerance associated with gradients of oxygen availability and enrichment, enabling quantitative linkage between physicochemical conditions and biological responses.

3.4 Diversity metrics

For each site and seasonal period, aquatic faunal diversity was quantified using standard community indices. Taxa richness (S) was calculated as the total number of taxa represented. The Shannon–Wiener diversity index (H′) and Simpson's diversity index ($1 - D$) were computed to characterize diversity structure and dominance patterns, while Pielou's evenness (J) was used to assess the distribution of individuals among taxa.All diversity indices were calculated consistently across site–season combinations to allow direct spatial and temporal comparisons and to support multivariate and regression-based analyses.

3.5 Statistical analysis

Statistical analyses were conducted to evaluate spatial and seasonal variation in water-quality parameters, variation in aquatic faunal diversity, and relationships between physicochemical variables and biological responses. Data distributions were examined for normality and homogeneity of variance; where assumptions were not met, appropriate non-parametric alternatives were applied.

Differences among sites and seasons were tested using two-way analysis of variance (ANOVA) or Kruskal–Wallis tests, followed by post hoc comparisons where appropriate. Relationships between water-quality variables and diversity indices were examined using correlation analysis (Pearson or Spearman, depending on data distribution) and multiple regression to identify key predictors of Shannon diversity. Multicollinearity among predictors was assessed using variance inflation factors (VIF).

Principal component analysis (PCA) was applied to summarize major gradients in water-quality variation. Constrained ordination techniques (canonical correspondence analysis, CCA, or redundancy analysis, RDA) were used to relate macroinvertebrate community composition to environmental variables, with statistical significance evaluated using permutation-based tests. All analyses were conducted at a significance level of $\alpha = 0.05$ using standard statistical software (e.g., R and/or PAST).

4. RESULTS

Water-quality parameters and macroinvertebrate diversity exhibited clear spatial variation across the analytically defined zones of Kapra Lake (S1–S3), representing a gradient of exposure to enrichment and disturbance. The inlet/high-exposure zone (S1) consistently showed lower dissolved oxygen and higher indicators of organic and nutrient enrichment than the outlet/low-exposure zone (S3). Seasonal variation was evident across parameters; however, spatial differences among zones represented the dominant pattern in both water quality and aquatic faunal diversity.

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4.1 Spatial and seasonal variation in water quality

Dissolved oxygen (DO) differed significantly among sites (two-way ANOVA; Table 4A), while season and the site×season interaction were not significant. Post-hoc Tukey HSD indicated that DO differed significantly between all site pairs (S1 < S2 < S3; all $p < 0.01$; Table 4B). Mean DO values were lowest at S1 and highest at S3 across seasons (Table 1; Figure 1). Organic and nutrient indicators (BOD_5, COD, NO_3–N, PO_4–P), along with EC, turbidity, and TDS, generally showed higher values at S1 than at S3 (Table 2), consistent with a site-wise enrichment gradient.

Table 1. Core physico-chemical parameters across Kapra Lake sites and seasons (mean ± SD; n = 3 replicates per site–season)

Site	Season	Temp_C	pH	DO_mgL	EC_uScm	Turbidity_NTU	TDS_mgL
S1	Pre-monsoon	29.60 ± 1.16	7.41 ± 0.03	3.64 ± 0.13	1545.55 ± 167.31	47.99 ± 4.72	1012.86 ± 25.25
S1	Monsoon	29.18 ± 0.82	7.53 ± 0.17	4.13 ± 0.16	1340.09 ± 75.23	42.50 ± 8.36	842.26 ± 84.46
S1	Post-monsoon/Winter	21.87 ± 0.52	7.54 ± 0.13	3.85 ± 0.58	1500.51 ± 129.49	43.27 ± 10.30	1006.91 ± 71.74
S2	Pre-monsoon	27.71 ± 1.26	7.58 ± 0.11	4.55 ± 0.17	1260.00 ± 158.79	33.51 ± 0.75	751.05 ± 78.74
S2	Monsoon	28.79 ± 1.47	7.57 ± 0.17	4.96 ± 0.72	1055.19 ± 90.88	28.10 ± 4.75	785.56 ± 52.90
S2	Post-monsoon/Winter	21.35 ± 0.82	7.57 ± 0.12	4.94 ± 0.42	1155.58 ± 57.75	35.37 ± 2.35	744.14 ± 59.83
S3	Pre-monsoon	29.21 ± 0.67	7.65 ± 0.14	5.63 ± 0.49	943.72 ± 107.76	18.64 ± 4.83	579.04 ± 65.58
S3	Monsoon	29.86 ± 1.83	7.60 ± 0.23	6.08 ± 0.21	815.36 ± 102.27	20.84 ± 8.80	588.30 ± 17.63
S3	Post-monsoon/Winter	20.81 ± 0.29	7.66 ± 0.09	5.60 ± 1.24	932.71 ± 102.82	14.21 ± 3.95	503.84 ± 36.74

Table 2. Organic and nutrient indicators across Kapra Lake sites and seasons (mean ± SD; n = 3 replicates per site–season)

Site	Season	BOD5_mgL	COD_mgL	NO3N_mgL	PO4P_mgL
S1	Pre-monsoon	12.77 ± 1.85	117.86 ± 2.46	4.07 ± 0.08	0.71 ± 0.08
S1	Monsoon	9.81 ± 0.64	85.21 ± 15.11	3.27 ± 0.34	0.55 ± 0.11
S1	Post-monsoon/Winter	12.27 ± 0.64	106.94 ± 6.51	3.91 ± 0.16	0.61 ± 0.10
S2	Pre-monsoon	9.46 ± 1.23	72.56 ± 8.02	2.94 ± 0.21	0.47 ± 0.04
S2	Monsoon	5.75 ± 0.27	53.39 ± 5.20	2.38 ± 0.13	0.32 ± 0.06
S2	Post-monsoon/Winter	9.02 ± 1.11	82.05 ± 7.28	2.35 ± 0.19	0.49 ± 0.14
S3	Pre-monsoon	5.34 ± 0.96	48.48 ± 2.96	1.61 ± 0.24	0.28 ± 0.24
S3	Monsoon	3.38 ± 1.26	35.61 ± 6.43	1.14 ± 0.04	0.24 ± 0.03
S3	Post-monsoon/Winter	5.94 ± 1.35	34.35 ± 4.34	1.73 ± 0.39	0.26 ± 0.03

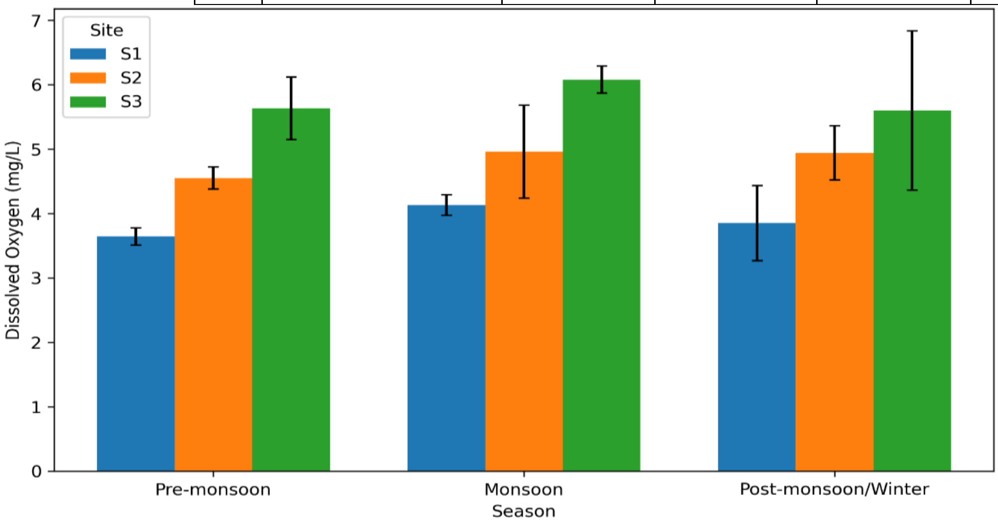

Figure 1. Location of Kapra Lake (Sainikpuri, Hyderabad, Telangana, India) showing lake boundary and analytically defined zones (S1–S3) used to represent an inflow–disturbance gradient (WGS84; scale bar and north arrow included).

4.2 Aquatic faunal diversity patterns

Macroinvertebrate diversity followed the same spatial pattern. Shannon diversity (H′) showed a significant site effect (two-way ANOVA; Table 3A), with Tukey HSD indicating higher H′ at S2 and S3 compared with S1 ($p < 0.01$), while the S2–S3 difference was not significant ($p > 0.05$; Table 3B). Across seasons, H′ was lowest at S1 and highest at S3 (Table 4; Figure 2). Richness and evenness displayed similar trends, with lower evenness at S1 indicating increased dominance under higher-stress conditions (Table 4).

Table 3. Two-way ANOVA results for dissolved oxygen and Shannon diversity, with Tukey HSD post-hoc comparisons between sites

Table 3A. Two-way ANOVA (Site × Season) (i) Dissolved oxygen (DO)

Source	SS	df	F	p
C(Site)	16.169	2	24.849	0.000007
C(Season)	0.902	2	1.386	0.275493
C(Site):C(Season)	0.200	4	0.154	0.958852
Residual	5.856	18	—	—

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(ii) Shannon diversity (H′)

Source	SS	df	F	p
C(Site)	0.499	2	19.210	0.000034
C(Season)	0.040	2	1.524	0.244602
C(Site):C(Season)	0.088	4	1.701	0.193696
Residual	0.234	18	—	—

Table 3B. Tukey HSD (Site-wise comparisons, pooled across seasons)

(i) DO (mg/L)

group1	group2	meandiff	p-adj	lower	upper	reject
S1	S2	0.9432	0.0030	0.3093	1.5770	True
S1	S3	1.8956	0.0000	1.2617	2.5294	True
S2	S3	0.9524	0.0027	0.3185	1.5863	True

(ii) Shannon diversity (H′)

group1	group2	meandiff	p-adj	lower	upper	reject
S1	S2	0.1982	0.0061	0.0536	0.3427	True
S1	S3	0.3308	0.0000	0.1863	0.4753	True
S2	S3	0.1326	0.0762	-0.0119	0.2772	False

Table 4. Macroinvertebrate diversity indices across sites and seasons (mean ± SD; n = 3 replicates per site–season)

Site	Season	Richness_S	Shannon_H	Simpson_1D	Evenness_J	N_total
S1	Pre-monsoon	7.33 ± 0.58	1.69 ± 0.11	0.79 ± 0.02	0.85 ± 0.06	184.67 ± 14.36
S1	Monsoon	7.00 ± 1.00	1.65 ± 0.14	0.78 ± 0.03	0.85 ± 0.02	142.33 ± 17.04
S1	Post-monsoon/Winter	6.67 ± 0.58	1.43 ± 0.14	0.69 ± 0.06	0.76 ± 0.05	160.33 ± 27.39
S2	Pre-monsoon	8.00 ± 0.00	1.81 ± 0.06	0.80 ± 0.01	0.87 ± 0.03	183.33 ± 20.03
S2	Monsoon	8.00 ± 0.00	1.80 ± 0.13	0.80 ± 0.05	0.86 ± 0.06	161.00 ± 7.00
S2	Post-monsoon/Winter	8.00 ± 0.00	1.76 ± 0.17	0.79 ± 0.06	0.85 ± 0.08	166.67 ± 6.43
S3	Pre-monsoon	8.00 ± 0.00	1.89 ± 0.09	0.83 ± 0.02	0.91 ± 0.04	179.33 ± 15.57
S3	Monsoon	8.00 ± 0.00	1.94 ± 0.05	0.84 ± 0.01	0.93 ± 0.03	144.67 ± 13.58
S3	Post-monsoon/Winter	8.00 ± 0.00	1.95 ± 0.08	0.84 ± 0.02	0.94 ± 0.04	166.33 ± 40.80

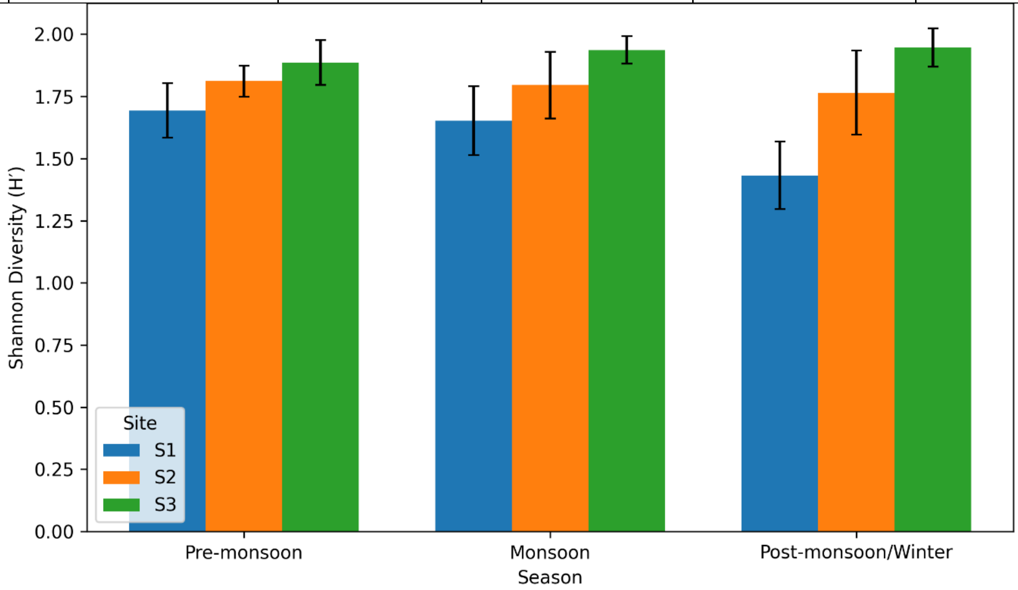

Figure 2. Shannon diversity index (H′) across Kapra Lake sites (S1–S3) and seasons (mean ± SD; n = 3)

4.3 Relationships between water quality and faunal diversity

Correlation analysis supported strong linkages between water quality and faunal diversity (Table 5). Shannon diversity was positively associated with DO and negatively associated with enrichment/organic loading indicators, including BOD_5, COD, NO_3–N, and PO_4–P (Table 5; Figure 3). Multiple regression further identified oxygen and enrichment/organic variables as predictors of Shannon diversity (Table 6). Variance inflation factors (VIF) for continuous predictors were within acceptable ranges, indicating no prohibitive multicollinearity (Table 6).

Table 5. Pearson correlation matrix between water-quality parameters and macroinvertebrate diversity indices

WaterVariable	Richness_S	Shannon_H	Simpson_1D	Evenness_J
Temp_C	0.114	0.151	0.190	0.150
pH	0.361	0.413	0.396	0.382
DO_mgL	0.684	0.549	0.512	0.470
EC_uScm	-0.680	-0.671	-0.693	-0.666
Turbidity_NTU	-0.610	-0.604	-0.611	-0.609
TDS_mgL	-0.630	-0.642	-0.675	-0.640
BOD5_mgL	-0.699	-0.719	-0.731	-0.662
COD_mgL	-0.701	-0.699	-0.697	-0.646
NO3N_mgL	-0.709	-0.700	-0.701	-0.641
PO4P_mgL	-0.577	-0.612	-0.664	-0.550

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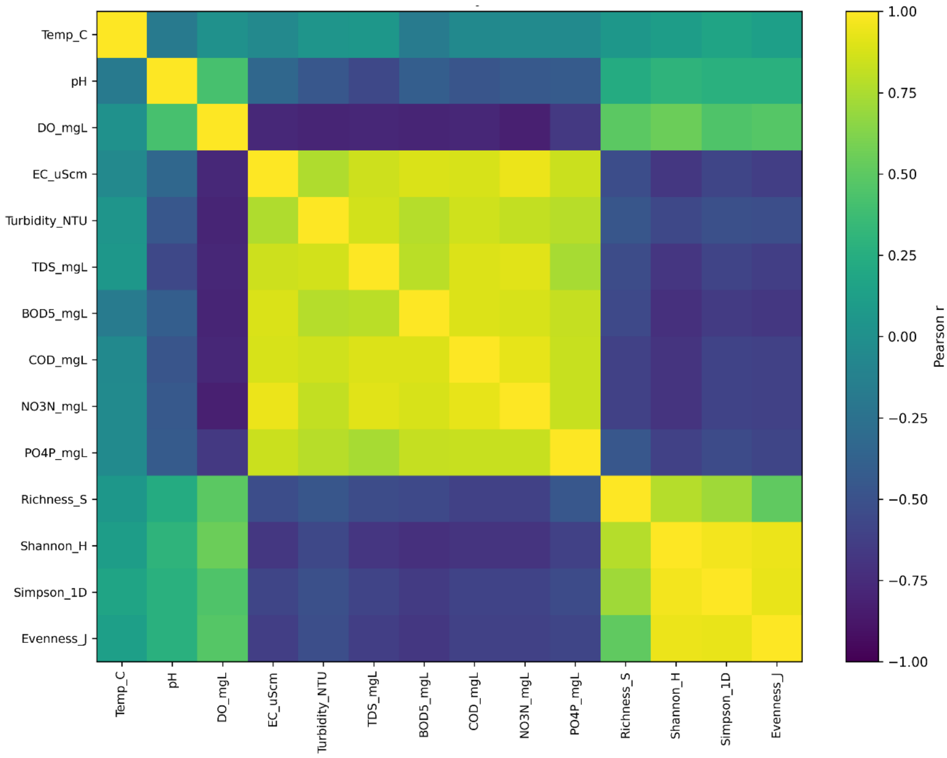

Figure 3. Correlation heatmap of water-quality parameters and macroinvertebrate diversity indices (Pearson r)

Table 6. Regression model summary for Shannon diversity (H′): coefficients, standard errors, p-values, model fit statistics, and VIF diagnostics

Table 6A. Multiple regression (Shannon_H as outcome)

Term	Coef	SE	t	p	CI_low	CI_high
Intercept	1.7697	0.6837	2.588	0.017525	0.3608	3.1786
C(Site)[T.S2]	0.2277	0.2176	1.046	0.307191	-0.2292	0.6845
C(Site)[T.S3]	0.5692	0.2227	2.555	0.019056	0.1014	1.0369
C(Season)[T.Monsoon]	0.1446	0.2121	0.682	0.502638	-0.3010	0.5903
C(Season)[T.Post-monsoon/Winter]	0.0286	0.2170	0.132	0.896163	-0.4263	0.4835
DO_mgL	0.0642	0.0543	1.183	0.249758	-0.0498	0.1781
BOD5_mgL	-0.0288	0.0195	-1.479	0.154882	-0.0700	0.0123
NO3N_mgL	-0.0471	0.0453	-1.039	0.310222	-0.1421	0.0479
PO4P_mgL	-0.0409	0.0750	-0.545	0.591575	-0.1985	0.1167

Table 6B. Model fit statistics

Metric	Value
N	27
R_squared	0.8384
Adj_R_squared	0.7567
AIC	-7.1489
BIC	4.1268

Table 6C. VIF (continuous predictors)

Variable	VIF
DO_mgL	3.351
BOD5_mgL	5.654
NO3N_mgL	6.559
PO4P_mgL	3.785

4.4 Multivariate structure of water-quality variation (PCA)

PCA of water-quality parameters based on site–season mean values revealed a dominant gradient separating observations primarily along PC1 (Figure 4). Loadings indicated that PC1 represented an enrichment/organic loading gradient (higher EC, turbidity/TDS, nutrients and organic load) in opposition to DO (Figure 4; Table 7). This multivariate structure aligned with the observed spatial pattern in macroinvertebrate diversity (Table 6).

Table 7. PCA loadings for water-quality variables (PC1 and PC2) and explained variance (site–season means)

Table 7A. PCA loadings

Variable	PC1	PC2
Temp_C	-0.0011	-0.9247
pH	-0.3078	0.2856
DO_mgL	-0.3376	-0.0251
EC_uScm	0.3403	0.0644
Turbidity_NTU	0.3349	-0.0854
TDS_mgL	0.3401	-0.1184
BOD5_mgL	0.3376	-0.0552
COD_mgL	0.3463	0.0019
NO3N_mgL	0.3390	0.1562
PO4P_mgL	0.3365	0.0302

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Table 7B. Explained variance

PC	ExplainedVarianceRatio
PC1	0.8460
PC2	0.1145

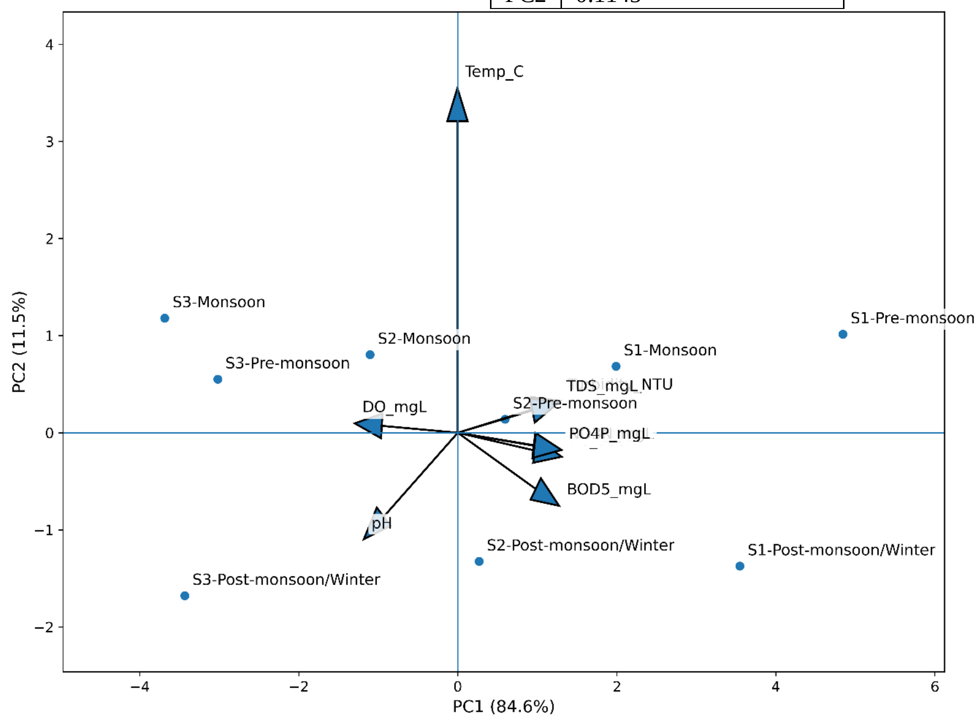

Figure 4. PCA biplot of water-quality parameters based on site–season means: scores and variable loadings (PC1 vs PC2)

5. DISCUSSION

The present findings indicate that spatial gradients in water quality are the principal drivers of aquatic faunal diversity in Kapra Lake, with dissolved oxygen and enrichment-related parameters exerting the strongest control on community structure. The consistent increase in dissolved oxygen from the inlet/high-exposure zone (S1) to the outlet/low-exposure zone (S3), together with higher macroinvertebrate diversity under less impacted conditions, supports H1 and underscores oxygen availability as a key ecological constraint in urban freshwater systems [12,13]. Lower oxygen conditions in high-exposure zones are most plausibly linked to elevated organic loading, which intensifies microbial respiration and selectively favors pollution-tolerant taxa, resulting in reduced richness and evenness—an ecological response widely documented in eutrophic lakes and urban water bodies [14,15].

The strong negative associations between diversity indices and organic and nutrient indicators (BOD_5, COD, nitrate, and phosphate) further support H2 and are consistent with enrichment-driven habitat simplification and dominance patterns reported across a range of urban and peri-urban lake systems [16–18]. Elevated organic matter and nutrients can increase oxygen demand directly and indirectly through enhanced primary production and decomposition, destabilizing oxygen regimes and reducing habitat suitability for sensitive taxa. These mechanisms are consistent with the observed relationships between DO, enrichment indicators, and macroinvertebrate diversity in the present analysis.

Multivariate analysis reinforced these relationships by revealing a dominant physicochemical gradient opposing enrichment and dissolved oxygen, which effectively structured zone–season groupings and aligned with observed diversity patterns. This supports H3 and demonstrates the utility of gradient-based ordination approaches for interpreting complex water-quality datasets and linking them to biological responses [19,20]. The comparatively weaker seasonal effects suggest that persistent, zone-specific catchment pressures—such as proximity to inflow pathways and localized wastewater influence—can override short-term seasonal dilution or concentration processes in Kapra Lake, a pattern increasingly recognized in highly urbanized watersheds [21,22]. Overall, these findings highlight the value of integrated physicochemical and biological assessments for diagnosing ecological impairment and indicate that management strategies targeting organic and nutrient inputs in high-exposure zones are likely to yield the greatest improvements in oxygen regimes and aquatic faunal diversity in Kapra Lake and similar urban freshwater ecosystems [23–25].

6. CONCLUSION

This study demonstrates that spatial gradients in water quality play a decisive role in shaping aquatic faunal diversity in Kapra Lake, with dissolved oxygen and enrichment-related parameters emerging as the primary ecological drivers. Zones characterized by higher organic and nutrient loading exhibited reduced dissolved oxygen, lower macroinvertebrate diversity, and greater dominance by tolerant taxa, whereas less impacted zones supported higher diversity and more balanced community structure. Multivariate analysis confirmed the presence of a dominant enrichment–oxygen gradient that structured zone–season variability and aligned closely with observed biological patterns. Collectively, these findings highlight the importance of integrating physicochemical variables with biological indicators for diagnosing ecological impairment in urban freshwater lakes. The results further suggest that management interventions prioritizing the reduction of organic and nutrient inputs in high-exposure zones are likely to yield the most effective improvements in oxygen regimes and aquatic faunal diversity in Kapra Lake and comparable urban lake systems.

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