ISBN: 978-628-96613-3-0. ISSN: 2414-6390. Digital Object Identifier: https://dx.doi.org/10.18687/LACCEI2026.1.1.374

Spatial and Temporal Dynamics of Trophic State Indicators in Lake Yojoa (2022-2025)

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Abstract– Eutrophication processes in lakes generate significant impacts on both aquatic biodiversity and the livelihoods of communities that depend on these ecosystems. This study evaluated the water quality of Lake Yojoa, Honduras, by analyzing temporal trends, spatial differences among three sites distributed from north to south, and the vertical structure of the water column. The research combined data from two monitoring periods (November 2022–April 2023 and November 2024–April 2025). Physicochemical variables such as Secchi depth, total phosphorus, total nitrogen, dissolved oxygen, and pH were analyzed to identify temporal and spatial patterns. In addition, the Trophic State Index (TSI) was calculated using Secchi depth, total phosphorus, and total nitrogen. Results showed increased water transparency and higher total nitrogen concentrations during 2024–2025, while total phosphorus remained relatively stable between periods. No significant differences were detected in surface water (epilimnion) among sites, suggesting a homogeneous composition likely driven by wind-induced mixing. In contrast, vertical profiles revealed significant differences in temperature, dissolved oxygen, phosphorus, and salinity, indicating thermal stratification and nutrient accumulation in deeper layers. Overall, the findings provide evidence of slight improvements in some water quality indicators after the reduction of intensive cage aquaculture, while also highlighting the persistent influence of internal and external nutrient loading on the trophic state of Lake Yojoa.

Keywords-- Lake Yojoa; eutrophication; trophic state index; nutrient loading; water quality.

I. INTRODUCTION

Aquatic ecosystems are essential not only for sustaining biodiversity but also for supporting the economic and social development of regions that depend on them. These systems provide important ecosystem services including fisheries, agriculture, mineral extraction, and renewable energy resources [1]. However, these activities can pose significant environmental risks because aquatic ecosystems are highly vulnerable to contamination from anthropogenic sources, which affects biodiversity and compromises sustainability. One of the main threats to aquatic ecosystems is nutrient-driven pollution, which alters nutrient flows and promotes eutrophication—a phenomenon characterized by nutrient enrichment and the excessive proliferation of algae and aquatic plants [2].

Eutrophication is one of the leading causes of degradation in both freshwater and marine ecosystems. It is driven primarily by excessive inputs of nitrogen and phosphorus derived from human activities. This process stimulates excessive algal growth, reducing dissolved oxygen concentrations and creating hypoxic zones that can lead to the death of aquatic organisms and negatively affect productivity and sustainability. Moreover, the decomposition of accumulated organic matter contributes to the emission of gases that produce unpleasant odors and local discomfort. Effective management practices—including improved environmental governance and stronger water-resource protection measures—are needed to mitigate these impacts [3]. In lacustrine ecosystems, eutrophication disrupts system functioning, decreases biotic diversity, alters community structure, and reduces water quality, which diminishes ecological value and restricts uses such as fishing and tourism [4].

Lake Yojoa is the only natural freshwater lake in Honduras and represents an important economic resource for the region. Its watershed hosts multiple anthropogenic activities, including agriculture, livestock production, mining, and tourism, all of which exert pressure on the ecosystem. Intensive aquaculture—particularly tilapia cage farming, which expanded substantially since the early 2000s—has become one of the main contributors of nutrient enrichment due to high releases of organic waste and uneaten feed. Tourism can also increase contamination when not adequately managed. These nutrient inputs alter the lake's trophic balance and promote uncontrolled growth of algae and phytoplankton [5].

Assessing the trophic state of a lake requires multiple indicators that reflect eutrophication processes. Key indicators include total phosphorus and total nitrogen concentrations, as these nutrients drive phytoplankton growth. Water transparency, commonly measured with a Secchi disk, provides insight into suspended particles such as algae and sediments. Additionally, chlorophyll-a concentration is a crucial parameter because it quantifies phytoplankton biomass [6]. The integration of these parameters enables a comprehensive evaluation of the trophic status of a natural reservoir.

The concept of the water column refers to the vertical continuum from the lake surface to the bottom, whose depth varies across the basin. Studying the water column allows the identification of processes such as thermal stratification, nutrient distribution, and oxygen availability [7]. Physicochemical analyses of the water column help reveal anthropogenic impacts and their effects on water quality [8, 9].

Characterizing nutrient dynamics, trophic state, and water-column conditions in Lake Yojoa is essential for evaluating the effects of contamination-prevention measures implemented in 2024 and for informing future management and conservation strategies. The use of modern analytical techniques enables a detailed diagnosis of current lake conditions, which can guide targeted recommendations to improve long-term ecosystem health [10]. This is crucial not only for biodiversity conservation but also for supporting the livelihoods of surrounding communities.

The main objective of this study is to evaluate the evolution of the trophic state of Lake Yojoa through the analysis of temporal trends, spatial comparisons, and vertical characterization of physicochemical parameters during the 2022–2023 and 2024–2025 monitoring periods. The specific objectives are: (i) to analyze temporal trends of trophic state variables between both periods; (ii) to compare key physicochemical parameters related to eutrophication among sampling sites; and (iii) to characterize stratification patterns in the water column across the three selected sites.

II. Materials and methods

A. Study Area

The study was conducted in Lake Yojoa, Honduras, between November 2024 and April 2025, and was complemented with data from a previous monitoring period carried out from November 2022 to April 2023 [11]. Lake Yojoa is situated between the departments of Comayagua, Cortés, and Santa Bárbara, at an elevation of 680 masl and with an average temperature of 23.4 °C. Annual precipitation ranges from 1,800 to 2,500 mm. The lake measures approximately 16 km in length and 6 km in width, covering a total surface area of 83 km². Its average depth is 14.63 m, and the maximum depth recorded during the study period was 29 m [12].

Previous research has identified five longitudinal sampling points used for semi-monthly monitoring since 2018 [13]. For the present study, three sites were selected to capture contrasting anthropogenic influences, designated R, B and E (Fig. 1). Site R is located in the northern zone and is influenced by nearby residential, mining and agricultural activity. Site E lies close to the area previously impacted by intensive tilapia cage aquaculture, which historically represented a major source of nutrient input. Site B receives drainage from urban and tourism-related activities and reflects pressures associated with these sectors.

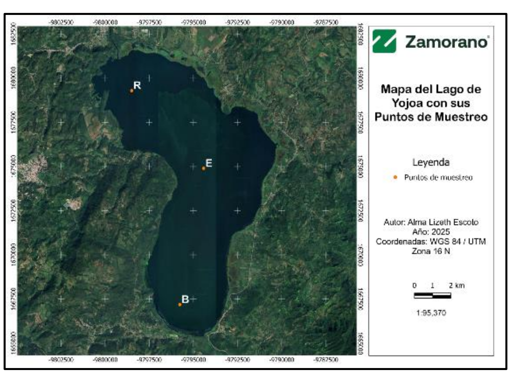

Fig. 1 Sampling locations (R, B, and E) in Lake Yojoa, Honduras.

B. Sampling Procedures and Evaluated Parameters

Water samples were collected every 16 days over a six-month period to evaluate nutrient dynamics and physicochemical conditions in the lake. A total of 30 samples were collected during the 2024–2025 period and 33 samples during the 2022–2023 period [11]. All samples were obtained at a depth of 1 m using a Van Dorn sampler. The sampling schedule and nomenclature assigned to each date are presented in Table 1.

TABLE I
Sampling dates and assigned nomenclature for each monitoring period

Nomenclature	Period 1 (2022-2023)	Period 2 (2024-2025)
Nov1	14/11/2022	11/11/2024
Nov2	22/11/2022	26/11/2024
Dic1	14/12/2022	12/12/2024
Dic2	23/12/2022	27/12/2024
Ene1	9/1/2023	14/01/2025
Ene2	23/01/2023	29/01/2025
Feb1	9/2/2023	14/02/2025
Feb2	25/02/2023	-
Mar1	14/3/2023	3/3/2025
Mar2	29/3/2023	18/3/2025
Abr1	14/4/2023	4/4/2025

Note. In Period 2, no second February sample was collected because the 16-day interval shifted the following sampling date to March.

The sampling window between November and April corresponds to the dry season in the Lake Yojoa basin, which is characterized by reduced surface runoff and greater hydrological stability. These conditions facilitate the detection of clear trophic-state patterns. Although sampling was limited to a single climatic season, the consistent six-month coverage and the 16-day interval were sufficient to capture short-term variability in the parameters of interest.

In March, an additional vertical sampling campaign was carried out at each of the three sites. Measurements were taken at depths of 1 m and 2 m and continued at 2 m intervals until the lake bottom was reached. This allowed a detailed characterization of the vertical structure of the water column. All collected samples were stored in white polyethylene bottles, preserved with sulfuric acid (H_2SO_4), refrigerated, frozen and transported to the Water Quality Laboratory of Zamorano University for subsequent analysis.

C. Analytical Methods

All laboratory procedures followed the guidelines established in *Standard Methods for the Examination of Water and Wastewater* [14]. Total nitrogen was determined through persulfate digestion and quantified using a Lovibond® visible spectrophotometer. Nitrate was analyzed using the second-derivative UV-visible spectrophotometric method with an Agilent® instrument. Total phosphorus was quantified by applying the ascorbic acid method described in *Standard Methods* [14], followed by spectrophotometric analysis using a Lovibond® instrument. Secchi depth was measured in situ with a standard Secchi disk.

Additional physicochemical parameters—temperature, dissolved oxygen, pH, conductivity, salinity and turbidity—were recorded using a Hydrolab® MS5 multiparameter probe. Interpretation of these variables was supported by established literature on lake eutrophication [15–19].

D. Trophic State Index (TSI)

To assess eutrophication patterns and biological productivity, the study employed Carlson's Trophic State Index. Transparency was evaluated through the Secchi depth-based TSI-SD equation [20]. Total phosphorus concentrations were used to calculate TSI-TP, also following the original model [20]. Total nitrogen contributions to trophic status were assessed using TSI-TN, based on the modified model developed for nitrogen evaluation [21]. These indices provided a quantitative assessment of lake productivity by integrating transparency and nutrient availability. Classification thresholds used in this study followed the interpretation ranges presented in previous work on trophic-state categorization [22].

E. Water-Column Physicochemical Analysis

Vertical profiling was performed at sites B, E and R to analyze the structural behavior of the water column and to identify physical and chemical gradients. Graphical representations of the profiles allowed the identification of thermal stratification, dissolved oxygen distribution and changes in chemical composition. Water temperature plays a central role in oxygen solubility, thermal layering and reaction kinetics, making it a key variable in the analysis of lake dynamics [17].

Turbidity measurements obtained with a HACH® turbidimeter provided information on suspended particles and light penetration, which influence algal biomass and photosynthetic activity [16]. Dissolved oxygen was analyzed to evaluate the potential occurrence of hypoxic or anoxic conditions associated with eutrophication. The pH of the water was also examined because it affects nutrient solubility, species adaptation and potential toxicity and responds to processes associated with contamination and acidification [18]. Electrical conductivity measurements helped identify variations in ionic concentration linked to dissolved solids and potential contamination inputs [19].

F. Statistical Analyses

Temporal and spatial trends were evaluated by comparing physicochemical variables and TSI values across study periods and sampling sites. Data distribution was assessed using the Shapiro–Wilk normality test, which is broadly applied in water-quality studies [23, 24]. When variables followed a normal distribution, comparisons between periods were performed using Student's t-test for independent samples. When the normality assumption was not met, the Mann–Whitney U test was applied [25].

Comparisons among the three sampling sites followed the same evaluation of normality. When data met parametric assumptions, one-way ANOVA was used, consistent with common approaches in spatial water-quality assessments [26]. For variables that did not exhibit a normal distribution, the Kruskal–Wallis test was applied. In cases where significant differences were observed, post-hoc analyses were performed using Tukey corrections for ANOVA results [27] and Bonferroni adjustments for Kruskal–Wallis outcomes [28]. Graphical representations, including boxplots, were used to support interpretation.

For water-column comparisons, mean values at each depth were analyzed to identify vertical patterns across sites. Shapiro–Wilk testing was again used to assess normality, guiding the selection between ANOVA and Kruskal–Wallis tests. Post-hoc procedures were applied as needed to determine which site pairs differed significantly. All statistical analyses were conducted using the JASP software package (version 0.19.1.0).

III. Results and Discussion

A. Temporal Trends Between Monitoring Periods

1) Secci Depth: Secchi depth exhibited a marked improvement in water transparency between the two monitoring periods. Mean transparency increased from 3.13 m in 2022–2023 to 4.61 m in 2024–2025, and minimum–maximum values were also higher in the second cycle. These changes indicate clearer conditions and increased variability. Corresponding TSI-SD values ranged from 34 to 47 in both cycles, classifying surface conditions from oligotrophic to mesotrophic. Although this may suggest reduced suspended matter, transparency can also be influenced by seasonal dilution, solar radiation or sediment resuspension [29] . Higher rainfall recorded early in 2024–2025 likely contributed to improved clarity.

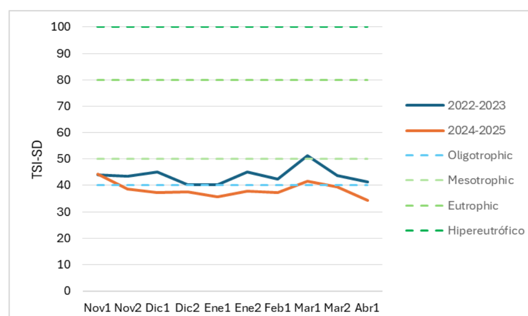

Fig. 2 Temporal variation of Secci depth.

2) Total Phosphorus: Total phosphorus showed no substantial temporal variation, with both cycles presenting a mean of 0.13 mg/L and similar dispersion. Despite the stability, maximum values increased slightly in 2024–2025. TSI-TPvalues placed the lake consistently in eutrophic conditions with occasional hypereutrophic events. This persistence indicates the combined effect of external nutrient inputs and internal sediment release under anoxic conditions, a process common in tropical lakes [30].

3) Total Nitrogen: Total nitrogen increased notably between periods, rising from 0.74 mg/L to 1.06 mg/L. TSI-TN values ranged from mesotrophic to eutrophic and were systematically higher in 2024–2025. These patterns align with watershed contributions from agriculture, aquaculture and residential activity [31, 32]. Together, these trends indicate that although transparency improved, nutrient enrichment remains a dominant pressure.

B. Spatial Variability Among Sampling Sites

Surface conditions were relatively homogeneous among the sampling sites (B, E and R). Secchi depth was highest at site R and lowest at site B, but statistical analyses did not detect significant differences. Total phosphorus and nitrogen also showed no significant spatial differences despite modest numerical variability. Dissolved oxygen and pH remained within acceptable ecological ranges across sites, suggesting an actively mixed epilimnion influenced by wind exposure and internal circulation.

C. Statistical Comparison Between Monitoring Periods

Statistical comparisons showed significant differences only for Secchi depth and total nitrogen. Transparency increased significantly in 2024–2025 ($p < 0.001$), while nitrogen also rose significantly ($p = 0.031$). Total phosphorus, dissolved oxygen and pH showed no significant differences between periods, although phosphorus consistently exceeded eutrophication risk thresholds [33]. Boxplots summarizing these comparisons are omitted here to comply with the two-figure limit.

D. Vertical Profiles of Physicochemical Parameters

1) Dissolved Oxygen: Dissolved oxygen profiles exhibited clear stratification patterns. Sites E and R developed anoxic conditions below 10 m, while site B remained more oxygenated throughout the water column due to greater mixing. Statistical analyses confirmed significant differences among sites, indicating contrasting mixing regimes and stronger stratification at deeper locations [34].

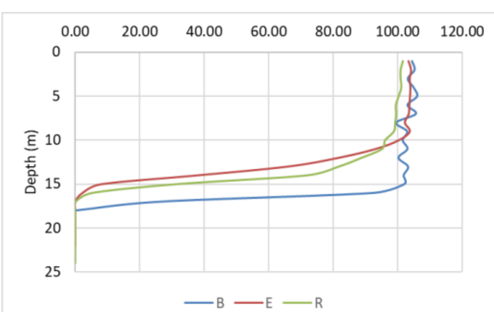

Fig. 3 Vertical dissolved oxygen profile.

2) Temperature, pH, Conductivity and Nutrients: Temperature decreased gradually with depth at all sites, indicating partial stratification. Corresponding pH declined with depth due to CO_2 accumulation, and conductivity was significantly higher at site B, reflecting more mineralized inflows. Total phosphorus and phosphate accumulated in the hypolimnion at site R, consistent with internal loading [35]. Nitrogen species showed greater mobility and spatial homogeneity, with nitrate significantly lower at site B due to stronger mixing and shorter residence time [13].

E. Implications for Lake Recovery

Despite signs of improved clarity, persistent eutrophic phosphorus levels, high nitrogen concentrations and deep-water anoxia indicate that Lake Yojoa remains strongly affected by eutrophication. Recovery in tropical lakes with similar characteristics may require 10–20 years due to sustained internal loading and watershed nutrient inputs [36–38]. Long-term management strategies addressing both external and internal sources are essential for ecological restoration.

IV. Conclusions

The temporal and spatial analyses conducted in Lake Yojoa demonstrate that, although water transparency improved during the 2024–2025 monitoring period, nutrient enrichment remains a persistent pressure on the ecosystem. Secchi depth increased significantly between periods, indicating clearer surface conditions likely influenced by rainfall-driven dilution and reduced suspended solids. However, total phosphorus remained consistently within eutrophic ranges across both monitoring cycles, and total nitrogen increased significantly in the second period, reflecting sustained external contributions from agricultural, aquaculture and urban sources. These trends confirm that improvements in clarity do not necessarily correspond to a reduction in trophic state.

Surface conditions were relatively homogeneous among sampling sites, suggesting strong influence of wind-driven mixing and epilimnetic circulation. Nevertheless, vertical analyses revealed clear stratification, with deep-water anoxia developing below 10 m in sites E and R and promoting internal phosphorus loading. This process, together with watershed nutrient inputs, continues to reinforce eutrophic conditions throughout the system. In contrast, nitrogen species exhibited greater vertical mobility and a more uniform distribution, consistent with watershed-driven dynamics and rapid mixing in shallow areas.

Overall, the combined evidence shows that Lake Yojoa remains in a eutrophic state despite localized improvements in optical properties. Internal loading, deep-water anoxia and sustained nutrient inflows suggest that ecological recovery will require long-term management efforts. Mitigation strategies must target both external nutrient sources in the watershed and internal processes occurring in bottom sediments to achieve meaningful and lasting improvements in water quality.

V. Recommendations

Based on the observed trends, management actions should prioritize the reduction of external nutrient inputs from agricultural, aquaculture and residential sources within the Lake Yojoa watershed. Strengthening erosion control, improving wastewater handling and promoting best management practices in fertilizer application would help reduce nitrogen and phosphorus inflows. Given the evidence of internal phosphorus loading, complementary measures targeting sediment processes should also be considered, particularly in deeper areas where anoxia persists. Long-term monitoring of key physicochemical and trophic indicators is essential to detect changes in water quality and assess the effectiveness of management interventions. Establishing integrated watershed–lake management plans will be critical to support the ecological recovery and long-term sustainability of Lake Yojoa.

Acknowledgment

The authors thank the Zamorano University Water Quality Laboratory for providing analytical support and access to monitoring equipment. Special appreciation is extended to the field and laboratory teams for their assistance during sample collection and data processing, and to the academic advisors who provided guidance throughout the study. The authors also acknowledge the institutions and local stakeholders involved in the management of Lake Yojoa for facilitating access to the study area.

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