Aquatic Ecosystems and Environmental Frontiers, Volume 4, Issue 3, September 2026 *ISSN: 3049-186X*
DOI: https://doi.org/10.70102/AEEF/V4I3/AF260302

Nutrient Enrichment and Eutrophication Processes in Freshwater Ecosystems Implications for Aquatic Biodiversity Conservation

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Abstract: Nutrient loading caused by agriculture, effluent discharge, and urbanization is currently considered to be one of the major stressors affecting freshwater ecosystems through the process of eutrophication and subsequent loss of aquatic biodiversity. In the present study, the effects of nutrient pollution on water quality, degree of eutrophication, and aquatic biodiversity along a chain of a river and a reservoir affected by different types of land use, including an upstream reference site, agricultural zone, urban-effluent site, and a downstream reservoir, were investigated. Samples of nutrients, dissolved oxygen, water clarity, and algal biomass, as well as surveys of algae, aquatic invertebrates, fish, and aquatic macrophytes, were conducted at 12 sites during three seasons. Concentrations of nutrients increased dramatically from the reference site to the urban-effluent site, with total nitrogen and total phosphorus concentrations being six and ten times higher, respectively. The peak of algal biomass was observed prior to the monsoon season, and cyanobacteria dominated in the enriched areas. The number of invertebrate taxa decreased from 34 to 12; pollution-sensitive taxa disappeared almost completely from the urban-effluent site; and fish diversity was reduced by more than half. Phosphorus pollution and low dissolved oxygen explained more than 50% of the biodiversity reduction. The ecosystem status score was found to have fallen from 84 in the reference area to 27 in the most enriched area. These results indicate that nutrient enrichment functions as the main cause of decline in biodiversity by influencing algal domination, oxygen depletion, and habitat transformation. Nutrient reduction in the entire catchment area, wastewater treatment, and preservation of remaining reference habitats are key in protecting freshwater biodiversity.

Keywords: Nutrient Enrichment; Eutrophication; Freshwater Biodiversity; Algal Blooms; Dissolved Oxygen; Conservation Management.

(Submitted: May 12, 2026; Revised: June 22, 2026; Accepted: August 04, 2026; Published: September 30, 2026)

I. Introduction

Freshwater ecosystems account for an extremely small area of the Earth's surface, but they are home to a wide variety of organisms, ranging from most of the world's fish species to a huge array of invertebrates, amphibians, plants and algae. Rivers, lakes, reservoirs, ponds and wetlands provide humans with water for drinking and irrigation, fisheries, recreation, and culture. Furthermore, these ecosystems help regulate floods, recycle nutrients, and link land and oceans. Due to their limited extent, fragmentation, and close interaction with the adjacent terrestrial environments, these ecosystems are highly vulnerable to human activities in their catchment areas.

During the last few decades, the amounts of nitrogen and phosphorus supplied to freshwater have significantly risen. Nitrogen-rich agricultural fertilizers and manure are washed off by rainfall, livestock facilities discharge nutrient-rich organic waste, and soil erosion carries phosphorus bound to soil particles. Moreover, growing cities pollute waters by sewage effluents, inadequately treated wastewater, detergents, and stormwater runoff. Untreated or partially treated wastewater is discharged into rivers in many developing countries.

Eutrophication occurs when the supply of nutrients in a water body exceeds its ability to assimilate them. Algae and aquatic plants proliferate; the water turns green and murky, with no sunlight reaching the bottom plants. As large quantities of algal biomass decay, oxygen gets depleted in particularly deep and sluggish bodies of water. The repetitive process of growth and decomposition can transform a water body with clear

water and abundant plant life into one that is turbid and has an algal bloom, which is extremely hard to restore. Warming and decreased water flow make it worse.

The effects are not limited to water quality issues but affect entire biological communities. Lower levels of oxygen result in fish die-offs and depletion of sensitive organisms, as some blue-green algae that form blooms produce toxins hazardous to all kinds of living beings. Spawning and feeding grounds are lost with the death of submerged plants, leaving room only for the organisms that can withstand harsh conditions. Therefore, eutrophication is damaging not just to water quality but to biodiversity as well.

Management programs are mostly based on chemical water quality goals, while the consequences of nutrient enrichment from a biological perspective have not yet been studied enough. It is necessary to develop a biodiversity-oriented approach, which will include nutrient sources, eutrophication processes, and their impact on aquatic organisms, so that conservation measures could address the most important pressure factors. Also, such an approach would allow identifying valuable habitats that need protection and degraded habitats that should be restored.

The goal of this research is to evaluate the impact of nutrient enrichment and eutrophication on aquatic biodiversity in freshwater ecosystems and draw conservation conclusions. The objectives of the work are:

1. To determine the values of nutrients and water quality in freshwater zones with different land use conditions.
2. To evaluate the spatial and seasonal distribution of eutrophication in the study area.
3. To determine the changes in aquatic biodiversity, including algae, invertebrates, fish, and aquatic plants.
4. To analyze the relationship between nutrient enrichment and biodiversity loss.
5. To determine the major ecological pressures causing the degradation of freshwater ecosystems.
6. To suggest adequate management and restoration measures for freshwater biodiversity conservation.

Section 1 provides the background, research problem, aim, objectives, and significance of the study. Section 2 covers the literature review on nutrient enrichment, eutrophication, aquatic biodiversity, ecological impacts, conservation approaches, and the research gap. Section 3 discusses the research design, the study area, the sampling strategy, water-quality and biodiversity assessment, eutrophication evaluation, and data analysis methods. Section 4 presents results on nutrient levels, seasonal eutrophication patterns, biodiversity changes, ecological stressors, and ecosystem condition. Finally, discussion, major conclusions, and future directions for study are discussed in Section 5 and Section 6.

II. Literature Review

Nutrient Sources in Freshwater Ecosystems

Nitrogen and phosphorus enter freshwater systems through point sources like wastewater effluent discharge and industrial discharge, as well as diffuse sources, including cropland, grazing land, and urban surfaces. A study monitoring a large canal-river system in a highly agricultural area found that the levels of nitrogen and phosphorus and their ratio were a good representation of runoff from farmlands and settlements in the area, making the two nutrients excellent indicators for the occurrence of eutrophication (Savic et al., 2022). The study of algae blooms from almost 250,000 lakes from all around the world found that there was an increase in the number of times when algae blooming occurred within the decade between 2010 and 2020, especially in areas of Asia and Africa where agriculture is dependent on fertilizers (Hou et al., 2022). A global scientific alert pointed out that approximately one-third of the freshwater discharge in the world now passes through agricultural, industrial, and urban infrastructure (Albert et al., 2021; Maasri et al., 2022).

Eutrophication Processes and Water Quality Changes

Eutrophication modifies the physical and chemical features of water bodies, which in turn are becoming more and more influenced by climate change. Long-term observations at hundreds of temperate lakes revealed extensive oxygen depletion in surface waters and bottom layer, resulting from warming and decreased transparency of water bodies (Jane et al., 2021). The climate change-induced increase in temperature also modifies the thermal niches of the species living in water bodies, with changes in stratification favoring oxygen depletion in bottom layers (Kraemer et al., 2021). An extensive review of the influence of climate change on lakes found that warming and increased stratification as well as other climate-related phenomena lead to the exacerbation of problems associated with nutrients, such as algal blooms and oxygen depletion (Woolway et al., 2022). Analysis of urban lakes using modeling approaches revealed that climate-induced warming may trigger the re-eutrophication of lakes even many decades after the introduction of nutrient reduction measures (Kong et al., 2023).

Effects of Nutrient Enrichment on Aquatic Biodiversity

Nutrient enrichment significantly affects biological communities. Meta-analysis of over 100 experimental studies revealed that nitrogen and phosphorus enrichment usually decreased the abundance of submergent plants and sensitive invertebrates while tolerant species were favoured (Neijnens et al., 2024). An analysis of over 1,800 records on long-term invertebrate diversity in Europe's rivers revealed that during the 1990s and 2000s the biodiversity increased because of the improvement of wastewater treatment, but then the increase stopped after 2010, and communities downstream from croplands and urbanized areas fared the worst (Haase et al., 2023). A first global assessment of freshwater species diversity revealed that roughly one quarter of all decapod crustaceans, fishes and dragonflies are at risk of extinction, and pollution and agriculture are among the main causes (Sayer et al., 2025).

Ecological Consequences of Algal Blooms and Oxygen Depletion

Harmful algal blooms are one of the most visible impacts of eutrophication on ecosystems. According to an analysis carried out globally, there has been an increase in the number of harmful blooms in inland waterways after the 1980s, with details of reduced water clarity, lack of bottom vegetation, oxygen depletion and consequent death of fish (Feng et al., 2024). In a study on sediment records from lakes with different degrees of human interference, it was found that cyanobacteria occurred earlier in disturbed environments and the capability of producing toxins increased with rising temperatures (Erratt et al., 2023). All these leads to positive feedback loops that further degrade habitats.

Existing Approaches for Eutrophication Control and Biodiversity Conservation

Minimization of external nutrient inputs continues to form the basis of managing eutrophication, but the effect of climate change could offset the advantages of minimizing nutrients; therefore, stricter nutrient goals coupled with in-lake measures have been suggested (Meerhoff et al., 2022). The restoration of nutrient-impacted lakes may necessitate more measures like sediment remediation and vegetation restoration to avoid falling back into the same state (Kong et al., 2023). In terms of conservation, an international discussion on key research questions for the conservation and restoration of freshwater biodiversity has come up with important questions in the measurement of the effects of water quality improvement for organisms and their communities (Harper et al., 2021).

Research Gap

Previous research has provided clear evidence of increases in nutrient input, increases in algal blooms and decreases in the freshwater biodiversity on a regional and global scale. Nevertheless, very few studies consider the link between nutrient concentration, eutrophication level and different biological groups in a single ecosystem of rivers and reservoirs covering various land use and seasonal conditions. Moreover, the priority of each of the stressors, like nutrient enrichment, oxygen deficiency and algal dominance, has not

been compared in a systematic way to help with the conservation management. This study aims to fill this gap.

III. Methodology

Study Design

A comparative field design was employed in order to study the effects of nutrient stress on the freshwater system. This field design entailed water quality analysis, biodiversity sampling, and eutrophication monitoring at the same sites on the same days, thus enabling a comparison of the nutrient stress level with biological response. The general structure of the research can be seen in figure 1.

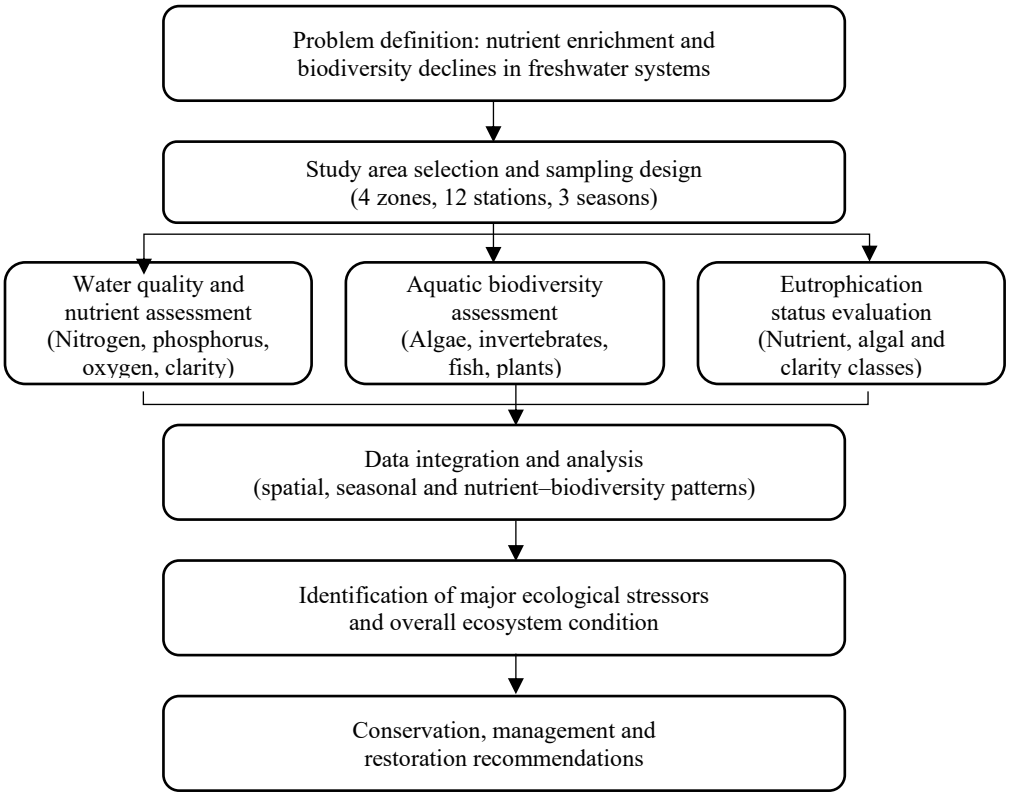


Figure 1: Study Framework for Freshwater Biodiversity Conservation

Study Area and Sampling Locations

The study site consisted of a river-reservoir system discharging from a mixed tropical catchment. Four zones were distinguished based on the type of land cover within each zone, namely, a reference zone upstream having forests and grasslands, an agricultural zone consisting of irrigated croplands, an urban-wastewater zone receiving sewage and stormwater runoff, and a downstream reservoir with slow moving water. Three stations were set up in each zone for a total of twelve stations shown in figure 2. Sampling was done during the pre-monsoon, monsoon, and post-monsoon seasons in order to account for variations in flow, temperature, and nutrient supply. The primary features of each zone are provided in table 1.

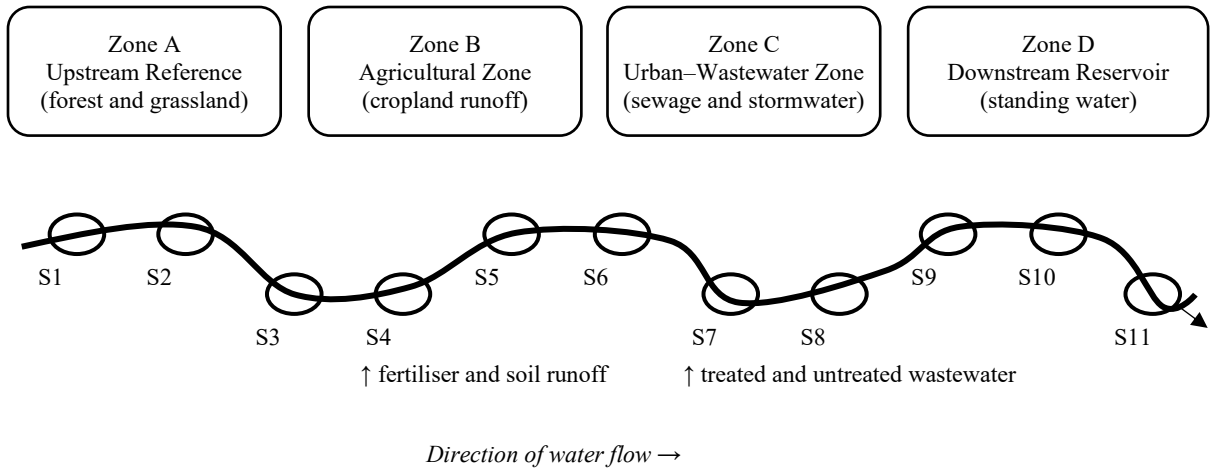


Figure 2: Sampling Zones and Stations

Table 1: Characteristics of the Sampling Zones

Zone	Stations	Dominant land use	Main nutrient source	Water body type
Upstream Reference	S1–S3	Forest and grassland	Natural background	Flowing river
Agricultural Zone	S4–S6	Irrigated cropland	Fertiliser and soil runoff	Flowing river
Urban–Wastewater Zone	S7–S9	Settlements and roads	Sewage and stormwater	Slow river
Downstream Reservoir	S10–S12	Mixed upstream inputs	Accumulated inflow loads	Standing water

Water Quality and Nutrient Assessment

Water samples were collected from each station, right below the water surface and at the bottom level in the reservoir. Temperature, dissolved oxygen, acidity, and conductivity were determined on-site with the help of portable field meters. Transparency of the water samples was measured using a standard transparency disc. Water samples were placed on ice and tested for total nitrogen, nitrate, ammonium, total phosphorus and dissolved phosphate using standard procedures for water analysis. The concentration of algal biomass was determined by measurement of the green chlorophyll-a pigment in the filtered water.

Aquatic Biodiversity Assessment

Biological samples were taken from four groups of organisms. Phytoplankton was collected using plankton nets and water samples and classified by genera into cyanobacteria, green algae, diatoms and others. Benthic invertebrates were collected using a hand net in fixed areas of mixed habitats and classified by families into pollution sensitive, moderate tolerant and pollution tolerant groups. Fish species were collected using cast and gill nets and equally effort at each station and identified to species. Aquatic vegetation was surveyed visually along transects.

Eutrophication Status Evaluation

The status of eutrophication in the system was determined based on comparison of the total phosphorus, total nitrogen, chlorophyll-a and transparency of water for each station with commonly accepted trophic classifications from oligotrophic (low nutrient content) to hypereutrophic (very high nutrient content). Station classification was done based on the predominant trophic class indicated by the indicators listed above. The frequency of occurrence of surface algal blooms and proportion of cyanobacteria in the algal community provided supplementary information on the status of the station.

Data Analysis

Results were presented in the form of averages for each zone and season. Statistical analysis was performed to compare differences between zones and seasons and correlation and trend fitting was used to estimate the dependence between nutrient concentrations and biological indicators. The contribution of each stressor to the decline in biodiversity was estimated using the relative explanatory power of each stressor in all the stations and seasons considered. An index of ecosystem status between 0 and 100 based on equal weighting of the indicators of water quality, eutrophication and biodiversity was generated.

IV. Results and Analysis

Nutrient Levels and Water Quality Characteristics

There was a significant difference in the water quality along the enrichment gradient as seen in table 2. There was an increase in total nitrogen content from 0.62 mg/L in the reference area to 3.94 mg/L in the urban-wastewater area. Total phosphorus content increased from 0.03 mg/L to 0.29 mg/L. The reservoir had high levels of these substances, which came from the upstream region. Dissolved oxygen decreased from 7.8 mg/L in the reference area to 3.4 mg/L in the urban-wastewater area. Bottom water in the reservoir had 2.1 mg/L dissolved oxygen shown in figure 3.

Table 2: Mean Water Quality Characteristics By Zone (Average of All Stations and Seasons)

Parameter	Upstream Reference	Agricultural Zone	Urban–Wastewater Zone	Downstream Reservoir
Total nitrogen (mg/L)	0.62	2.85	3.94	2.31
Nitrate (mg/L)	0.38	1.92	1.74	1.36
Ammonium (mg/L)	0.04	0.21	0.96	0.33
Total phosphorus (mg/L)	0.03	0.18	0.29	0.14
Dissolved phosphate (mg/L)	0.01	0.09	0.17	0.06
Dissolved oxygen (mg/L)	7.8	5.6	3.4	4.9 (bottom 2.1)
Chlorophyll-a (µg/L)	3.5	24.8	38.1	33.3
Water clarity (m)	1.9	0.8	0.45	0.6
Trophic status	Oligo–mesotrophic	Eutrophic	Hypereutrophic	Eutrophic

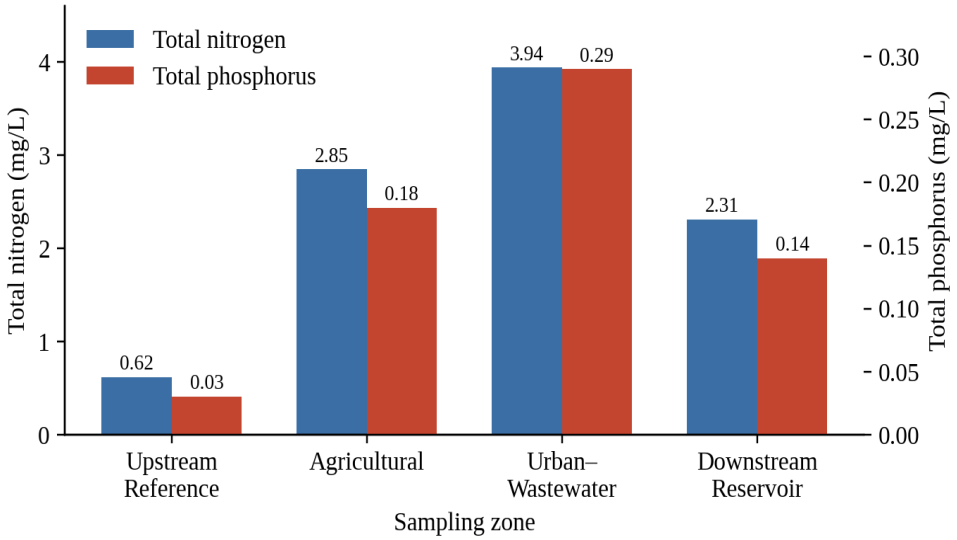


Figure 3: Mean Total Nitrogen and Total Phosphorus Concentrations Across Sampling Zones

Spatial and Seasonal Variation in Eutrophication

Algal biomass, as represented by chlorophyll-a concentration, showed both a spatial and temporal variation shown in figure 4. In all enriched regions, the maximum algal biomass was observed during pre-monsoon season, which had warm water temperature, low flow, and high nutrient concentrations. Nutrient dilution due to monsoon flows reduced algal biomass by about 40 to 50%, but algal biomass rapidly increased again after the monsoon season. In the reference region, the minimum algal biomass was observed for all seasons. Surface blooming could be observed at eight out of nine enriched sites during pre-monsoon season.

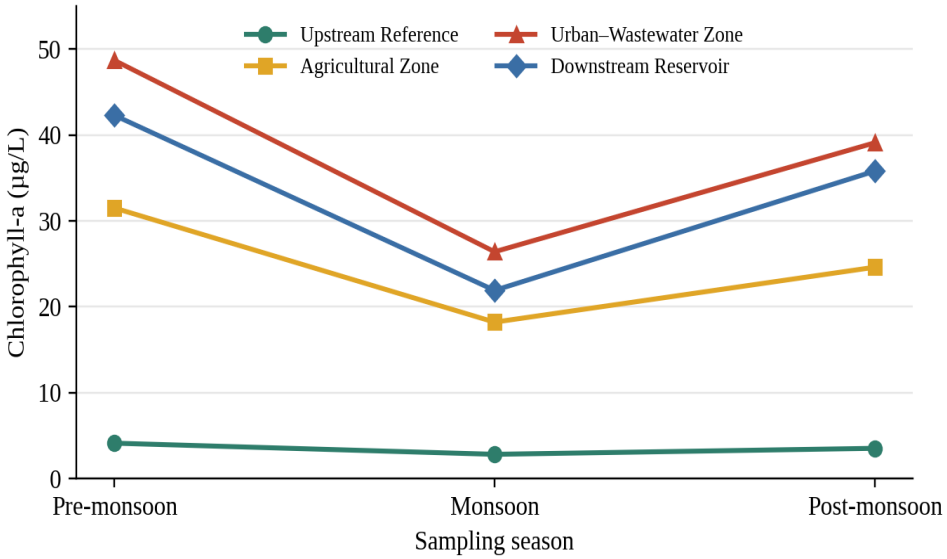


Figure 4: Seasonal Variation In Chlorophyll-a Across The Four Sampling Zones

Relationship Between Nutrient Enrichment and Biodiversity

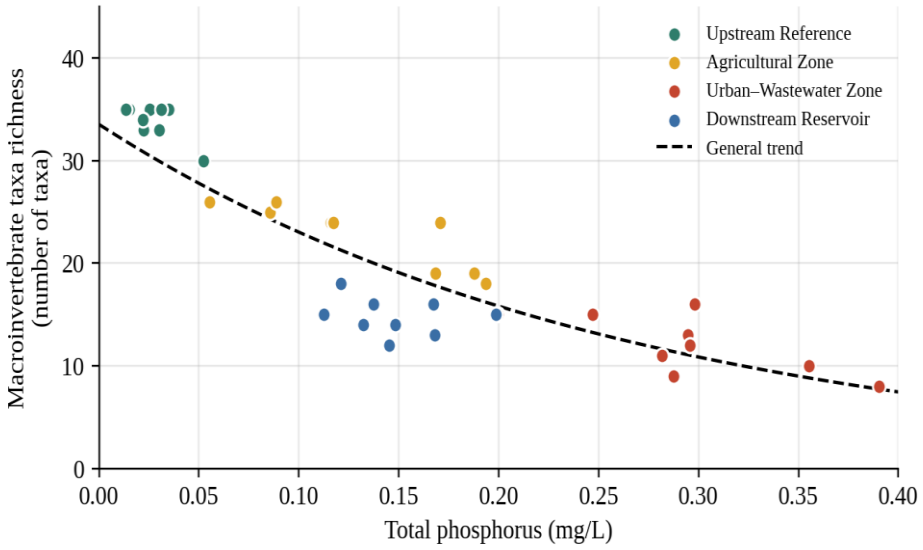


Figure 5: Relationship Between Total Phosphorus and Macroinvertebrate Taxa Richness Across All Stations and Seasons

There was a significant negative correlation between phosphorus and richness for the 36 station-season measurements figure 5. There was a sharp decrease in richness at low and intermediate phosphorus values, followed by a leveling off at high phosphorus values, indicating that all sensitive species disappear early during the enrichment process. The same was true for the correlations between nitrogen and richness, and chlorophyll-a and fish species.

Changes in Aquatic Biodiversity

There was a clear reduction in the richness of all biological groups with increased enrichment. The richness of invertebrates was reduced from an average of 34 taxa in the reference zone to 21 in the agricultural zone, 16 in the reservoir and 12 in the urban-wastewater zone. There was a reduction in the number of fish species from 22 to 15, 12 and 8 respectively, and the sensitive native fish species were replaced by a few tolerant fish species. Cyanobacteria constituted 8% of the algae community in the reference zone but 61% in the urban-wastewater zone and 54% in the reservoir. Cover of submerged vegetation declined from about 45%in the reference stations to below 5% in the highly enriched stations, where floating plants such as water hyacinth dominated. The composition of communities changed dramatically: pollution-tolerant invertebrates constituted 52% of the community in the reference stations but only 7 percentage in the urban-wastewater zone, while there was an increase in tolerance from 15 to 65% figure 6.

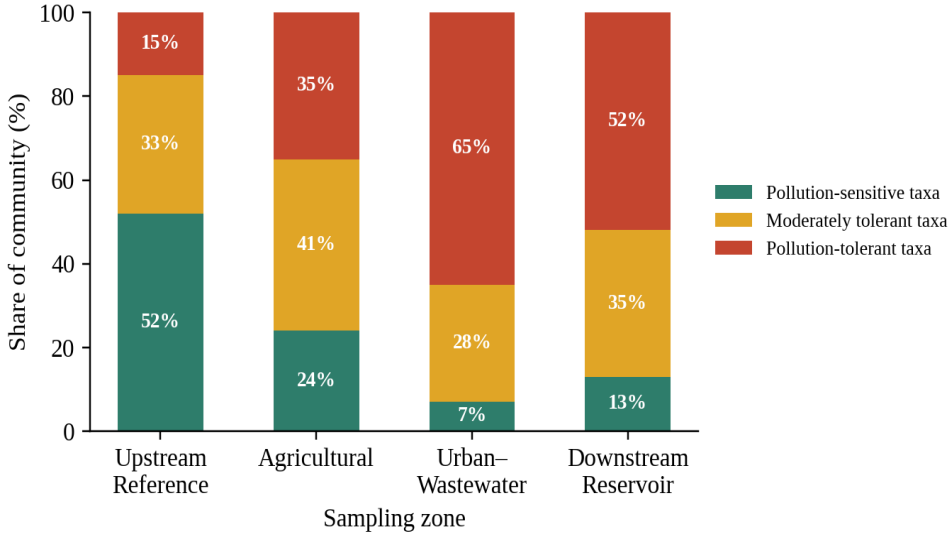


Figure 6: Composition of Invertebrate Communities by Pollution Tolerance in Each Sampling Zone

Identification of Major Ecological Stressors

Phosphorus enrichment became the most significant stressor contributing 31%to the biodiversity loss, followed by low dissolved oxygen 22%and nitrogen enrichment 17 percentage. Figure 7: Algal bloom dominance made up 14%of the cause, reduced water clarity 9 %, and physical habitat alteration 7 %. Altogether, the nutrient stressors and their effects contributed more than 90%of the overall decline, thus supporting the statement that eutrophication is the main pressure in the system.

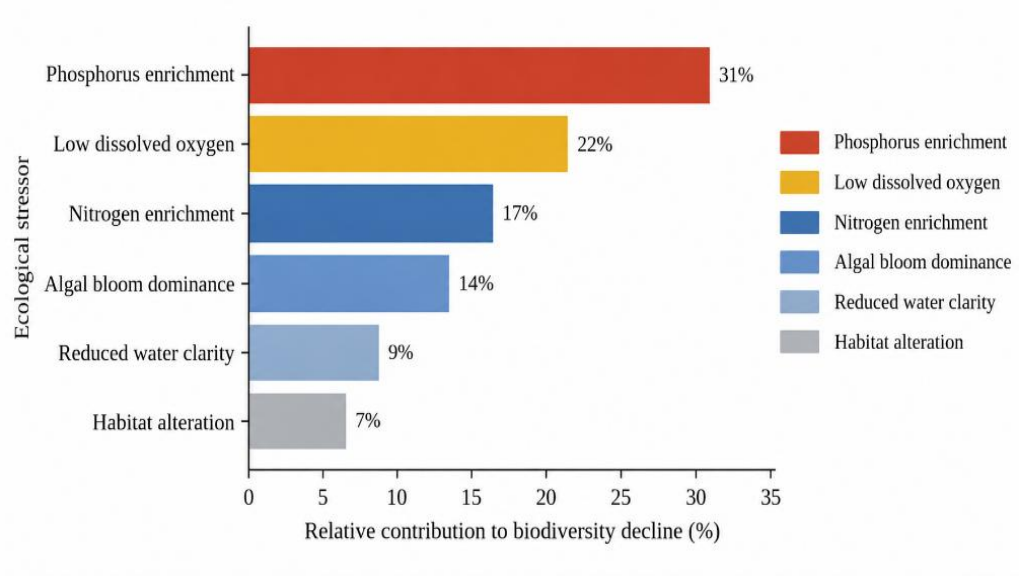


Figure 7: Relative Contribution of Major Ecological Stressors to Biodiversity Decline

Overall Freshwater Ecosystem Condition

The ecosystem condition was assessed based on the combined effect of nutrients, eutrophication, and biodiversity loss. Figure 8: The reference zone had an ecosystem condition score of 84, which indicated good condition. The agricultural zone got 52 (moderate) score, the reservoir got 41 (poor), and the urban–wastewater zone 27 (very poor). The condition score was directly related to the dissolved oxygen level, and all zones having mean oxygen concentration below the stress value of 5 mg/L were classified as poor or very poor.

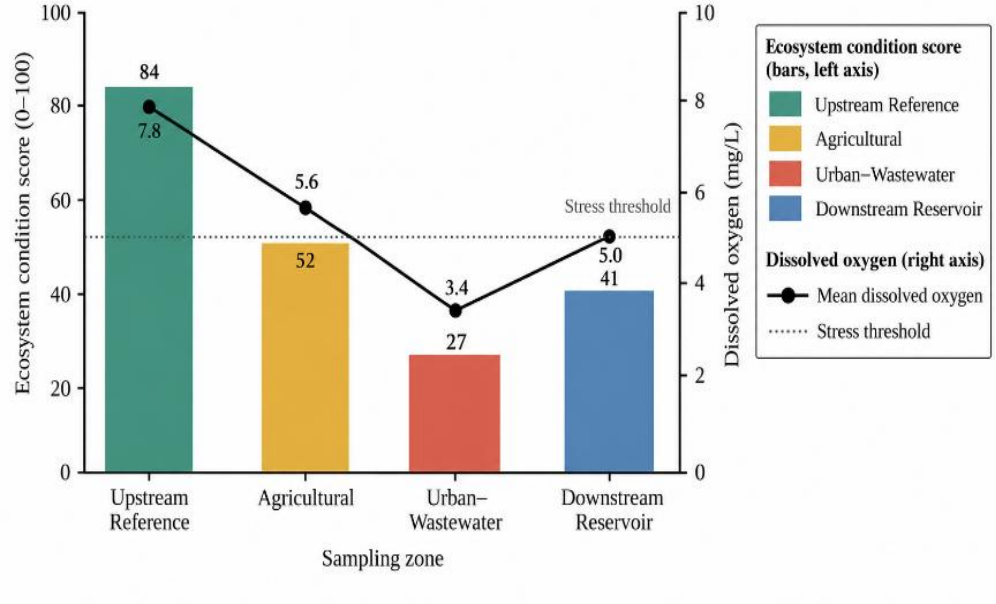


Figure 8: Ecosystem Condition Score and Mean Dissolved Oxygen Across Sampling Zones

V. Discussion

The findings clearly show how the increase of nutrients is related to eutrophication intensification and aquatic biodiversity in the river–reservoir system. The concentrations of nutrients showed significant increase from the upstream reference site towards the sites that are influenced by agriculture and urban–wastewater. This trend is also visible in high concentrations of phosphorous and ammonium at the urban zone. In addition, the findings revealed that the increased nutrients are associated with the increased concentrations of chlorophyll-a, decrease of water transparency and decreased oxygen. Seasonality was found to play an important part since algal biomass increased during pre-monsoon season due to the increased temperature and low water flows which allowed for the increase of nutrients and bloom development. The impact on biodiversity was similar with significant reduction of richness of invertebrates, fish diversity and submerged plants' cover while cyanobacteria and organisms with tolerance to pollution become more prominent. The negative relationship between phosphorus concentration and richness of macroinvertebrates further proved rapid response of biodiversity to nutrients. Phosphorus enrichment and low dissolved oxygen proved to be the main factors affecting the ecosystems and together explained the large share of observed decline.

VI. Conclusion

This study clearly indicates nutrient enrichment as a major cause for eutrophication and loss of biodiversity in freshwater ecosystems. Both nitrogen and phosphorous levels were high in zones impacted by agriculture and sewage compared to the reference zones, causing high algal biomass, dominance of cyanobacteria, low transparency of water and oxygen depletion, especially before monsoon season in the reservoir. All these factors were highly correlated with biodiversity loss. The number of invertebrates, fish species and aquatic vegetation coverage all decreased following the enrichment gradient, while community composition changed to include only pollution tolerant organisms. The combination of phosphorus enrichment and low oxygen was responsible for more than half of the observed biodiversity loss, while the overall ecosystem state dropped from good to very poor with increasing nutrients pressure. Nutrient management is, thus, crucial for biodiversity conservation in freshwaters. Wide-spread reduction of fertilizer and sewage inputs into the river catchments, along with riparian buffer, wetlands treatment, restoration of reservoirs and preservation of reference habitats represent the best way forward. The conservation objectives have to be set up with respect to the needs of the sensitive species and not just by using water. The future research would have to be done over several years, looking at the impacts of climate change, studying the importance of nutrient availability from the sediments, evaluating the biodiversity impact of certain restoration techniques, and also taking into account more groups like amphibians and microorganisms.

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