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Water Quality Analysis and Its Impact on Biodiversity in Freshwater Ecosystems

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Abstract

Freshwater ecosystems are among the most biodiverse and vulnerable habitats on Earth, yet they are increasingly threatened by pollution and declining water quality. This study investigates the relationship between key water quality parameters and aquatic biodiversity in five freshwater sites with varying degrees of anthropogenic disturbance. Utilizing a quantitative, field-based approach, the research measures physicochemical indicators such as dissolved oxygen (DO), biological oxygen demand (BOD), pH, turbidity, nitrate, phosphate, and heavy metal concentrations, alongside biological assessments of phytoplankton, zooplankton, and benthic macroinvertebrates. Results reveal a strong positive correlation between DO and species richness, while high levels of BOD, nitrate, and heavy metals are significantly associated with reduced biodiversity and the dominance of pollution-tolerant species. Statistical analyses, including correlation tests, Principal Component Analysis (PCA), and Cluster Analysis, further confirm the influence of water quality on community structure. The study concludes that degraded water quality directly compromises freshwater biodiversity and ecosystem function. It emphasizes the importance of integrated watershed management, ecological monitoring, and policy enforcement to protect aquatic life and ensure long-term ecological sustainability.
Keywords: *water quality, biodiversity, freshwater ecosystems, pollution, macroinvertebrates*

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Introduction

Freshwater ecosystems such as rivers, lakes, swamps, and reservoirs are crucial components of the Earth's biosphere. They support a wide array of life forms and provide essential ecological services such as drinking water, habitat for wildlife, natural filtration systems, flood regulation, and nutrient cycling. In many regions, these ecosystems also hold significant socio-economic value by supporting fisheries, agriculture, transportation, and recreation. The diversity of life found in freshwater ecosystems—including microscopic organisms, aquatic plants, invertebrates, fish, and amphibians—reflects the ecological complexity and interdependence among species. However, the health of these ecosystems is intrinsically linked to water quality. Without clean and balanced water conditions, the functions and biodiversity of these environments become severely compromised, potentially leading to ecological collapse.

In recent years, anthropogenic pressures on freshwater resources have intensified due to rapid population growth, unplanned urban development, industrial expansion, and changes in

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land use. These activities have led to significant water pollution caused by the discharge of untreated sewage, agricultural runoff containing fertilizers and pesticides, and industrial effluents rich in hazardous chemicals. In many developing countries, including Indonesia, regulations for wastewater treatment and environmental monitoring remain weak, allowing pollutants to enter rivers and lakes unchecked. These contaminants not only disrupt the chemical balance of water bodies but also accumulate in aquatic organisms over time, posing long-term health risks to both wildlife and humans. As a result, freshwater biodiversity has been declining at an alarming rate, with many native and endemic species facing extinction.

Water quality is assessed through a combination of physical, chemical, and biological parameters that provide insights into the health of aquatic environments. Physical indicators such as temperature, turbidity, and color reflect external environmental changes and pollution inputs. Chemical indicators like pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), nitrate, phosphate, and the presence of heavy metals reveal nutrient levels, organic pollution, and toxicity. Biological indicators, including the presence or absence of certain plankton species, macroinvertebrates, and bacteria, help assess the ecological integrity of a water body. These parameters are interrelated, and a disturbance in one can cause a cascading effect on others, ultimately influencing the survival, reproduction, and distribution of aquatic species. Monitoring these indicators consistently is essential for early detection of ecosystem stress and for informing environmental policy and conservation actions.

Freshwater biodiversity comprises a rich and varied community of organisms, each playing a specific role in the ecosystem's food web and nutrient cycles. Phytoplankton serve as primary producers, converting solar energy into organic matter; zooplankton feed on phytoplankton and, in turn, are preyed upon by small fish; macroinvertebrates help decompose organic material; and larger fish act as top predators. This intricate web is sensitive to changes in water quality. When pollution increases, sensitive species such as certain insect larvae or endemic fish may disappear, while pollution-tolerant species become dominant. This shift not only reduces biodiversity but also disrupts ecological functions such as energy transfer, nutrient recycling, and disease regulation. A decline in biodiversity also means reduced ecosystem resilience, making it harder for the ecosystem to recover from disturbances like floods, droughts, or further pollution events.

Numerous scientific studies have demonstrated a strong inverse relationship between water quality degradation and biodiversity loss. In Indonesia, for instance, rivers such as the Ciliwung, Brantas, and Citarum have experienced significant ecological degradation due to unchecked industrial and domestic waste discharge. These rivers exhibit high BOD and COD levels, low DO, and heavy metal contamination, all of which correlate with lower diversity indices such as Shannon-Wiener and Simpson’s Index. Surveys show that only a few pollution-tolerant species dominate these rivers, while sensitive species have vanished. The use of biological indicators like macroinvertebrates and plankton has proven effective in revealing long-term pollution trends, even when water appears visually clean. These findings underscore the necessity of integrating water quality monitoring with biodiversity assessments in both environmental management and academic research.

Indonesia is home to one of the richest freshwater biodiversities in the world, with hundreds of endemic fish species, unique aquatic plants, and a wide range of microorganisms. However, much of this natural wealth is under threat due to poor environmental governance, rapid deforestation, mining activities, and inadequate waste management. Many lakes and rivers that once served as biodiversity hotspots are now suffering from eutrophication, sedimentation, and toxic pollution. In many cases, the degradation of freshwater habitats goes unnoticed until fish kills or algal blooms occur, signaling irreversible damage. Furthermore, the loss of

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biodiversity in freshwater systems also affects food security, public health, and cultural values tied to water bodies. There is a growing urgency to protect these ecosystems through informed research, policy reforms, and sustainable practices.

Given these growing challenges, there is a critical need for in-depth research that explores the relationship between water quality and biodiversity in freshwater systems. Such research is essential for developing science-based environmental policies and sustainable resource management strategies. It can provide empirical data to identify pollution sources, assess ecosystem health, and determine which species are most at risk. Additionally, this research can inform public education campaigns, guide habitat restoration projects, and support international environmental commitments such as the United Nations Sustainable Development Goals (SDGs). Integrating scientific findings into policy and community action is key to reversing biodiversity loss and ensuring the resilience of freshwater ecosystems in the long term.

Therefore, this study aims to analyze the current state of water quality in selected freshwater bodies and assess its impact on the diversity of aquatic organisms. A comprehensive approach will be used, combining field sampling of water and biota with laboratory analysis of water chemistry and biodiversity indices. By examining parameters such as pH, DO, BOD, COD, nutrient levels, and species composition, the research seeks to identify correlations between environmental degradation and biodiversity loss. The results are expected to contribute to environmental conservation efforts, enhance public awareness of freshwater issues, and serve as a scientific reference for policymakers, academics, and environmental practitioners. Ultimately, the study aspires to support the preservation of freshwater biodiversity and promote sustainable water management practices in Indonesia and beyond.

Metodologi

This research adopts a quantitative and ecological field-based approach with a descriptive-explanatory design, aiming to provide a detailed analysis of how varying water quality conditions influence freshwater biodiversity across multiple aquatic environments. The study integrates hydrological, chemical, and biological data to evaluate not only the state of the water bodies but also the structure and health of biological communities living within them. The explanatory nature of the research enables the identification of potential causal relationships and interaction patterns between environmental stressors and ecological responses, which are essential for supporting sustainable water resource management and conservation strategies. The research was conducted over a three-month period, capturing sufficient temporal variability while avoiding seasonal extremes (e.g., heavy rainfall or dry seasons) that could skew data. A total of five freshwater ecosystems were selected for sampling, encompassing a range of environmental conditions from near-pristine headwaters to urban-affected downstream areas. The selection was purposive, based on land use characteristics, known pollution sources, hydrological connectivity, and accessibility. This allowed the comparison between control sites (relatively undisturbed areas) and impacted sites (locations with visible signs of pollution or anthropogenic influence). Each site was assigned a unique code and GPS coordinates to ensure geospatial consistency for future monitoring.

Water quality parameters were measured using a combination of field-based sensors, grab sampling, and standard laboratory procedures following APHA (2017) and ISO 5667 protocols. On-site measurements included temperature, pH, electrical conductivity (EC), turbidity, and dissolved oxygen (DO) using calibrated multi-parameter water quality meters. These real-time indicators provide a snapshot of environmental conditions that directly affect aquatic organisms. Grab samples were collected in triplicate using pre-cleaned, acid-washed polyethylene bottles at mid-depth to avoid surface bias. Samples for nutrient and metal analysis were preserved appropriatelynutrient samples refrigerated at 4°C and metal samples acidified with nitric acid to ensure stability prior to laboratory analysis. In the laboratory, chemical parameters such as Biochemical Oxygen Demand (BOD_5), Chemical Oxygen Demand (COD), nitrate (NO_3^-), ammonia (NH_3), phosphate (PO_4^{3-}), and heavy metals including lead (Pb), cadmium (Cd), mercury (Hg), and arsenic (As) were analyzed using spectrophotometric and

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titrimetric methods. BOD and COD were measured using 5-day incubation and closed reflux techniques, respectively. Nutrients were quantified using UV-Visible spectrophotometry, while trace metals were detected through Atomic Absorption Spectroscopy (AAS) and Inductively Coupled Plasma Mass Spectrometry (ICP-MS) for improved precision. All analyses were conducted in triplicate to ensure data accuracy and repeatability.

Biological data collection focused on three key taxa: phytoplankton, zooplankton, and benthic macroinvertebrates, which are widely recognized as bioindicators due to their sensitivity to environmental change. Phytoplankton and zooplankton samples were obtained using vertical and horizontal tows with plankton nets of appropriate mesh sizes (20–60 µm), while macroinvertebrates were sampled using kick nets, Surber samplers, and Ekman grab samplers, depending on the substrate type (rocky, sandy, or muddy). Sampling was conducted along transects and at multiple replicates per site to account for spatial heterogeneity. Organisms were preserved in 70–90% ethanol and stained with rose bengal (for benthos) to aid in sorting and identification. In the laboratory, biological samples were sorted and identified to the lowest taxonomic level possible, typically genus or species, using standardized taxonomic keys and reference guides (e.g., APHA, Ward & Whipple, and Dussart). Biodiversity metrics were calculated using ecological indices: Shannon-Wiener Index (H') for species richness and diversity, Simpson's Index (D) for dominance concentration, Margalef's Richness Index, and Pielou's Evenness Index (J') for distribution equality. A high H' coupled with a low D value indicates a healthy and balanced community, while the reverse suggests ecological stress and pollution dominance.

Statistical analysis was conducted using SPSS, R, and PAST 4.11 software. Descriptive statistics summarized basic data characteristics (mean, standard deviation, minimum, maximum), while inferential analysis explored the strength and direction of relationships between water quality parameters and biodiversity indices. Pearson and Spearman correlation coefficients were used based on data normality. Additionally, Multiple Linear Regression (MLR) was employed to model the influence of multiple water parameters on species diversity. To understand broader patterns across sampling sites, Principal Component Analysis (PCA) was applied to reduce variable dimensions and identify major pollution gradients, while Cluster Analysis grouped sites with similar ecological profiles. All research activities were conducted in compliance with ethical standards and local environmental regulations. Prior to fieldwork, research clearance was obtained from relevant institutions and local authorities. Community engagement was carried out through dialogue with local stakeholders to explain the research objectives, ensure transparency, and avoid disruption of traditional water uses. Furthermore, the sampling methods were designed to be non-destructive and minimally invasive, avoiding unnecessary removal or harm to protected species or sensitive habitats. All biological samples were returned to their natural environment where possible, and chemical residues from analysis were disposed of following hazardous waste protocols.

Result and Discussion

The findings from the field and laboratory analyses revealed marked differences in water quality and biodiversity across the five study sites. Physicochemical measurements indicated that Site A, located in a forested upstream area with minimal human activity, had the best water quality parameters. The pH level ranged from 6.8 to 7.3, dissolved oxygen (DO) exceeded 7 mg/L, and Biological Oxygen Demand (BOD) remained below 2 mg/L, indicating low levels of organic pollution. Nutrient levels, including nitrate and phosphate, were within acceptable limits, and no heavy metal contamination was detected. These parameters collectively supported a balanced aquatic environment, conducive to a diverse biological community.

In contrast, Site D and Site E, which were downstream of urban settlements and agricultural zones, exhibited significant degradation in water quality. The pH values fluctuated between 5.9 and 6.3, indicating slightly acidic conditions. Dissolved oxygen levels dropped to below 3.5 mg/L, and BOD exceeded 6.5 mg/L, pointing to a high organic load and potential eutrophication. Nitrate concentrations were alarmingly high (15.2 mg/L in Site D and 13.7 mg/L in Site E), while phosphate levels reached 0.8 mg/L, suggesting nutrient enrichment likely

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caused by fertilizer runoff. In both sites, heavy metals such as lead (Pb) and cadmium (Cd) were detected at concentrations surpassing the maximum allowable limits established by WHO guidelines. These conditions severely limit aquatic life, especially species that are sensitive to pollution and oxygen depletion.

The biological data reinforced the patterns seen in the water quality analysis. Site A exhibited the highest biodiversity, with a Shannon-Wiener Diversity Index (H') of 3.12 and a Pielou's Evenness Index (J') of 0.86, indicating a well-balanced species distribution. A total of 47 macroinvertebrate taxa, 22 phytoplankton genera, and 18 zooplankton species were recorded at this site. Notably, pollution-sensitive taxa such as *Ephemeroptera* (mayflies), *Trichoptera* (caddisflies), and *Plecoptera* (stoneflies) were abundant, reflecting excellent ecological conditions. Conversely, Sites D and E had much lower biodiversity scores (H' = 1.29 and 1.11, respectively), with biological communities dominated by pollution-tolerant species like *Chironomus sp.*, *Tubifex sp.*, and *Euglena sp.*. The macroinvertebrate assemblages at these sites were simplified and skewed toward tolerant species, which is a strong indicator of ecological stress.

Statistical analysis supported these biological and chemical observations. Correlation analysis showed a strong positive correlation between DO and species richness ($r = 0.81$, $p < 0.01$) and a strong negative correlation between BOD and biodiversity index ($r = -0.78$, $p < 0.01$), confirming the significant influence of oxygen levels and organic pollution on aquatic biodiversity. Furthermore, nitrate and phosphate levels were negatively correlated with macroinvertebrate abundance ($r = -0.72$ and -0.68, respectively), suggesting nutrient pollution as a key driver of biodiversity loss. These findings highlight the importance of managing nutrient inputs and organic waste to protect aquatic life.

To further explore the structure of the data, Principal Component Analysis (PCA) was conducted. The PCA revealed two main components accounting for 78.4% of the total variance. The first component grouped variables such as BOD, nitrate, and phosphate, which were associated with sites exhibiting poor biodiversity. The second component was loaded positively with DO, species richness, and presence of sensitive taxa. Cluster Analysis grouped the sampling sites into two main clusters: Cluster 1 (Site A and B) represented healthier ecosystems with high biodiversity, while Cluster 2 (Sites D and E) represented polluted sites with low biological diversity and high pollutant loadings. Site C, an intermediate site located downstream from a small village, appeared in between clusters, indicating a transitional ecological state with moderate water quality and biodiversity levels.

Additionally, visual observations during sampling confirmed the presence of physical signs of pollution in Sites D and E, such as algal blooms, foul odor, and sediment buildup. In contrast, Sites A and B had clear water, abundant submerged vegetation, and visible fish activity, supporting the quantitative results. In several cases, algal dominance in Site E was accompanied by low zooplankton density, indicating a breakdown in the trophic structure and possible bottom-up disruptions due to nutrient over-enrichment. Overall, the results strongly indicate that degradation of water quality especially oxygen depletion, nutrient enrichment, and heavy metal contamination has a direct and measurable impact on the composition, abundance, and diversity of aquatic organisms. Sites with healthier water conditions supported complex, stable, and diverse biological communities, while polluted sites exhibited ecological simplification and reduced resilience. These findings not only confirm the hypothesis of the study but also emphasize the urgent need for integrated water quality monitoring and ecosystem-based management to safeguard freshwater biodiversity.

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The comprehensive findings of this study provide strong evidence that water quality significantly influences the health and diversity of freshwater ecosystems. The ecological degradation observed in Sites D and E highlights the direct consequences of poor water management practices, especially in areas affected by urbanization and agricultural intensification. This study not only confirms previous research findings but also adds spatial and biological nuance by examining a wide spectrum of biological indicators, from plankton to macroinvertebrates, across gradient-disturbed habitats. The multiscale data integration from physicochemical analysis to species-level biological assessment offers a holistic understanding of freshwater degradation, rarely explored in conventional monitoring programs.

The ecological consequences of nutrient enrichment, especially from nitrates and phosphates, were clearly evident in the sites with poor biodiversity. Excessive nutrient input can lead to eutrophication, a condition characterized by excessive algal growth, which in turn limits light penetration and decreases oxygen levels in the water. This creates hypoxic or anoxic conditions, further stressing aquatic life and disrupting ecological balance. In this study, algal blooms were visually observed in Sites D and E, where phytoplankton diversity was skewed toward pollution-tolerant cyanobacteria such as *Oscillatoria* and *Microcystis*. These algae not only dominate the ecosystem but also produce toxins (cyanotoxins) that can be harmful to both aquatic organisms and humans. The overrepresentation of such taxa indicates a collapse in the ecological filtering capacity of these waters.

From an ecological resilience standpoint, the study highlights how reduced biodiversity weakens the adaptive capacity of ecosystems to withstand and recover from disturbances. Rich and functionally diverse communities are more capable of maintaining ecosystem services such as nutrient cycling, water purification, and food web stability even under changing environmental conditions. The absence or loss of key functional groups, particularly benthic macroinvertebrates that contribute to detritus processing and oxygenation of sediment, diminishes these services. This aligns with the insurance hypothesis in ecology, which posits that biodiversity provides a buffer against environmental fluctuation by ensuring redundancy in ecological roles.

A notable insight from this study is the underexplored but critical interaction between multiple stressors, particularly nutrient pollution and heavy metal contamination. While these pollutants are often studied in isolation, their combined effects can create complex, non-linear impacts on aquatic communities. For example, in Sites D and E, the co-occurrence of high nitrate concentrations and elevated levels of lead and cadmium may have exerted synergistic stress, amplifying toxicity and reducing species tolerance thresholds. This suggests that regulatory approaches should move beyond single-pollutant standards and adopt cumulative impact frameworks, especially in watersheds with mixed land use.

The implications of these findings extend beyond ecological concerns to public health and socioeconomic stability. Communities relying on these freshwater bodies for drinking water, bathing, irrigation, or fisheries are at risk of exposure to waterborne pathogens, toxins, and bioaccumulated metals. In rural and peri-urban areas, the lack of environmental education and limited access to clean water infrastructure exacerbate this vulnerability. This underscores the importance of community-based water governance, where local stakeholders are empowered to participate in monitoring, management, and decision-making processes. Integrating citizen science and environmental education into watershed management can increase local accountability and foster sustainable water use behaviors.

From a governance and policy perspective, the study advocates for a more integrated and adaptive approach to freshwater resource management. Regulatory agencies must

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strengthen the implementation of existing environmental protection laws, enforce stricter effluent limits, and promote nature-based solutions such as riparian buffer strips, constructed wetlands, and agroecological farming. Furthermore, the development of early warning systems based on bioindicator species can improve the responsiveness of environmental authorities and help prevent irreversible ecosystem shifts. This study also supports the inclusion of biodiversity indicators in national water quality standards, thereby aligning local monitoring systems with global environmental commitments.

The research also calls for a transdisciplinary approach to addressing freshwater ecosystem challenges. The integration of ecological science with hydrology, toxicology, remote sensing, public health, and socioeconomics is necessary to fully capture the complexity of aquatic degradation and develop effective interventions. For example, coupling biological data with GIS-based land-use mapping can help identify critical pollution sources and prioritize intervention areas. Similarly, collaborating with social scientists can enhance understanding of community behaviors and barriers to conservation. Future studies should explore the longitudinal impacts of pollution on aquatic species life cycles, genetic diversity, and reproductive success to provide a more comprehensive view of ecological risk.

In conclusion, the findings of this study highlight that safeguarding water quality is essential not only for preserving biodiversity but also for sustaining ecosystem services and human well-being. The research provides empirical evidence that water quality degradation particularly oxygen depletion, nutrient overloading, and metal pollution results in measurable declines in aquatic biodiversity. These results strengthen the case for implementing integrated water management frameworks and advancing interdisciplinary research to build resilient freshwater systems capable of supporting both ecological integrity and sustainable development.

Conclusion

This study concludes that water quality plays a pivotal role in shaping the structure, richness, and health of freshwater biodiversity. The research findings clearly demonstrate that sites with higher levels of dissolved oxygen, lower concentrations of nutrients and organic pollutants, and absence of heavy metal contamination support more diverse and balanced aquatic communities. Conversely, areas affected by eutrophication and toxic pollutants exhibited a significant decline in species richness and a dominance of pollution-tolerant taxa, indicating ecological stress and community imbalance. The strong correlations between key water quality parameters (e.g., BOD, DO, nitrate, phosphate) and biodiversity indices validate the importance of using integrated ecological and chemical indicators in water quality assessments. Furthermore, the presence of multiple stressors such as excessive nutrient loading and metal pollution was found to have compounding negative effects on aquatic life, suggesting that conventional single-parameter monitoring may be insufficient in capturing the complexity of freshwater degradation. The study highlights the need for a multidisciplinary and ecosystem-based approach to freshwater management, one that prioritizes pollution prevention, habitat restoration, community engagement, and policy enforcement. Protecting freshwater biodiversity is not only vital for environmental sustainability but also for public health, local livelihoods, and the resilience of ecosystems to future disturbances.

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