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LINKING NUTRIENT ENRICHMENT AND OXYGEN DYNAMICS TO ECOLOGICAL WATER QUALITY IN FRESHWATER SYSTEMS

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Abstract
The integrated assessment is important to detect emerging changes in the ecological condition of freshwaters, which is dependent on interacting nutrient, biological, physicochemical and oxygen-related processes. This study aimed to characterize freshwater water quality and examine temporal and statistical relationships among total phosphorus, chlorophyll-a, turbidity, dissolved oxygen, and supporting physicochemical indicators. The data from 23 monitoring observations between October 2022 and April 2023 were analyzed quantitatively to examine the changes over time. Total phosphorus was available for 12 observations. The following descriptive statistics, Shapiro–Wilk testing, Spearman rank correlations, temporal trend analysis and HC3-robust univariable regression models were used. Chlorophyll-a and turbidity increased significantly over time (ρ = 0.859 and 0.823; both $p < 0.001$), whereas dissolved oxygen declined ($\rho = -0.622$, $p = 0.002$). Chlorophyll-a was strongly associated with turbidity ($\rho = 0.856$, $p < 0.001$), while dissolved oxygen was inversely associated with chlorophyll-a ($\rho = -0.490$, $p = 0.018$) and turbidity ($\rho = -0.532$, $p = 0.009$). The turbidity accounted for 37.67% of the variation in DO, whereas chlorophyll-a accounted for 24.85%. There was no significant relationship found between total phosphorus and chlorophyll-a, dissolved oxygen, or BOD. The results suggest that ecological and oxygen indicators provided better temporal information than the available phosphorus measurements and should be routinely used in combination with phosphorus in freshwater water-quality assessments.

Keywords: *freshwater quality, nutrient enrichment, dissolved oxygen, chlorophyll-a, turbidity*

1. Introduction

In the pharmaceutical, Biodiversity, drinking-water resources, food production, recreation, and ecological processes that directly impact human wellbeing are provided by freshwater ecosystems. Water quality is important for their ecological integrity, as shifts in chemical and physical water conditions may impact habitat suitability, biological communities and ecosystem function. The importance of protecting aquatic biodiversity is increasingly linked to ensuring adequate water-quality conditions (Lynch et al., 2023). The factors responsible for the quality of fresh water are interdependent, and their impact differs depending on environmental and seasonal conditions (Klimaszyk & Gołdyn, 2020). Therefore, measures of water quality must include measures of both environmental and ecological conditions. Physicochemical parameters may give an idea about the condition of the water column, while biological parameters may give an idea about the response of the ecosystem, which may not be subject to individual chemical parameters (Vasistha & Ganguly, 2020). The enrichment of nutrients is a special concern, since nutrient excess may cause a change in primary productivity and thus lead to a progressive change in the ecology. A trend toward increased nutrient load and its interactions with environmental variability can have long-term impacts on water quality and ecological dynamics, as seen in shallow lakes (Lin et al., 2021). Long-term nutrient pressure can also decrease the stress tolerance of aquatic ecosystems and make them more vulnerable to ecosystem degradation (Adams et al., 2020). Phosphorus is one of the largest contributors to nutrient enrichment in freshwaters. It is sourced from many sources, and loads can significantly rise with intensified use of catchments (Fink et al., 2018). Various land uses, such as agriculture, wastewater inputs, urban development, and others, can contribute to nutrient loading to surface waters, which can lead to eutrophication conditions (Álvarez et al., 2017). However, the ecological impacts of phosphorus enrichment are dependent on the interaction between nutrient availability and biological activity and on the physical and chemical environment. Therefore, managing phosphorus in combination with ecological and oxygen parameters can help to better represent the condition of freshwater resources.

Chlorophyll-a is a common pigment used to estimate phytoplankton biomass and is a useful tool for assessing the biological response in an aquatic environment. It can adjust its concentration in response to nutrient availability, but also may be influenced by suspended material and underwater light conditions. Phytoplankton chlorophyll-a parameters are known to change due to inorganic turbidity, which affects the physical space for photosynthesis (Nunes et al., 2022). Nutrient enrichment causes changes in algal biomass, productivity, and composition as well (McCormick et al., 2019), but the responses are influenced by the local ecological conditions. The nutrient-chlorophyll-a relationship is of special concern when considering eutrophication. Large-scale analyses have shown that both phosphorus and nitrogen are important driving factors for differences in chlorophyll-a, but in different proportions in lakes (Liang et al., 2020). A global evaluation also revealed a widespread correlation between TP and chl, and showed that there was significant variation in the strength of the relationship between TP and chl across different freshwater systems (Quinlan et al., 2021). The results suggest that the magnitude or timing of ecological response may not be well captured by the concentration of phosphorus. Dissolved oxygen is also a useful complement since it is a function of photosynthesis, respiration, decomposition, temperature and physical mixing. Thus, the changes in biological productivity/ organic matter processing can be related to the changes in the oxygen availability. The results of eutrophic shallow lakes show that, in the presence of interacting ecological and environmental controls, DO can vary considerably over time, and this information can be useful to assess changes in ecosystem conditions (Zhang et al., 2025). Biological oxygen demand (BOD) and chemical oxygen demand (COD) are other characteristics of oxygen-demanding material, and turbidity and chlorophyll-a are indicators of the suspended and biological portion of the water column. These parameters can be studied together to identify ecological–oxygen relationships that single parameters may not be able to detect.

There are existing data that support the connection between nutrient enrichment, phytoplankton productivity, turbidity, and oxygen conditions, which are often measured separately. Less focus has been placed on identifying direct impacts of phosphorus associations as compared to co-occurring changes in chlorophyll-a, turbidity, and dissolved oxygen in a specific freshwater monitoring period.

This is relevant since ecological responses can occur even though short-term nutrient measurements may not provide statistical relationships. A multi-dimensional analysis including nutrient concentrations, temporal ecological shifts, and oxygen levels must therefore be developed to describe the water-quality characteristics of freshwater environments without relying on the assumption that nutrient concentrations are a direct cause of observed ecological responses.

The objective of the study was to characterize the physicochemical, nutrient, ecological, and oxygen-related conditions in the monitored freshwater system, to look at temporal trends and correlations between total phosphorus, chlorophyll-a, turbidity, dissolved oxygen, and other indicators of supporting water quality, and to quantify individual relationships between chlorophyll-a and turbidity with dissolved oxygen. The purpose of these objectives was to help define the relationship between nutrient status and ecological water quality and oxygen over the monitoring period.

2. Methodology

2.1 Research Design

A quantitative, longitudinal design was used to evaluate nutrient enrichment, oxygen dynamics and ecological water-quality response over the course of the monitoring. The analysis was directed at temporal changes and statistical relationships of the water-quality indicators i.e., dissolved oxygen, total phosphorus, chlorophyll-a, turbidity and supporting physicochemical factors. The freshwater quality data were analyzed by descriptive, correlation, temporal trend and regression analysis to describe freshwater conditions, but with no attempt to derive cause-and-effect relationships.

2.2 Data Source

The freshwater monitoring data reported by Kulkarni and Khare (2024) for Khadakwasala Reservoir, Pune, India were used for water-quality observations. Records were repeated measurements taken from October 2022 to April 2023. The parameters available were physicochemical parameters, nutrient status, oxygen characteristics, and ecological water quality responses.

2.3 Data Preparation and Variables

Before analysis, the data were screened for inconsistencies in observations, dates, missing data, and data formats. The final data set consisted of 23 measurements of pH, temperature, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), chlorophyll-a and turbidity. There were 12 valid observations for total phosphorus. No imputation was made for missing phosphorus measurements, and analyses that included this parameter were carried out based on available cases. The sampling records were sorted chronologically prior to temporal analysis.

2.4 Descriptive and Distributional Analysis

Summary values such as the means, standard deviations, medians, quartiles, minima, and maxima for water-quality parameters were used. The Shapiro–Wilk test was performed to evaluate distributional assumptions. Several variables deviated from a normal distribution, and therefore, Spearman's rank-based techniques were chosen for association and temporal analyses. The chlorophyll-a, turbidity and DO data were normalized as z-scores to allow comparisons in graphical form of the temporal changes of the three variables on a common scale.

2.5 Correlation and Temporal Trend Analysis

Nutrient, ecological, oxygen-related and physicochemical indicators were correlated using Spearman's rank correlation coefficient (ρ). The temporal trends were determined by comparing each water quality parameter to the number of days since monitoring began. Available information was retained for total phosphorus as well as other parameters by using pairwise complete observations. The level of statistical significance was set as $p<0.05$, higher degrees of significance as $p<0.01$ and $p<0.001$.

2.6 Dissolved Oxygen Modelling

Separate univariable ordinary least-squares regression models were fitted with dissolved oxygen (DO) as the response variable and chlorophyll-a and turbidity as individual predictors. The high correlation between the two ecological predictors meant that separation of models was preferred. To support inference under the small sample size, HC3 provided robust standard errors. Model estimates were reported as regression coefficients, robust standard errors, 95% confidence intervals, p-values, R^2 and adjusted R^2. The model diagnostics examined were residual normality, heteroscedasticity and influential observations.

2.7 Statistical Analysis

All statistical tests were two-sided, and $p < 0.05$ was considered statistically significant. Observed measurements were analyzed without missing phosphorus values being imputed or excluding observations that were only on the basis of extreme measurements.

3. Results

3.1 Overall Water-Quality Characteristics

The monitoring data included 23 measurements of the main physicochemical and ecological parameters, while the total phosphorus data comprised 12 measurements. Table 1 shows that pH varied within a relatively narrow range of 6.90–8.30, with a mean of 7.678 ± 0.344. Water temperature averaged 23.226 ± 1.235 °C and varied from 21.20 to 25.50 °C. Dissolved oxygen (DO) concentrations ranged from 6.90 to 8.20 mg/L, with a mean of 7.539 ± 0.438 mg/L. BOD averaged 3.800 ± 0.556 mg/L, while COD showed greater dispersion, ranging from 14.20 to 24.20 mg/L and averaging 18.004 ± 3.180 mg/L. Chlorophyll-a concentrations ranged from 0.115 to 0.231 µg/L, whereas turbidity ranged from 1.66 to 3.97 NTU. Of the 12 measurements of phosphorus, the average concentration was 1.565 ± 0.515 mg/L.

Table 1. Descriptive statistics of water-quality parameters

Variable	n	Mean	SD	Median	Q1	Q3	Minimum	Maximum
pH	23	7.678	0.344	7.800	7.450	7.900	6.900	8.300
Temperature (°C)	23	23.226	1.235	23.300	22.200	24.200	21.200	25.500
Dissolved oxygen (mg/L)	23	7.539	0.438	7.700	7.150	7.800	6.900	8.200
BOD (mg/L)	23	3.800	0.556	3.700	3.450	4.050	3.100	5.600
COD (mg/L)	23	18.004	3.180	16.800	15.500	19.750	14.200	24.200
Chlorophyll-a (µg/L)	23	0.178	0.040	0.175	0.146	0.219	0.115	0.231
Turbidity (NTU)	23	2.489	0.801	1.960	1.850	3.055	1.660	3.970
Total phosphorus (mg/L)	12	1.565	0.515	1.545	1.156	1.871	1.002	2.500

Note: SD, standard deviation; Q1, first quartile; Q3, third quartile; BOD, biological oxygen demand; COD, chemical oxygen demand.

3.2 Temporal Dynamics of Ecological and Oxygen Indicators

There were clear transitional periods throughout the monitoring. Standardized temporal trends of chlorophyll-a, turbidity and DO are presented in Figure 1, enabling the variables to be directly compared, despite being measured on different scales. As indicated in Figure 1A, the chlorophyll-a concentration trend was toward increasingly more average concentrations in the early observations and to increasingly more above-average concentrations in the later observations, with DO trends mostly opposite. A similar increase is observed in standardized turbidity in February and later, with mostly subnormal DO throughout the monitoring period (Figure 1B).

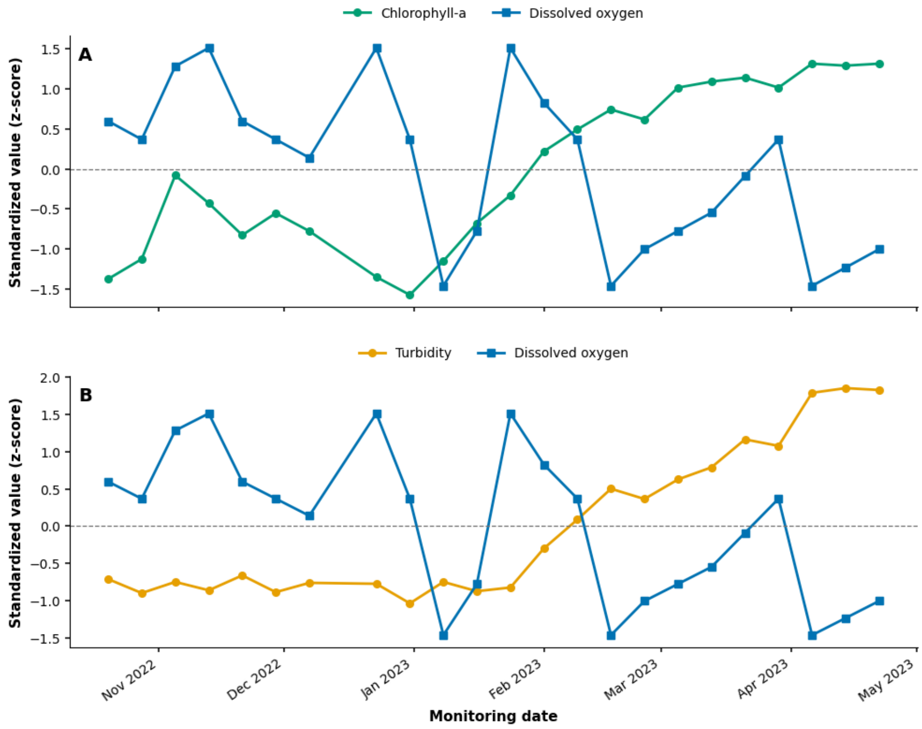

Figure 1. Temporal dynamics of ecological and oxygen-related water-quality indicators. (A) Standardized chlorophyll-a and dissolved oxygen across the monitoring period. (B) Standardized turbidity and dissolved oxygen across the monitoring period.

Rank-based trend analysis was used to support the observed temporal patterns. Table 2 shows that chlorophyll-a had a strong positive temporal trend ($\rho = 0.859$, $p < 0.001$), as did turbidity ($\rho = 0.823$, $p < 0.001$). In contrast, DO decreased significantly over time ($\rho = -0.622$, $p = 0.002$). COD also declined ($\rho = -0.533$, $p = 0.009$). No statistical trends in time for pH, temperature, BOD or total phosphorus were found.

Table 2. Temporal trends in water-quality indicators

Variable	n	Spearman's ρ	p-value	Significance	Direction
pH	23	−0.180	0.410	ns	Decreasing
Temperature	23	0.159	0.470	ns	Increasing
Dissolved oxygen	23	−0.622	0.002	**	Decreasing
BOD	23	−0.119	0.587	ns	Decreasing
COD	23	−0.533	0.009	**	Decreasing
Chlorophyll-a	23	0.859	<0.001	***	Increasing
Turbidity	23	0.823	<0.001	***	Increasing
Total phosphorus	12	−0.252	0.430	ns	Decreasing

**Note: ns, not significant; **p < 0.01; ***p < 0.001.*

3.3 Relationships Among Ecological Indicators and Dissolved Oxygen

There were significant associations between oxygen and each ecological indicator identified through pairwise analysis. The three main relationships between turbidity, chlorophyll-a and DO are presented in Figure 2. A strong positive monotonic correlation between turbidity and chlorophyll-a

(ρ = 0.856, $p < 0.001$, n = 23) was observed, as indicated in Figure 2A, with an increase in chlorophyll-a with increasing turbidity. Figure 2B illustrates an inverse relationship between turbidity and DO (ρ = −0.532, p = 0.009, n = 23) such that higher turbidity was associated with lower oxygen. A similar inverse correlation was found between chlorophyll-a and DO (ρ = −0.490, p = 0.018, n = 23), as shown in Figure 2C.

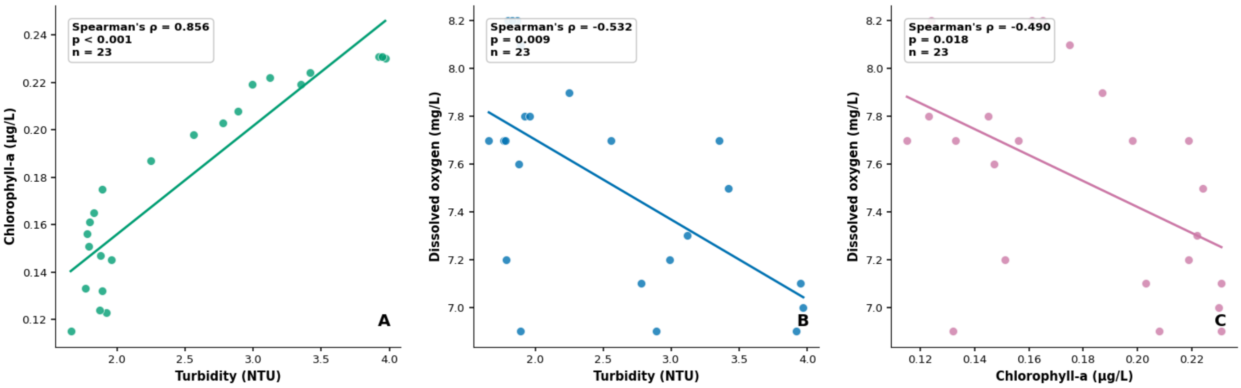

Figure 2. Relationships among ecological indicators and dissolved oxygen. (A) Turbidity versus chlorophyll-a. (B) Turbidity versus dissolved oxygen. (C) Chlorophyll-a versus dissolved oxygen.

As shown in Table 3, there was no significant relationship found between phosphorus and chlorophyll-a (ρ = −0.014, p = 0.966), DO (ρ = −0.128, p = 0.692) or BOD (ρ = −0.014, p = 0.965) within the 12 observations for which phosphorus was measured. DO was also not significantly related to BOD (ρ = 0.065, p = 0.769), COD (ρ = 0.391, p = 0.065), or temperature (ρ = −0.038, p = 0.862). The closest correlation of the variables selected was between chlorophyll-a and turbidity.

Table 3. Key Spearman correlations among water-quality indicators

Variable 1	Variable 2	n	Spearman's ρ	p-value	Significance
Chlorophyll-a	Total phosphorus	12	−0.014	0.966	ns
DO	Total phosphorus	12	−0.128	0.692	ns
BOD	Total phosphorus	12	−0.014	0.965	ns
DO	Chlorophyll-a	23	−0.490	0.018	*
BOD	Chlorophyll-a	23	−0.261	0.230	ns
DO	BOD	23	0.065	0.769	ns
DO	COD	23	0.391	0.065	ns
Temperature	DO	23	−0.038	0.862	ns
DO	Turbidity	23	−0.532	0.009	**
Chlorophyll-a	Turbidity	23	0.856	<0.001	***

**Note: DO, dissolved oxygen; BOD, biological oxygen demand; COD, chemical oxygen demand; ns, not significant; *p < 0.05; **p < 0.01; ***p < 0.001.*

3.4 Overall Correlation Structure of Water-Quality Indicators

The overall correlation pattern showed that the most prominent correlations were found between turbidity, chlorophyll-a, COD and DO. The strongest positive relationship was found between chlorophyll-a and turbidity (ρ = 0.86, $p < 0.001$) as illustrated in Fig. 3. DO was inversely correlated with both variables, and COD was negatively correlated with chlorophyll-a (ρ = −0.60, p = 0.003) and turbidity (ρ = −0.68, $p < 0.001$). The other correlations with pH, temperature, BOD and total phosphorus were relatively weak and statistically insignificant.

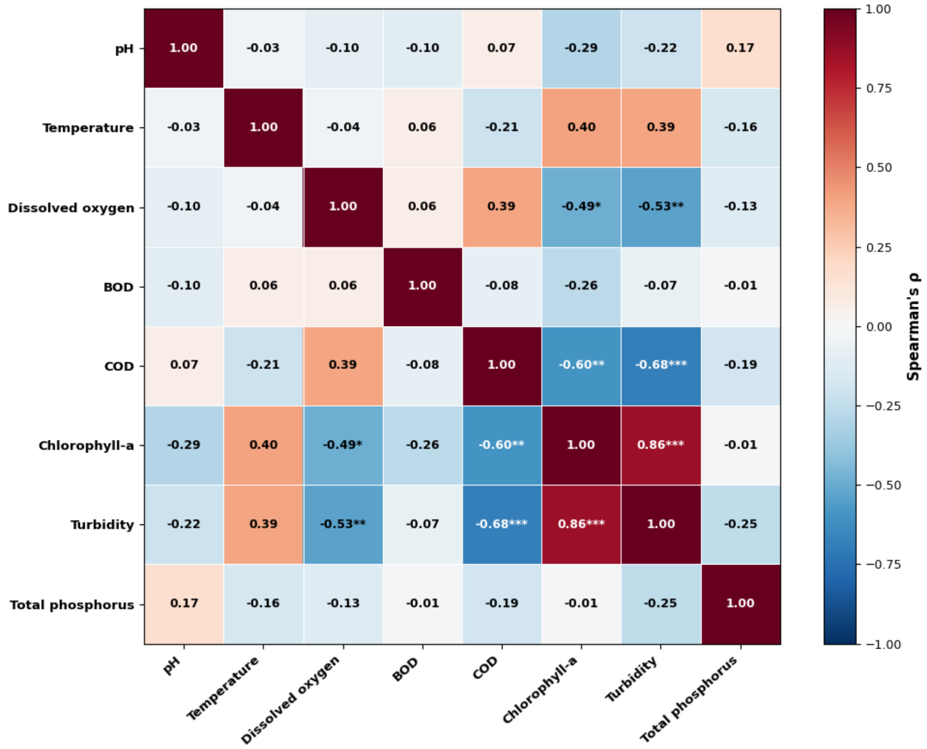

Figure 3. Spearman correlation matrix of physicochemical, ecological, nutrient, and oxygen-related water-quality indicators.

3.5 Regression-Based Assessment of Dissolved Oxygen

Since chlorophyll-a and turbidity were highly correlated, only univariable models of DO with chlorophyll-a or turbidity were used. Table 4 shows that chlorophyll-a was negatively associated with DO (B = −5.4303, robust SE = 1.9454, 95% CI: −9.2433 to −1.6173, p = 0.0052). The model with chlorophyll-a explained 24.85% of the variation observed in DO ($R^2 = 0.2485$). Turbidity also showed a significant negative association with DO (B = −0.3353, robust SE = 0.0803, 95% CI: −0.4927 to −0.1779, $p < 0.001$). Its model explained 37.67% of the variation in DO ($R^2 = 0.3767$), with an adjusted R^2 of 0.3470.

Table 4. Univariable regression models for dissolved oxygen

Predictor	n	B	Robust SE	p-value	95% CI Lower	95% CI Upper	R^2	Adjusted R^2
Chlorophyll-a	23	−5.4303	1.9454	0.0052	−9.2433	−1.6173	0.2485	0.2127
Turbidity	23	−0.3353	0.0803	<0.001	−0.4927	−0.1779	0.3767	0.3470

Note: B represents the unstandardized regression coefficient; SE, standard error; CI, confidence interval. HC3 robust standard errors were used.

4. Discussion

The water-quality profile showed that ecological data were not consistent with oxygen data throughout the monitoring time. The overall mean dissolved oxygen concentration was reasonably high, 7.539 mg/L, but the significant decrease in the mean (ρ = −0.622, p = 0.002) was an indication that the mean concentration alone was not representative of a directional change within the system. This drop paralleled significant increases in chlorophyll-a ($\rho = 0.859$, $p < 0.001$) and turbidity ($\rho = 0.823$, $p < 0.001$), which gave a consistent trend: increase in ecological activity or suspended material, decrease in oxygen availability. The correlations between these variables support this conclusion. The strongest association was between chlorophyll-a and turbidity ($\rho = 0.856$, $p < 0.001$), suggesting that an increase in chlorophyll-a was closely linked with an increase in turbidity in the water column. The relationship between both of these indicators and dissolved oxygen was negative, with correlations of −0.490 for chlorophyll-a and −0.532 for turbidity. Consistent evidence was obtained from the univariable models: chlorophyll-a accounted for 24.85% of the DO variance, while turbidity accounted for 37.67% of the DO variance. The turbidity's explanatory power was greater, indicating that variability in suspended material and related ecological conditions were of specific interest with respect to oxygen monitoring. There was no significant relationship between Total phosphorus and chlorophyll-a, DO or BOD. This finding should not be interpreted as evidence that phosphorus was ecologically unimportant. There were fewer phosphorus observations (12) than the other indicators (23), which limits the ability to determine contemporaneous nutrient relationships. Rather, the results indicate chlorophyll-a and turbidity better reflected the observed ecological–oxygen pattern than did the available information on phosphorus. COD also showed a marked decreasing trend over time, whereas BOD did not show a significant trend, indicating that the decreasing pattern of DO was not uniform with the increasing pattern of the conventional oxygen-demand indicators.

Chlorophyll-a increased significantly and is a good indicator of the biological productivity of freshwaters. The change in chlorophyll can indicate variations in the phytoplankton biomass and the overall ecosystem response, and is especially valuable for identifying shifts in freshwater ecosystems' state of affairs (Mineeva, 2022). The correlation between chlorophyll-a and turbidity also suggests that it was not only the optical or suspended-material conditions that changed, but also the biological conditions. Similar studies in freshwater have shown that physical processes can interact with biological responses, with changes in the water-column characteristics not representing biotic production alone (Frantzich et al., 2018). The co-occurrence of ecological changes and decreases in DO also aligns with the emergence of freshwater responses from multiple stressors. Ecosystem response to agricultural and nutrient-related pressures is dependent upon trophic status, community structure, and ecosystem biodiversity–function relationships that can affect the direction and magnitude of ecosystem water quality impacts (Polazzo et al., 2022). In addition, water-quality behaviour may also change under different hydrological and climatic conditions, indicating the need to assess water-quality behaviour in the context of its environment, not just by single measurements, but by temporal patterns (Shrestha & Wang, 2020).

It is important to note that there were no significant relationships with phosphorus. The cycling of phosphorus in shallow eutrophic systems is tightly linked with oxygen conditions, temperature, sediment processes and exchange of water between the water column, and only a single contemporaneous phosphorus measurement may not reflect the nutrient processes affecting ecological responses (Kirol et al., 2024). Water chemistry, chlorophyll, hydrological regimes, and nutrient enrichment can also have complex multiyear relationships without any synchronous response to these factors, as observed in the reservoir (HaRa et al., 2020). The non-significant relationship between phosphorus and chlorophyll supports careful interpretation of this relationship. The downward DO trend is consistent with data showing nutrient and ecological trends can affect the temporal variation of DO in water bodies. There is significant spatial and temporal heterogeneity in DO that has been linked to nutrient additions, especially where biological productivity is coupled with oxygen consumption (Coffin et al., 2021). The current trend therefore seems more logical based on an integrated ecological response rather than a single variable nutrient mechanism. This interpretation also reflects the perspective that water quality is the result of feedback between transport processes, local environmental conditions and ecological responses throughout interconnected aquatic systems (Teurlincx et al., 2019).

The results highlight the importance of using nutrient data in addition to ecological and water oxygen data to assess the quality of freshwater resources. Chlorophyll-a and turbidity data were more useful in determining the temporal change than the phosphorus data, and DO data had a

countertrend that could suggest changes in ecosystem functioning. Monitoring programs that rely primarily on periodic nutrient concentrations may then overlook changes that take place within the water column that are biologically expressed. A combination of phosphorus, chlorophyll-a, turbidity and DO will give a better indication of emerging ecological changes. The strong correlation between turbidity and chlorophyll-a further suggests that turbidity should not be considered a completely physical water quality parameter but should be used in conjunction with biological parameters.
A few limitations should be considered. The analysis was based on 23 monitoring observations spanning approximately six months, which restricted assessment of longer-term seasonal and interannual variability. Only 12 observations were available for total phosphorus, resulting in less statistical power for nutrient-related relations. The data set also did not include other nutrient fractions that would give a more comprehensive description of the nutrient availability. Future monitoring should be expanded to encompass full annual cycles, consistent sampling of phosphorus and include nitrogen and other pertinent nutrient measurements. The nutrient–chlorophyll–oxygen relationships, which are lagged, could also be examined, and the ecological and oxygen trends observed here would be examined in the context of different hydrological and seasonal conditions if observations were repeated over longer time periods.

5. Conclusion

The water quality pattern for the freshwater was clearly ecological–oxygen based throughout the monitoring period. Chlorophyll-a and turbidity levels showed significant increases, while dissolved oxygen showed a significant decrease, implying that changes in biology and suspended materials were closely related to oxygen variability. Chlorophyll-a and turbidity were heavily correlated and had significant negative relationships with dissolved oxygen. Regression analysis also showed that turbidity and chlorophyll-a were significant independent variables for DO, with turbidity showing more variance. Total phosphorus showed no significant correlation with chlorophyll-a, DO, or BOD concentrations, however, and the impacts on the water on the ecological changes were not directly attributed to the available phosphorus measurements. These results are consistent with the concept of an integrated freshwater monitoring program where nutrient data is used in conjunction with ecological and oxygen data, not alone. Regular monitoring of phosphorus, chlorophyll-a, turbidity and dissolved oxygen can help establish a more definitive understanding of emerging water-quality changes and ecological response as a function of time.

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