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Environmental Drivers of Nile Tilapia (Oreochromis niloticus) Abundance in Lake Buluan: A Principal Component Analysis of Physicochemical Water Parameters

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Abstract

Understanding the environmental factors that influence fish abundance is essential or sustainable fisheries management in tropical freshwater ecosystems. This study investigated the environmental drivers of Nile tilapia *(Oreochromis niloticus)* abundance in Lake Buluan, a major inland fishery in Mindanao, Philippines, using physicochemical water quality parameters and multivariate statistical analyses. Physicochemical measurements were collected from eight sampling sites representing littoral and limnetic zones. Fish sampling was conducted using standardized fishing gears. Principal Component Analysis (PCA) was employed to identify major environmental gradients, while a Generalized Linear Model (GLM) was used to evaluate the influence of these gradients on Nile tilapia abundance. The lake generally exhibited physiochemical condition suitable for freshwater fisheries, although notable spatial variation was observed among sampling sites. Nile tilapia was widely distributed throughout the lake. Results reveal distinct environmental gradients characterized primarily by variations in conductivity, temperature, pH, and turbidity. Additionally, Nile tilapia abundance was positively associated with conductivity and turbidity and negatively associated with temperature and pH. Furthermore, the primary environmental gradient significantly influenced spatial variation in tilapia abundance, whereas dissolved oxygen exerted comparatively limited influence under the observed conditions. The findings indicate that physiochemical water quality contributes to the spatial distribution of Nile tilapia in Lake Buluan. However, the relatively modest explanatory power of the model suggests that additional ecological and anthropogenic factors also influence abundance patterns. These results provide baseline information for fisheries management and support the integration of water quality monitoring into conservation and sustainable utilization strategies for Lake Buluan.

Understanding the environmental factors of fish abundance is important in sustainable fisheries management in tropical freshwater environments. This study monitored environmental factors of Nile tilapia (Oreochromis niloticus) abundance in Lake Buluan,a major inland fishery in Mindanao, Philippines, using physicochemical water quality parameters and multivariate statistics. Physicochemical samples were taken from eight sampling sites (littoral and limnetic areas). Fish were sampled using standard fishing gears. Principal Component Analysis (PCA) was applied to identify major gradients of environmental quality and a Generalized Linear Model (GLM) was applied to measure the impact of different gradients on Nile tilapia abundance. The lake was generally in good physiochemical condition for freshwater fisheries, but there is significant spatial variation between sampling sites. Nile tilapia was found to be common throughout the lake. We found a wide range of environmental gradients that are mostly affected by conductivity, temperature, pH, and turbidity. Nile tilapia abundance was also positively correlated with conductivity and turbidity, and negatively associated with temperature and pH. In addition, the dominant environmental gradient was also significant in terms of variation of tilapia abundance, whereas dissolved oxygen exerted comparatively limited influence under the observed conditions. This study clearly indicates that physiochemical water quality is involved in the distribution of Nile tilapia in Lake Buluan, but the low explanatory power of the model also shows that there are some other ecological

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and anthropogenic factors contributing to the abundance pattern. These findings provide a useful basis for fisheries management and support the incorporation of water quality monitoring for conservation and sustainable use of Lake Buluan.

Keywords: ***generalized linear model (GLM), Lake Buluan, Nile tilapia, principal component analysis (PCA), water quality***

Introduction

Lake Buluan is one of the most important freshwater ecosystems in Mindanao, Philippines. The lake is situated between Maguindanao del Sur and Sultan Kudarat provinces and is the third largest lake in Mindanao and one of the major inland water bodies in the country (Noquilla, 2021). It is a shallow tropical lake with an average depth of 3.5 meters and a maximum depth of 5.5 meters (Noquilla et al., 2020; Yap et al., 1983). Moreover, Lake Buluan has a wide range of aquatic resources and can offer important ecosystem services including fisheries production, biodiversity conservation, water management, and livelihood opportunities to the surrounding communities. The lake was identified as a highly productive freshwater ecosystem in the early years of limnological research with favorable water and fish growth and reproduction conditions that contributed to food security and economic development in the region (Yap et al., 1983). The lake's rich microbial diversity and ecological significance have recently been identified as one of the most important water bodies as a biologically productive inland water body in southern Philippines (Tabugo et al., 2023). Tropical shallow lakes like Lake Buluan are very dynamic ecosystems where environmental conditions are very important for aquatic productivity and fisheries sustainability (Jeppesen et al., 2014; Wetzel, 2001).

Fisheries are the main economic activity in many of the communities around Lake Buluan. The lake is key to food, employment and income for thousands of fisherfolk and their families. Among the fish species harvested in the lake, Nile tilapia (*Oreochromis niloticus*) is the most economically valuable one. Due to its fast proliferation and wide environmental tolerance, highly efficient feed conversion and high consumer demand, Nile tilapia has become one of the most important freshwater fish species in the Philippines and across the world (El-Sayed, 2020; Guerrero, 2019). The previous fisheries studies in Lake Buluan revealed that Nile tilapia accounts for most of the fish catches and plays an important role in local livelihoods and food security (Pinsoy et al., 2025). For fisheries conservation and rural development, the species' ecological adaptability and economic value mean sustainable management is a priority.

Nile tilapia is well-known in nature for its ability to adapt to all environmental conditions. However, the abundance, distribution and productivity of this species depend extensively on the physicochemical composition of the ecosystem. The dissolved oxygen (DO), temperature, pH, conductivity, and turbidity of water are critical to fish physiology, metabolism, feeding behavior, reproduction and survival (Kelany et al., 2024; Makori et al., 2017). DO is most important for respiration and growth and temperature affects metabolic activity and reproductive performance of fish (El-Sayed, 2020; Azaza et al., 2008). Similarly, pH is relevant for processing and nutrient availability while conductivity is related to the ionic composition of water, and is often used to determine the quality of nutrients and ecosystem productivity of fish. The higher dissolved ion concentrations of water are associated with a higher primary productivity and increased food quality (Geidam et al., 2026; Boyd & Pillai, 1985). Turbidity affects light penetration, primary productivity and habitat availability (Boyd & Tucker, 2012). So, the abundance and distribution of fish in freshwater ecosystems can be affected by these environmental conditions.

Physicochemical water parameters are considered to be key in the development of fish communities and ecosystem in lakes and reservoirs. Change in water quality can impact habitat conditions, species interaction, habitat availability, and resource availability, thereby affecting fish abundance and distribution (Jeppesen et al., 2014; Matthews, 1998). Elevated nutrient inputs can be beneficial for overall productivity but may also lead to eutrophication, oxygen depletion and habitat loss when nutrient concentration exceeds ecological limits (Jeppesen et al., 2017; Dodds & Smith, 2016). This means that understanding the interplay between physicochemical factors is key to the assessment of environmental conditions that allow for sustainable fisheries development.

Given the fact that Nile tilapia is an important ecological and economic resource in Lake Buluan, much is still not known about the environmental factors that give rise to the abundance of Nile tilapia in the lake. In addition, few studies in Philippine inland lakes have used multivariate statistics to determine the main environmental gradients affecting populations of fish. Consequently, there is still a gap on the relative importance of physicochemical water parameters in determining the abundance of Nile tilapia in Lake Buluan.

Principal Component Analysis (PCA) is a powerful multivariate statistical tool that reduces the complexity of the environmental data into a few principal components that represent major environmental gradients (Jolliffe & Cadima, 2016). PCA is used to summarise correlations among various physicochemical variables and to identify the most dominant environmental agents in the ecology of plants and animals. The application of PCA in fish and aquatic ecology is helpful to understand the relationship between fish and environment and to identify the environmental forces that drive the abundance of species in freshwater environments (Odulate et al., 2014; Shrestha & Kazama, 2007).

Therefore, this study aims to examine the environmental drivers of Nile tilapia (O. niloticus) abundance in Lake Buluan by PCA of physicochemical water parameters. Specifically, it aims to characterize the physicochemical water quality of Lake Buluan in terms of DO, pH, temperature, specific conductivity, and turbidity; determine the abundance of Nile tilapia across sampling sites; major environmental gradients in the lake using PCA, and the relationship between physicochemical water quality parameters and Nile tilapia abundance. The findings of this study will contribute to the understanding of the fish-environment interactions in tropical freshwater ecosystems in a more ecological way and provide scientific evidence to guide sustainable fisheries management, lake conservation and fisherfolk' livelihood enhancement measures for fisherfolk that depend on Lake Buluan water resources.

Methods

Study Area

The study was conducted in Lake Buluan, a large freshwater lake within the provinces of Maguindanao del Sur and Sultan Kudarat, Philippines. Eight sampling sites were selected to represent the major hydrological and habitat area of the lake (Figure 1). Sampling sites are in littoral and limnetic environments to capture the spatial variations in environment and fish abundance.

S1 and S8 were located in the lake margins (littoral zone), S2 and S6 were located on fish landing sites (littoral zone), S3 and S7 were located in open water (limnetic zone), S4 was located near the lake outlet and S5 was located near the main inlet. At each site, three replicate sampling plots separated by approximately 100 m were established, resulting in a total of 24 sampling plots across the lake.

In Situ Physicochemical Measurements

Physicochemical parameters were measured in situ during a rapid environmental assessment using a calibrated Aqua TROLL 600 Multiparameter Sonde. Measurements included dissolved oxygen (DO), pH, specific conductivity, water temperature, and turbidity.

Measurements were taken at a depth of about 0.3-0.5 m below the water surface at each replicate plot. Before the field deployment the instrument was calibrated to the manufacturer's specifications to ensure accurate and consistent measurements

Fish Collection

Fish sampling was conducted simultaneously across all sampling sites using a combination of passive fishing gears to maximize species capture and reduce gear selectivity bias. The fishing gears consisted of five multifilament gill nets (mesh sizes ranging from 12-70 mm; dimensions: 10 m X 2 m) and five baited fish pots.

Fishing operations were carried out in a standard overnight sampling procedure. Fishing gears were deployed at 3:00 pm and 5:00 pm (UTC+08:00) and soaked for about 12 h. Retrieval occurred after 5:00 am to 7:00 am (UTC+08:00) the following morning. Fish were collected and sorted according to sampling site and gear type and were immediately placed in insulated coolers with ice in order to ensure specimens were preserved during storage and transfer to the laboratory.

Fish Processing and Species Identification

The morphological examination, documentation, identification, and preservation of the fish samples were performed immediately at the laboratory. Fish samples were sorted by species and sampling site. The abundance of each species was determined by directly counting the number of captured individuals.

Morphometric measurements were obtained for each species. Standard length (SL), total length (TL) and fork length (FL) were measured to the nearest 0.01 mm using digital calipers and measuring boards. Body weight was measured to the nearest 0.1 g with a calibrated digital weighing scale. Standard length was used as the main morphometric measure as it is not affected by damaged or missing caudal fins and allows for consistent comparisons among species with different caudal fin morphologies.

Representative specimens were photographed as well as kept in storage and preserved. Species identification was done to the lowest possible taxonomic level using standard taxonomic keys, published literature on Philippine freshwater fishes, online databases (Froese & Pauly, 2026), and the IUCN Red List of Threatened Species (IUCN, 2026). The scientific names and taxonomic validity of the species were confirmed through Eschmeyer's Catalog of Fishes (Eschmeyer et al., 2026).

Data Analysis

Descriptive statistics were used to summarize the physicochemical characteristics of the sampling sites and the abundance of Nile Tilapia (*Oreochromis niloticus)*. The measured water quality parameters were compared to the Department of Environment and Natural Resources Administrative Order No. (DAO) 2016-08 for DO, pH and temperature, Department of Health Administrative Order No. (DOH AO) 2017-0010 for turbidity and World Health Organization (2017) for the specific conductivity.

To reduce multicollinearity between environmental variables and identify the major environmental gradients affecting the abundance of Nile tilapia, PCA was performed using standardized physicochemical variables. The components with eigenvalues larger than 1.0 were left to be interpreted according to the Kaiser criterion used in ecological multivariate analyses (Geidam et al., 2026; Jolliffe & Cadima, 2016). Nile tilapia abundance was then fitted as an additional variable to PCA to visualize the association between Nile tilapia abundance and environmental gradients.

The relationship between the environmental gradients and Nile tilapia abundance was then examined via a Generalized Linear Model (GLM) with a Poisson error distribution and log-link function. The principal component scores from the PCA were used as predictor variables, and Nile tilapia abundance as the response variable. The significance of the model was checked using likelihood ratio chi-square tests with $\alpha = 0.05$. All statistical analyses were performed using Jamovi statistical software package (version 2.7.6).

Results and Discussion

Water Quality Characterization of Lake Buluan

The physicochemical characteristics of Lake Buluan varied in the sampling sites but generally reflected conditions suitable for sustaining freshwater fisheries (Figure 2). Dissolved oxygen (DO) concentrations ranged from 5.6 to 7.4 mg/L, with the highest value recorded at S2 and the lowest at S6. All DO concentrations were above 5.0 mg/L, which is the minimum required for Class C freshwater bodies under DAO 2016-08 and indicates that oxygen is available for aquatic organisms. DO is a critical factor in the growth, metabolism, and survival of fish so DO levels above 5 mg/L is favorable for most freshwater fish species such as Nile tilapia (El-Sayed, 2020; Boyd & Tucker, 2012). The relatively high DO levels observed across sampling sites suggest that oxygen availability was unlikely to be a limiting factor for fish production during sampling period.

pH ranged from 6.1 to 8.4. Most sampling sites were within the DAO 2016-08 recommended range of 6.5-9.0 for Class C waters, though slightly acidic conditions were observed at S7 (6.1 pH). The measured pH ranges indicate generally good conditions for freshwater biota and fisheries production (Wetzel, 2001). The pH is critical for physiological processes, nutrient availability, and productivity of aquatic systems. Nile tilapia tolerates a relatively wide pH range but 6.5-8.5 is optimal for growth and reproduction (El-Sayed, 2020). The pH conditions thus indicate that most areas of Lake Buluan are favorable for the species.

Elevated temperatures in shallow tropical lakes are associated with increased solar radiation, shallow water depth, and reduced riparian shading (Jeppesen et al., 2017). Temperature is a major environmental factor that influences fish metabolism, feeding activity, growth rate, and DO dynamics. Nile tilapia is best growing in 25°C to 32°C (El-Sayed, 2020). However, prolonged increases in water temperature may alter oxygen availability and ecosystem processes, potentially affecting fish productivity and community structure.

Specific conductivity ranged from 15,000 to 23,000 µS/cm which suggests that dissolved ionic content was very different among sampling sites. Higher conductivity values were seen at S6, S7, and S8, which are located near fish landing areas and lake margins. Conductivity is the concentration of dissolved ions in water and is influenced by watershed geology, agricultural runoff, aquaculture, and nutrient inputs (Wetzel, 2001). Higher conductivity may reflect higher dissolved ion concentrations and nutrient inputs which can affect ecosystem productivity as the presence of nutrients and primary production is positively related to the conductivity in freshwater (Makori et al., 2017; Boyd & Pillai, 1985). Therefore, the high conductivity in Lake Buluan could be related to the combination of natural watershed processes and anthropogenic activities in the lake catchment including aquaculture and agricultural runoff (Quimpang et al., 2019).

Turbidity exhibited the greatest spatial variability among the measured parameters, ranging from 32 to 200 NTU. The highest turbidity was at S6 and lowest turbidity at S1. Elevated turbidity is associated with sediment resuspension, surface runoff, shoreline disturbance, fishing, and organic matter input (Boyd & Tucker, 2012). An increased turbidity reduces light penetration and may affect primary productivity, aquatic vegetation, and habitat quality. Nile tilapia, however, is a diverse species that can adapt to moderately turbid conditions (El-Sayed, 2020). The elevated turbidity recorded at several sampling sites may therefore not necessarily limit tilapia occurrence, although sustained increases could alter ecological processes and water quality conditions.

Nile Tilapia Abundance

A total of 237 Nile tilapia (*Orechromis niloticus)* individuals were recorded across eight sampling sites in Lake Buluan (Table 1). The abundance for each sampling site varied markedly, indicating a heterogeneous spatial distribution within the lake (Figure 3). The highest abundance was found in S4 with 85 individuals, accounting for 35.9% of the total catch, followed by S6 (38 individuals; 16.0%), S8 (32 individuals; 13.5%), S3 (24 individuals; 10.1%), S1 (21 individuals; 8.9%) and S5 (13 individuals; 5.5%).

Nile tilapia distribution in Lake Buluan is uneven which suggests habitat and resources availability differences. The high abundance at S4 indicates that the area can provide the habitat for fish growth, reproduction and survival (El-Sayed, 2020). Nile tilapia is known to thrive in shallow productive freshwater habitats with sufficient DO levels, good temperature and food sources. The dominance of the species at S4 reflect the combined influence of favorable physicochemical conditions and habitat characteristics that enhance its ecological success.

Spatial variation in fish abundance is a common feature of tropical freshwater ecosystems and is often due to environmental conditions, habitat complexity, food availability, hydrological processes, and anthropogenic activities (Jeppesen et al., 2014; Matthews, 1998). In Lake Buluan, physicochemical conditions of sampling sites can have influenced the abundance pattern. Sites with moderate temperature and sufficient DO concentrations and relatively stable environmental conditions are likely to provide more suitable habitats for Nile tilapia. The abundance at a lower level can be due to environmental conditions, habitat loss, fishing and/or local ecological issues.

Nile tilapia is widely recognized for its wide environmental tolerance and its adaptability to different freshwater conditions. However, changes in water quality (DO, temperature, pH, conductivity and turbidity) can play a role in fish physiology, feeding behavior, reproductive performance and population dynamics (El-Sayed 2020; Makori et al., 2017). Thus, these environmental factors may be responsible for the difference in abundance between sampling sites.

The predominance of Nile tilapia throughout Lake Buluan reflects its ecological adaptability and competitive advantage over many native freshwater fish species. Previous studies have shown that Nile tialpia has high growth rate, high reproductive ability, good utilization of food resources and tolerance to the various environmental conditions to survive in tropical freshwater ecosystems (Canonico et al., 2005; De Silva et al., 2004). This may explain its high prevalence and high numerical success in all sampling sites in this study.

Principal Component Analysis of Physicochemical Water Parameters and Nile Tilapia Abundance

The first two principal components explained 86.21% of the variance in the physicochemical data, with PC1 accounting for 44.99% and PC2 accounting for 41.22% (Figure 4). The large variance indicates that the first two components adequately described the environmental variability among sampling sites and also provided a good description of the most important physicochemical gradients in the lake. Similar proportions of the explained variance have been found to be sufficient for ecological interpretation in freshwater ecosystem studies with multivariate analysis (Jolliffe & Cadima, 2016; ter Braak & Šmilauer, 2014).

The PCA ordination revealed distinct clustering patterns among sampling sites, indicating spatial heterogeneity in water quality conditions across Lake Buluan. S3 and S5 clustered on the positive side of PC1 and were found to have similar physicochemical characteristics while S6, S7, and S8 were in a very close cluster on the negative side of PC1 and positive side of PC2. S2 was distinctly separated from the remaining sampling locations along the negative side of PC2, indicating unique environmental conditions, while S1 occupied an intermediate position. S4 was located near the center of the ordination space, suggesting transitional physicochemical characteristics between the major site groupings. The close clustering of replicate samples within each site further indicates consistency in the measured physicochemical parameters and supports the reliability of the sampling design.

The correlation circle identified pH, temperature, DO, specific conductivity and turbidity as the main variables contributing to the environmental gradients (Figure 5). Temperature and pH were positively correlated, as they were oriented in the same direction and warmer parts of the lake had higher pH values. This is typical in productive freshwater ecosystems where photosynthesis lowers dissolved carbon dioxide concentration and pH levels (Wetzel, 2001). DO, in contrast, was negatively correlated to temperature, due to less solubility of oxygen in warmer waters and hence higher metabolic oxygen requirements as high temperatures were encountered (Boyd & Tucker, 2012). Specific conductivity was negatively related to pH, suggesting different environmental conditions of the sampling sites, and that dissolved ionic content and watershed effects were different.

The PCA also showed that different regions of Lake Buluan had different physicochemical profiles. S3 and S5 were characterized by a relatively higher pH and temperature while S6, S7, and S8 had a more pronounced effect on conductivity and turbidity. These environmental variations may be due to hydrological processes, sediment dynamics, watershed inputs, and human activities in different parts of the lake. A similar pattern of water quality variation has also been found in tropical freshwater lakes where environmental conditions can affect habitat suitability and biological productivity (Jeppesen et al., 2014).

To further explore the relationship between environmental conditions and fish abundance, Nile tilapia abundance was projected as a supplementary variable onto the PCA ordination. The abundance vector was oriented towards the negative side of PC1 and was the most consistent with specific conductivity, suggesting that the conductivity in Nile tilapia is positively related to the fish abundance. Conductivity is often used as a proxy for dissolved ions, nutrients availability and ecosystem productivity and can increase food quality and fish biomass in freshwater (Dodds & Smith, 2016; Wetzel, 2001). Previous studies of tropical freshwater environments have shown positive correlations between conductivity and fish abundance with higher ionic levels indicating high levels of nutrients that can support phytoplankton and detrital production (Geidam et al., 2026; Euclide et al., 2023). The association thus suggests that areas with high conductivity have favourable habitat for Nile tilapia in Lake Buluan.

Nile tilapia abundance is negatively associated with pH and temperature and thus the abundance vector is not oriented in the same direction. Although Nile tilapia is very tolerant of different environmental conditions and can survive in a wide range of physicochemical parameters, too much warm water might lead to increased metabolic stress, reduced feeding efficiency, and changes in habitat suitability (El-Sayed, 2020). The inverse relationship with pH may reflect site-specific environmental conditions rather than direct physiological limitations, given that the measured pH values generally remained within the species' tolerance range.

The abundance vector was almost perpendicular to the DO vector, indicating a weak relationship between DO and Nile tilapia abundance at sampling sites. This finding may be attributed to the relatively narrow range of DO concentration observed throughout the lake, all of which exceeded the minimum requirement for freshwater fish survival. Consequently, DO was unlikely to be a limiting factor affecting tilapia distribution during sampling period. Similarly, turbidity exhibited only a weak positive association with abundance, suggesting that although Nile tilapia can tolerate moderately turbid conditions, turbidity along may not be a primary determinant of its spatial distribution.

Generalized Linear Model of Environmental Gradients and Nile Tilapia Abundance

A generalized linear model (GLM) with a Poisson distribution and log-link function was employed to evaluate the influence of PCA-derived environmental gradients on the abundance of Nile tilapia *(O. niloticus)* in Lake Buluan (Table 2). The overall model was highly significant (χ^2=75.50, df = 2, $p < 0.001$), indicating that the principal environmental gradients identified though PCA significantly influenced the spatial distribution of Nile tilapia. The model explained about 20.6% of the variations in abundance (Pseudo-R^2 = 0.206), implying that physiochemical conditions had to play a significant role in the abundance patterns, but other ecological factors, such as climate, also played a role in the distribution of the species.

Among the predictor variables, PC1 had a significant negative effect on the abundance of Nile tilapia (β = -0.371, SE + 0.047, z = -7.932, $p <$ 0.001). The incidence rate ratio (Exp(B) = 0.690) indicates that for every one-unit increase in PC1, the expected abundance of Nile tilapia decreased by approximately 31%. In contrast, PC2 did not significantly influence abundance (β = 0.036, SE = 0.037, z = 0.973, p + 0.331), indicating that the secondary environmental gradient represented by this component contributed minimally to the observed variation in fish abundance.

The significant influence of PC1 is ecologically meaningful because this component was primarily associated with increasing pH and temperature decreasing specific conductivity and turbidity (Table 3), as identified in the PCA correlation circle. Thus, the negative regression coefficient indicates that Nile tilapia abundance decreases in sites with relatively high pH and temperature and rises in sites with high conductivity and turbidity. These results indicate that the environmental gradient of PC1 was the main physiochemical driver of Nile tilapia abundance in Lake Buluan.

The positive association between Nile tilapia abundance and specific conductivity may reflect better ecosystem productivity in areas with higher concentrations of dissolved ions and nutrients. Conductivity is frequently used as an indicator of nutrient enrichment and ionic availability in freshwater ecosystems and may enhance primary productivity and lead to higher levels of trophic production (Dodds & Smith, 2016; Wetzel, 2001). Studies in comparable tropical lake systems have shown that conductivity ranging from 100 to 2,000 µS/cm is favorable for fish growth and production, as it reflects optimal nutrient conditions for sustaining food webs (Geidam et al., 2026; Makori et al., 2017). The high conductivity values (15,200-23,000 µS/cm) indicates rich nutrients and may explain the high tilapia population but these values are beyond the typical range of the freshwater environment and need further investigation. Increased productivity may enhance food availability for tilapia through greater phytoplankton and detrital production, thereby availability for tilapia through greater phytoplankton and detrital production, thereby supporting larger populations. Similarly, the weak positive association between abundance and turbidity may reflect the species' adaptability to moderately turbid environments. Nile tilapia is known to tolerate elevated turbidity levels and may benefit from reduced predation pressure and increased availability of suspended food particles in productive waters (El-Sayed, 2020). Studies have shown that turbid conditions may reduce visual predation on juvenile tilapia while providing sufficient light to produce phytoplankton that is required in the food chain (Roth et al., 2025; Qiu et al., 2024). However, turbidity above 100 NTU can affect feeding efficiency and gill function, and the high turbidity values at some Lake Buluan sites (up to 200 NTU) could represent suboptimal conditions for tilapia.

The negative correlation with abundance and temperature indicates that higher temperatures may decrease habitat suitability in some areas of the lake. While the eurythermal Nile tilapia is able to grow at a wide temperature range, increased temperatures can affect metabolism, feeding efficiency and physiological functioning (El-Sayed, 2020; Azaza et al., 2008). Nile tilapia can grow at a temperature range of 26°C to 30°C but performance is lower at temperatures above 32°C due to the thermal stress and reduced DO solubility (Hamed et al., 2024; Hamed et al., 2021). Lake Buluan (28.0-31.8°C) is at the upper end of the species temperature optimum, hence the negative relationship with abundance. The relationship above suggests that in the lake, areas at lower temperatures could provide better conditions to sustain larger tilapia populations.

A negative association was also observed between abundance and pH. However, pH values across Lake Buluan generally remained within the tolerance level of Nile tilapia, this is probably due to the environmental differences in sampling sites and not to any physiological limitations. Similar observations have been reported in freshwater ecosystems where pH functions as an indirect indicator of broader environmental processes influencing fish distribution and habitat quality (Boyd & Tucker, 2012).

The absence of a significant effect of PC2 indicated that the environmental gradient represented primarily by DO and secondary variation in temperature and turbidity had limited influence on Nile tilapia abundance during the sampling period. DO concentrations were higher than the minimum required for freshwater fisheries at all sampling sites and oxygen availability was not an issue for the species. This finding is consistent with previous studies demonstrating that Nile tilapia can maintain normal growth and survival when DO concentrations remain within acceptable ecological ranges (Makori et al., 2017).

Although the model showed significant relationships between physiochemical gradients and Nile tilapia abundance, the relatively small explanatory power (Pseudo-R^2 = 0.206) indicates that environmental conditions alone do not fully explain abundance patterns in Lake Buluan. This level of explained variance is consistent with other fisheries studies employing PCA-based environmental models where Pseudo-R^2 values typically range from 0.15 to 0.35 because of the effects of unmeasured variables (Geidam et al., 2026; Euclide et al., 2023). Fish abundance is influenced by various interaction of abiotic and biotic factors, including habitat structure, food resource availability, fishing pressure, reproductive dynamics, interspecific competition, and hydrological conditions (Jeppesen et al., 2014; Matthews, 1998). In Lake Buluan, additional factors such as aquaculture activities, fishing intensity, and seasonal hydrological fluctuations likely contribute to the spatial variation in tilapia abundance nont captured by the physicochemical gradients alone (Quimpang et al., 2019). Consequently, while conductivity, turbidity, temperature, and pH emerged as important environmental correlated of Nile tilapia abundance, additional ecological variables should be considered in future studies to develop a more comprehensive understanding of the factors governing fish distribution and productivity in Lake Buluan.

Conclusion and Recommendations

This study examined the environmental drivers of Nile tilapia *(Oreochromis niloticus)* abundance in Lake Buluan through analysis of selected physicochemical water quality parameters using Principal Component Analysis (PCA) and Generalized Linear Model (GLM). The physicochemical assessment revealed that DO and pH generally remained within acceptable ranges for freshwater fisheries, while temperature, specific conductivity, and turbidity exhibited notable spatial variation among sampling sites. These finding indicate the presence of environmental heterogeneity within the lake that may influence habitat suitability for fish populations.

A total of 237 Nile tilapia individuals were recorded across the eight sampling sites, with abundance varying considerably among locations. The highest abundance was observed at S4 which indicates that local environmental conditions may play an important role in determining habitat suitability and fish distribution within the lake.
PCA described the physicochemical variability of Lake Buluan, where the first two principal components account for 86.21% of the variance. The analysis determined the major environmental gradients of the lake to be conductivity, pH, temperature, and turbidity. Based on the PCA ordination, the abundance of Nile tilapia was shown to be positively associated with conductivity and turbidity and negatively associated with pH and temperature.

The GLM also showed that the primary environmental gradient PC1 was significant for Nile tilapia abundance, but the second gradient PC2 did not affect the abundance. In the model, sites with higher conductivity and turbidity but lower temperature and pH were associated with a larger abundance of Nile tilapia.

Overall, the study demonstrates that physicochemical water quality contributes significantly to the spatial variation of Nile tilapia abundance in Lake Buluan, with conductivity, temperature, pH, and turbidity emerging as important environmental correlates. Nevertheless, additional ecological and anthropogenic factors likely influence fish abundance and should be considered in future fisheries management and ecological investigations. Based on the findigs of this study, the following recommendations are proposed:

1. Implement regular water quality monitoring programs in Lake Buluan to track temporal changes in DO, pH, temperature, conductivity, and turbidity, particularly in areas exhibiting high fisheries productivity.
2. Prioritize the protection ang management of habitats associated with high Nile tilapia abundance, particularly sites exhibiting favorable physicochemical conditions, to sustain fisheries production and support local livelihoods
3. Develop science-based fisheries management strategies that integrate water quality conservation, habitat protection, and sustainable harvesting practices to ensure long-term productivity and ecological integrity of Lake Buluan.

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Figures

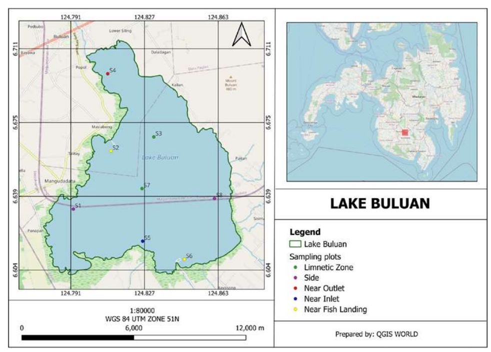

Figure 1. Map of the Sampling Sites in Lake Buluan.

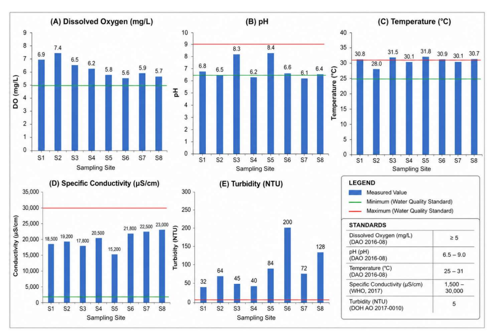

Figure 2. Graph in dissolved oxygen, pH, temperature specific conductivity, and turbidity among sampling sites in Lake Buluan.

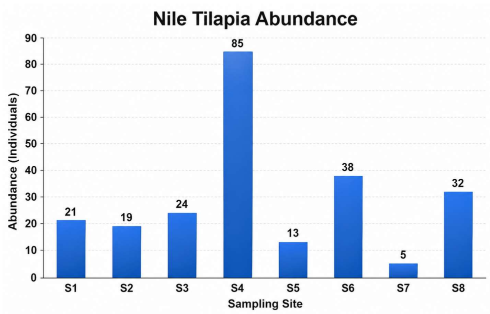

Figure 3. Abundance of Nile tilapia *(Oreochromis niloticus)* across eight sampling sites in Lake Buluan.

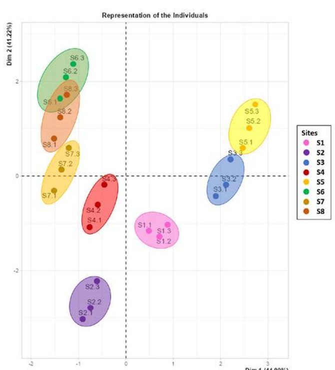

Figure 4. Principal Component Analysis (PCA) ordination showing the distribution of smapling sites based on physicochemical water quality parameters in Lake Buluan.

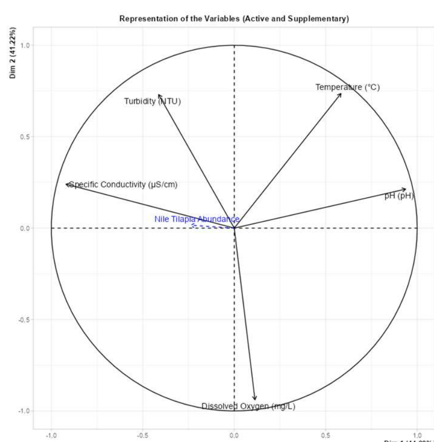

Figure 5. Principal Component Analysis (PCA) correlation circle illustrating relationships among physicochemical water quality parameters and Nile tilapia abundance in Lake Buluan.

Tables

Table 1. Abundance and relative abundance of Nile tilapia (*Oreochromis niloticus)* across sampling site in Lake Buluan.

Site	Abundance (Individuals)	Relative Abundance (%)
S1	21	8.9
S2	19	8
S3	24	10.1
S4	85	35.9
S5	13	5.5
S6	38	16
S7	5	2.1
S8	32	13.5
Total	**237**	**100**

Table 2. Results of the generalized linear model (Poisson distribution with log-link function) assessing the effects of PCA-derived environmental gradients on Nile tilapia *(Oreochromis niloticus)* abundance.

Exp(B) 95% Confidence Intervals

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-

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25 30

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0.6

0.

PC1 -7.932

83.15

3.3287

		0.				
			0.	1.		0.
		1.0				
PC2	0.0355				0.973	

Table 3. Principal Component Analysis (PCA) loadings, component scores, and uniqueness values for physicochemical water quality variables and Nile tilapia *(Oreochromis niloticus)* abundance in Lake Buluan.

	Component		**Unique**
	1	**2**	
Dissolved Oxygen (mg/L)		-0.948	0.1012
pH (pH)	0.959		0.0667
Specific Conductivity (µS/cm)	-0.881	0.327	0.1176
Temperature (°C)	0.63	0.68	0.1405
Turbidity (NTU)	-0.306	0.761	0.3265
Nile Tilapia Abundance	-0.394		0.8403

Note. 'varimax' rotation was used