

Article

Environmental Patterns of Phytoplankton Community Composition Across Lentic and Lotic Systems in Ecuador

Andrés Arévalo-Moreno ¹, Mabel Cadena ², Kevin Valencia ³ and Ibon Tobes ^{1,*}¹ Centro de Investigación de la Biodiversidad y Cambio Climático (BioCamb), Facultad de Ciencias de Medio Ambiente, Universidad Tecnológica Indoamérica, Quito 170103, Ecuador; aarevalo2@indoamerica.edu.ec² Departamento de Planificación Estratégica, Universidad Metropolitana del Ecuador, Quito 170517, Ecuador; mabelcadenazum@gmail.com³ Fundación Museos del Ecuador, Yaku Parque Museo del Agua, Quito 170407, Ecuador; kevin.valencia@fmcquito.gob.ec

* Correspondence: ibontobes@uti.edu.ec

Abstract

Phytoplankton are key indicators of water quality and low-cost tools for freshwater monitoring, yet their diversity and ecological drivers remain poorly documented in the Tropical Andes. This study provides the first national-scale, multi-ecosystem assessment of net phytoplanktonic communities (including microalgae and cyanobacteria), across Ecuador, integrating physicochemical, multivariate, and geospatial analyses. Eighteen lakes and rivers from three biogeographic regions and a wide altitudinal gradient were surveyed, yielding 129 taxa, 77 identified at species level, the most comprehensive checklist reported to date for Ecuador. Community structure showed a clear lentic–lotic differentiation driven by hydrodynamic contrasts, while the absence of distance–decay patterns indicated high dispersal and environmental filtering pattern rather than spatial structuring. Anthropogenic pressure acted as a secondary gradient: pristine high-Andean lakes were dominated by desmids and diatoms, whereas agricultural and urban basins showed chlorophyte and potentially toxic cyanobacterial assemblages. Palmer’s Index detected organic pollution but underestimated eutrophication in endorheic, geochemically enriched lakes. Land-use effects presented strong basin-scale signals in lakes but weak correlations in rivers due to overriding hydromorphological constraints. These findings establish a robust spatial baseline for freshwater bioassessment in the Andes, demonstrating the value of phytoplankton as effective, low-cost indicators readily applicable to national water-quality assessment programs.

Keywords: cyanobacteria; tropical Andes; microalgae; bioindicators; high-altitude lakes; Palmer organic pollution index; land-use impacts



Academic Editor: Ryszard Goldyn

Received: 4 December 2025

Revised: 8 January 2026

Accepted: 15 January 2026

Published: 15 February 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Ecuadorian aquatic ecosystems exhibit great diversity due to their distribution across the country’s three main continental natural regions: Coast, Sierra (Andean region), and Amazon [1]. The Andean region or Sierra hosts páramo ecosystems that serve as important water sources and include bofedales, as well as numerous lakes and lagoons of glacial and volcanic origin [2]. These formations feed an extensive network of watersheds that drain into the Pacific Ocean through 77 basins, while the Amazon region is traversed by seven basins covering 52% of the national territory [3]. Climatic factors such as evapotranspiration, precipitation, and relative humidity, along with edaphic and vegetation conditions, directly

influence the configuration and functioning of the hydrological systems in each region [4]. It is estimated that the country's annual volume of surface freshwater reaches 376.0 km³, distributed among rivers, lakes, and reservoirs [5].

These aquatic ecosystems fulfill fundamental roles by providing ecosystem services such as water supply, climate regulation, habitat for biodiversity, and opportunities for education and scientific research [6]. However, they face increasing pressures from anthropogenic activities including population growth, physical alterations of watercourses, deforestation, wetland degradation, continental water pollution, and mining [7]. Additionally, land-use changes such as agricultural expansion, urban growth, livestock activity, and watershed modification, constitute one of the most pervasive pressures driving ecological degradation [8]. These activities increase nutrient and sediment inputs, alter hydrological regimes, and modify key environmental gradients that directly shape phytoplankton communities [9,10]. Lakes and rivers located in basins with high proportions of anthropogenic land use typically exhibit deteriorated water quality, reduced habitat heterogeneity, and increased vulnerability to eutrophication processes [11]. Here, lentic and lotic ecosystems are compared based on their contrasting hydromorphological contexts rather than on water-quality thresholds.

Eutrophication is one of the main consequences of pollution, especially in lentic ecosystems affected by human activities such as agriculture, livestock farming, and direct discharge of wastewater. This process entails a progressive deterioration of water quality due to the excessive input of autochthonous or allochthonous nutrients [12], leading to an uncontrolled increase in phytoplankton biomass, particularly microalgae and cyanobacteria [13]. Changes in land use strongly modulate these processes because intensively managed agricultural and urbanized catchments act as continuous sources of nitrogen, phosphorus, and dissolved organic matter [14].

Due to their high sensitivity and rapid response to variations in nutrient and organic matter concentrations, phytoplankton communities have become effective tools for assessing water quality through bioindication [15]. These photosynthetic microorganisms, both eukaryotic and prokaryotic, occur in planktonic or benthic forms and colonize a wide range of freshwater habitats [16]. Their distribution in lotic and lentic ecosystems is regulated by environmental gradients associated with temperature, irradiance, nutrient availability, pH, turbidity, depth, and hydrodynamic regime [17]. Furthermore, their broad geographic distribution patterns are explained by their high capacity for passive dispersal, facilitated by atmospheric and biological vectors such as wind and aquatic birds, that enable their transport among watersheds and regions [18]. The organic pollution index proposed by Palmer [19] is one of the most widely used methods worldwide due to its applicability, low cost, and reliability. This index is based on the presence of genera or species tolerant to high levels of organic matter. Its correct application requires adequate taxonomic identification of the organisms present in each water body. In recent years, Palmer's index has been used to assess water quality in aquatic ecosystems both in Ecuador [20,21] and other regions worldwide [22–25].

Despite the ecological relevance of phytoplankton in Andean freshwater systems, existing studies in Ecuador remain spatially isolated and taxonomically incomplete. Most research has focused on individual lakes, single river reaches, or localized watershed assessments, without providing an integrated perspective across lentic and lotic environments or across the country's major biogeographic regions. Furthermore, previous work has rarely combined taxonomic inventories, Palmer's organic pollution index, and multivariate analyses within the same analytical framework. As a result, there is still no baseline describing how environmental gradients, land use, and hydrodynamics jointly structure phytoplankton communities at a national scale.

Addressing this gap is essential for informing freshwater monitoring programs and for understanding the ecological responses of tropical mountain watersheds to growing anthropogenic pressures. In this context, the present study provides the first national-scale, comparative assessment of phytoplankton community structure across 18 lentic and lotic ecosystems in Ecuador, integrating taxonomic inventories, Palmer's Index, multivariate community analyses, and geospatial land-use data to establish a spatial baseline across contrasting environmental, altitudinal, and land-use contexts

2. Materials and Methods

2.1. Study Area

The analyzed samples were collected from nine lakes and nine rivers located in various provinces across the Coast, Sierra, and Amazon regions of Ecuador (Figure 1, Table 1). These water bodies range in altitude from 5 to 3914 m above sea level. The wide altitude and geographic distribution along the mountain range, spanning both Amazonian and Pacific watersheds, generates highly diverse territorial contexts in terms of topography, climate, flora, fauna, and human settlements. The study sites were selected taking into account their altitudinal range, trophic status, and easy access for sample transport. For the purposes of this study, lentic and lotic systems were classified based on hydromorphological characteristics rather than on threshold values of water quality variables. Lentic systems correspond to standing waters with longer residence times, potential vertical stratification, and reduced turbulence, whereas lotic systems correspond to flowing waters characterized by unidirectional flow, shorter residence times, and higher physical disturbance. This classification was used consistently throughout the analyses.

Table 1. Geographical location and physicochemical characteristics (pH, temperature (°C), electrical conductivity (EC, $\mu\text{S cm}^{-1}$), and dissolved oxygen (DO, mg/L)) of the sampling sites across continental Ecuador. Site codes used in the figures combine the ecosystem type (L: lentic; R: lotic) with the initials of each water body and its elevation (e.g., LY2180), although in the table code and elevation are presented in separate columns for clarity.

Code	Altitude (m.a.s.l.)	Sampling Sites	Type of Ecosystem	Standard UTM	pH	T (°C)	EC ($\mu\text{S cm}^{-1}$)	DO (mg/L)
LY	2180	Yahuarcocha Lake	Lentic	17N 0822235 0040409	7.9	20.1	649	4.6
LSP	2672	San Pablo Lake	Lentic	17N 0807481 0023814	7.4	18.4	300	6.5
LS	2760	El Salado Lake	Lentic	18N 0189606 0064481	7	10.4	41	6.9
LYB	2767	Yambo Lake	Lentic	17M 0768255 9878620	8.7	17.9	2190	6.7
LC	3202	Caricocha Lake	Lentic	17N 0802961 0015187	7.2	14.4	39	7.4
LSM	3429	San Marcos Lake	Lentic	18N 0169786 0012537	8.1	12.2	38	7.1
LP	3436	Papallacta Lake	Lentic	17M 0816300 9958392	7.5	12.4	630	9.0
LT	3890	Toreadora Lake	Lentic	17M 0697554 9692753	7.5	10.4	46	6.8
LM	3914	La Mica Lake	Lentic	17M 0810222 9940119	7.7	10.8	321	6.9

Table 1. Cont.

Code	Altitude (m.a.s.l.)	Sampling Sites	Type of Ecosystem	Standard UTM	pH	T (°C)	EC ($\mu\text{S cm}^{-1}$)	DO (mg/L)
RM	5	Manta River	Lotic	17M 0530971 9894346	8.5	26.0	231	7.0
RS	720	Santiago River	Lotic	17M 0809152 9667703	7	20.4	71	6.9
RZ	890	Zamora River	Lotic	17M 0775510 9604375	7.1	17.2	86	6.5
RC	1070	Copueno River	Lotic	17M 0821765 9745407	7.9	11.8	81	7.2
RQ	1500	Quijos River	Lotic	18M 0191349 9965303	6.9	14.8	89	8.2
RA	1625	Abanico River	Lotic	17M 0811459 9751014	7.8	10.5	61	6.3
RP	2260	Pachanlica River	Lotic	17M 0767512 9853766	8.7	12.6	124	7.4
RAQ	2465	Apaquí River	Lotic	18N 0183536 0055325	8	13.6	106	7.1
RAA	3400	Agua Amarilla Stream	Lotic	18N 0194614 0080494	7.3	10.1	35	5.9

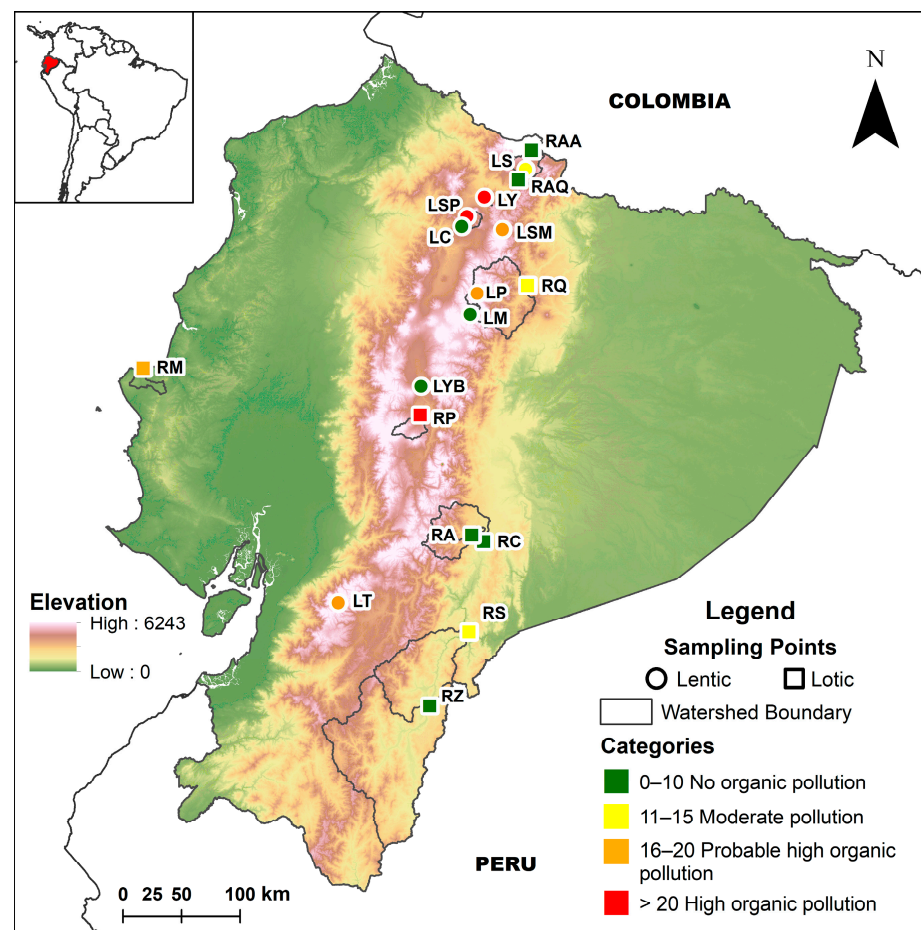


Figure 1. Geographical distribution of sampling sites across Ecuador. Circles indicate lentic systems and squares represent lotic systems. Colors correspond to Palmer's Index categories of organic pollution. Thin black lines delineate watershed boundaries for each sampling site.

2.2. Sample Collection and Analysis

Samples were collected at different times between January 2021 and November 2022. Sampling timing varied among sites; each site was sampled once, under comparable hydrological conditions (non-extreme events) and was not intended to capture seasonal succession. In both lakes and rivers, samples were collected using a plankton net with a 25 μm mesh size. This sampling approach primarily targets the net phytoplankton fraction, providing a standardized basis for comparing this component of community composition across sites. In lentic ecosystems, horizontal tows were performed on the lake surface with the plankton net in the limnetic zone for approximately one minute from a boat traveling at low speed. Additionally, in littoral areas, 100 L of water were towed and filtered using a 25-L stainless steel bucket. In lotic water bodies, 100 L of water were filtered through the plankton net. Depending on the river's size, the water sample was taken either at the bank or closer to the river's center. In both the littoral zone and the limnetic zone, samples of 250 mL were obtained in triplicate and subsequently fixed with Transeau solution in a 1:1 ratio [26]. For qualitative and quantitative analysis, Sedgwick-Rafter counting chambers were used. Taxonomic analysis was conducted with a Carl Zeiss Axio Vert. A1 (Carl Zeiss, Oberkochen, Germany) inverted microscope using 40 $\times$ and 63 $\times$ objectives.

Taxonomic identification was carried out using specialized literature: Bicudo & Menezes [26], Coesel & Meesters [27], Felisberto & Souza [28], Komárek [29], Kim [30–32], Komárek & Zapomelová [33], Rai & Misra [34] and Rosini et al. [35]. Additionally, the online database AlgaeBase [36] was used to verify valid names and synonyms.

2.3. Physicochemical Parameters

At each site, temperature ($^{\circ}\text{C}$), electrical conductivity ($\mu\text{S cm}^{-1}$), pH, and dissolved oxygen (mg/L) were measured in situ using a multiparameter YSI EXO1 device (YSI, Yellow Springs, OH, USA), previously calibrated with certified standards. In lakes, temperature and dissolved oxygen were measured in the surface layer of the water column (upper ~ 0.5 m), whereas in rivers measurements were taken at shallow depth in flowing water, representative of surface conditions. Physicochemical variables are presented to characterize environmental contexts across sites rather than to define threshold-based water quality categories or to perform replicated site-level comparisons.

2.4. Water Quality Assessment

Water quality was evaluated by applying Palmer's organic pollution index, which assigns scores to different phytoplankton genera based on their tolerance to organic matter (Table 2). The total score per site corresponds to the sum of the values assigned to the identified genera. The established categories were: 0–10 (no organic pollution), 11–15 (moderate pollution), 16–20 (probable high organic pollution), and >20 (high organic pollution). According to the original methodology, only genera with an abundance exceeding five individuals per milliliter were considered. In this study, Palmer's Organic Pollution Index was used as a qualitative, integrative biological indicator of organic enrichment and not as a quantitative proxy for chemical concentrations or nutrient gradients. Nutrient-related variables were not included because comparable data were not available for all sites.

2.5. Statistical Analysis

To assess sampling completeness and estimate total taxonomic richness, a species accumulation analysis was performed using presence/absence data from all 18 sites. The observed richness was compared with non-parametric estimators (Chao2, Jackknife1, and Bootstrap), appropriate for binary (presence/absence) data and moderate sample sizes. The analysis was performed in PRIMER v7 [37] with 999 random permutations and the

mean cumulative number of taxa per sample. Sampling completeness was calculated as the ratio between observed and estimated richness.

Table 2. Organic Pollution Index by phytoplankton genera [19].

Phytoplankton Genera	Pollution Index	Phytoplankton Genera	Pollution Index
<i>Anacystis</i>	1	<i>Micractinium</i>	1
<i>Ankisthodesmus</i>	2	<i>Navicula</i>	3
<i>Chlamydomonas</i>	4	<i>Nitzschia</i>	3
<i>Chlorella</i>	3	<i>Oscillatoria</i>	5
<i>Closterium</i>	1	<i>Pandorina</i>	1
<i>Cyclotella</i>	1	<i>Phacus</i>	2
<i>Euglena</i>	5	<i>Phormidium</i>	1
<i>Gomphonema</i>	1	<i>Scenedesmus</i>	4
<i>Lepociclis</i>	1	<i>Stigeoclonium</i>	2
<i>Melosira</i>	1	<i>Synedra</i>	2

Taxonomic richness was calculated as the number of taxa present at each site. Differences between lentic and lotic environments were tested using a Wilcoxon rank-sum test, and richness patterns were visualized with boxplots. To examine associations between environmental variables and taxonomic richness, negative binomial generalized linear models (GLMs) were used because the response variable exhibited overdispersion, with the variance exceeding the mean. Model diagnostics confirmed that the negative binomial distribution provided a better fit than Poisson models. Predictor variables included temperature (°C), electrical conductivity ($\mu\text{S cm}^{-1}$), pH, dissolved oxygen (mg/L), and the Palmer Algal Pollution Index. Collinearity was assessed using variance inflation factors (VIF), which indicated no problematic multicollinearity. Model selection followed a backward stepwise AIC procedure, implemented in the MASS package (version 7.3-60.2) in R (version 4.4.1) [38].

All spatial analyses were conducted using ArcGIS Pro (Version 3.5). Watershed delineation was based on the Shuttle Radar Topography Mission (SRTM) V3 30 m-resolution DEM [39]. The DEM was processed using standard hydrological tools, including Fill Sinks, Flow Direction, and Flow Accumulation. The Watershed tool was then applied using differentiated hydrological methodologies for each ecosystem type: for the 9 lotic sites, the upstream catchment was delineated from the sampling point, while for the 9 lentic sites, the complete drainage basin was delineated by manually identifying the outlet point of each lake.

Subsequently, these 18 watershed polygons were intersected with the Land Cover and Use map [40]. The “absolute anthropogenic area” was calculated as the sum of the area (in km^2) for all classes related to direct human activity, specifically agricultural land (defined as areas under crop and pasture rotation) and anthropic zones (including populated areas and infrastructure).

Finally, a Pearson Correlation was used to evaluate the relationship between the Palmer Index and the absolute anthropogenic area, analyzing the lentic and lotic subsets independently. Due to the wide distribution of the area data, this variable was $\log_{10}$ -transformed for the analysis.

To analyze community composition and similarity patterns, resemblance analyses were performed. All community analyses were based on presence/absence data, and interpretations therefore focus on community composition rather than quantitative dominance. Singleton taxa (present in only one site, $n = 33$; around 26% of the total) were removed to reduce noise and emphasize shared compositional patterns among sites. The similarity

matrix was constructed using the Jaccard coefficient and analyzed by hierarchical clustering (group-average linkage) with a SIMPROF test (999 permutations, $\alpha = 0.05$) performed using PRIMER-e v7 [37].

Additionally, differences in species composition were assessed using PERMANOVA with all taxa included (adonis2, binary Jaccard distances, 999 permutations) in R [38]. Two models were evaluated: (i) habitat type (lentic vs. lotic) and (ii) environmental variables (temperature, conductivity, pH, dissolved oxygen, and Palmer Index). Homogeneity of multivariate dispersion was tested using betadisper to determine whether significant PERMANOVA results reflected differences in centroid location or multivariate dispersion.

To test for spatial autocorrelation in community composition considering all taxa, we performed a Mantel test between Jaccard ecological distances (presence/absence) and Haversine geographic distances (9999 permutations) using R [38]. Geographic distances were calculated from site coordinates using a spherical Earth model (geosphere package). Ecological distances were computed using the vegdist function (binary Jaccard), and Mantel significance was evaluated under a free permutation model (vegan package, version 2.6-6.1).

To explore associations between phytoplankton community composition and broad physicochemical contexts, we performed a Canonical Correspondence Analysis (CCA) using PAST v4.11 [41]. Prior to ordination, and to reduce noise caused by extremely rare taxa, species occurring in ≤ 3 sites (tripletons and rarer) were removed, and 43 taxa were retained. Environmental variables included pH, temperature (T), electrical conductivity (EC), and dissolved oxygen (DO). Palmer's Index was excluded from the CCA because it is calculated directly from the presence of a subset of phytoplankton genera included in the species matrix, which would violate the assumption that explanatory variables are independent from the response and introduce circular species–environment relationships. Elevation was also removed because it is not a direct physicochemical variable; its effects on phytoplankton communities are expressed indirectly through changes in physicochemical conditions and, in this study, were reflected by a strong correlation with temperature ($r = -0.65$).

Significance of the CCA was assessed using permutation tests (999 permutations) for (1) the full model, (2) individual axes, and (3) individual terms. Given the exploratory nature of this analysis, interpretation focused on whether broad physicochemical contexts were associated with variation in community composition, while ordination plots were used as visualizations of species–environment relationships.

3. Results

3.1. Physicochemical Parameters of the Water

The pH of the water bodies ranged from 6.9 (Quijos River) to 8.7 (Yambo Lake and Pachanlica River), indicating neutral to slightly alkaline conditions (Table 1). Temperature varied between 10.1 °C (Agua Amarilla Stream) and 26.0 °C (Manta River), likely reflecting altitudinal differences among sites. Electrical conductivity showed a wide range: the highest value was recorded in Yambo Lake (2190 $\mu\text{S cm}^{-1}$) and the lowest in Agua Amarilla Stream (35 $\mu\text{S cm}^{-1}$). Regarding dissolved oxygen, values fluctuated between 4.6 mg/L (Yahuarcocha Lake) and 9.0 mg/L (Papallacta Lake), corresponding to trophic status and local environmental conditions.

3.2. Taxonomic Richness and Community Composition

Here, diversity is expressed as taxonomic richness and presence–absence–based community composition.

Qualitative analysis of samples from the 18 water bodies allowed the identification of 129 different phytoplankton taxa (microalgae and cyanobacteria) (Table S1). The estimators predicted slightly higher values (Chao2 = 144, Bootstrap = 145, and Jackknife1 = 160 taxa), indicating high sampling completeness ($\approx 80\text{--}90\%$) and suggesting that additional effort would yield few new taxa. The close agreement among estimators supports the adequacy of sampling coverage and the representativeness of the dataset for subsequent community analyses.

From the captured 129 taxa, 77 of them were identified to species level, and the remaining 52 to genus level. They were distributed across 90 genera, 58 families, 31 orders, 12 classes, and seven phyla. The most representative phyla were Charophyta (32%) and Chlorophyta (29%), followed by Heterokontophyta (19%) and Cyanobacteria (13%). Other phyla such as Euglenophyta, Dinoflagellata, and Cryptista had lower proportions. Additionally, 39 species were new records for Ecuador.

Taxonomic richness differed significantly between habitats (Figure 2). Lentic sites exhibited higher richness (mean = 34.1 ± 12.4 SD) than lotic sites (mean = 12.1 ± 5.5 SD), as confirmed by a Wilcoxon test ($W = 68$, $p = 0.017$). The negative binomial GLM indicated that habitat was strongly associated with taxonomic richness: lotic sites had 64% lower richness than lentic sites (estimate = -1.04 , $p < 0.001$). Environmental modeling further showed that the Palmer index displayed the strongest statistical association with taxonomic richness (estimate = 0.048 , $p < 0.001$), and simpler models including only Palmer performed as well as more complex ones.

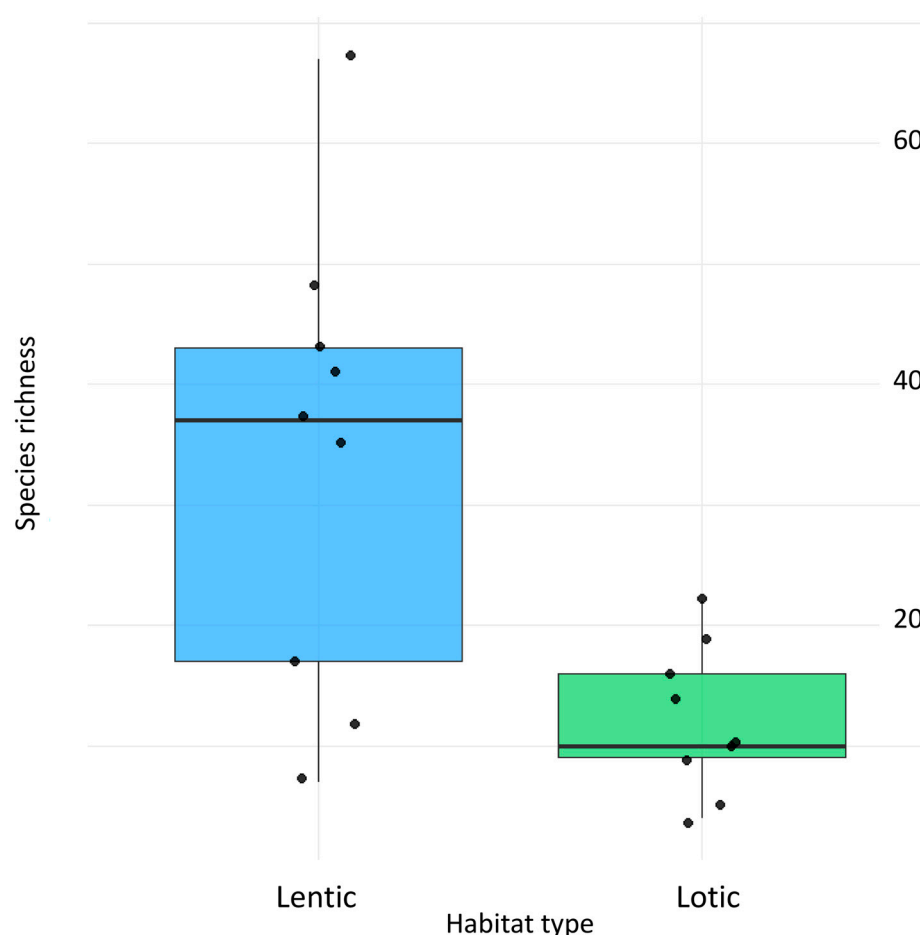


Figure 2. Boxplot showing differences in phytoplankton taxonomic richness between lentic (blue) and lotic (green) sites. The solid black line indicates the median value.

Most of the recorded species were planktonic. Among the most frequent genera were *Gomphosphaeria*, *Closterium*, *Staurastrum*, *Elakatothrix*, *Ankistrodesmus*, *Eudorina*, *Oocystis*, *Pandorina*, *Dinobryon*, *Ceratium*, *Euglena*, and *Phacus* (Figure 3). Additionally, potentially toxic cyanobacteria such as *Dolichospermum* sp. and *Microcystis aeruginosa* were identified in the lakes Yahuarcocha, San Marcos, San Pablo, Toreadora, El Salado, Yambo, and in the Manta River. *Raphidiopsis* sp. was detected only in Yahuarcocha Lake (Table A1).



Figure 3. Species of phytoplankton taxa from the study sites. (A) *Dolichospermum* sp. (B) *Microcystis aeruginosa*. (C) *Raphidiopsis* sp. (D) *Fragilaria* sp. (E) *Gomphonema* sp. (F) *Surirella* sp. (G) *Closterium acerosum*. (H) *Elakatothrix* sp. (I) *Acutodesmus bernardii*. (J) *Trachelomonas armata*. (K) *Ceratium* sp. (L) *Dinobryon* sp. Scale 20 μ m.

Diatoms (Heterokontophyta) were common in both lotic and lentic ecosystems, with notable genera including *Fragilaria*, *Gomphonema*, *Navicula*, *Surirella*, and *Synedra*. Regarding Charophyta, their distribution was mainly lentic, except for species such as *Cosmarium botrytis*, *C. formosulum*, *C. goniodes*, *C. humile*, *C. quadrifarium*, and *Euastrum denticulatum*, which were exclusive to Agua Amarilla Stream (Figure 3).

Among lentic ecosystems, Lake San Pablo showed the highest taxonomic richness with 67 species, followed by Yahuarcocha Lake (48), San Marcos Lake (43), Toreadora Lake (41), La Mica Lake (37), and Papallacta Lake (35). In all these water bodies, Chlorophyta, Charophyta, Heterokontophyta, and Cyanobacteria predominated (Figure 4). In contrast, lotic ecosystems exhibited lower taxonomic richness. Manta River presented 22 species, followed by Pachanlica River with 19, while Copueno River registered only four species, belonging to the phyla Heterokontophyta (3) and Charophyta (1).

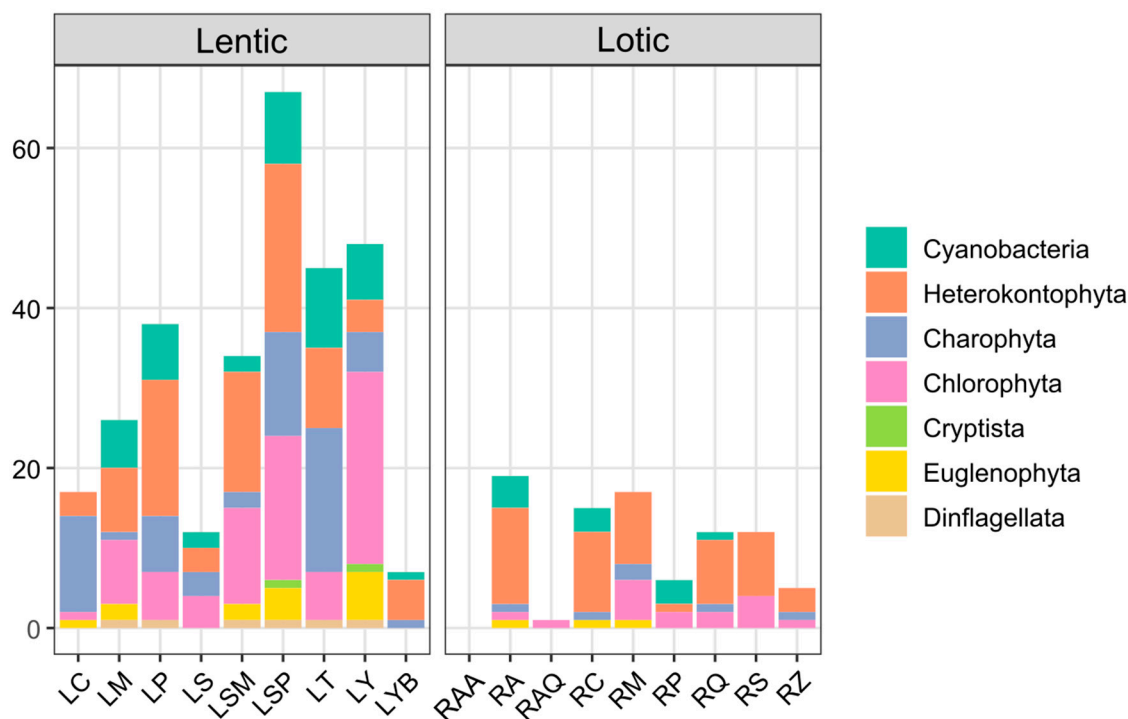


Figure 4. Distribution of phytoplankton taxonomic richness by sampling site.

3.3. Palmer's Organic Pollution Index

According to Palmer's Organic Pollution Index, seven water bodies were classified as having high or probable high organic pollution: five lakes (San Pablo, Yahuarcocha, Papallacta, San Marcos, and Toreadora) and two rivers (Pachanlica and Manta) (Figure 4). These high scores were associated with the presence of pollution-tolerant genera such as *Oscillatoria*, *Chlamydomonas*, *Scenedesmus*, and *Euglena*. Moderate organic pollution (index values between 12 and 14) was recorded in El Salado Lake and in the Quijos and Santiago rivers. In contrast, low index values (0–9), indicating the absence of organic pollution according to Palmer's methodology, were observed in the lakes Caricocha, La Mica, and Yambo, as well as in the rivers Apaquí, Abanico, Copueno, Zamora, and Agua Amarilla Stream.

3.4. Correlation Between Land Use and Water Quality

A geospatial correlation analysis was conducted to quantify the relationship between the absolute anthropogenic area (km²) and the Palmer Index, analyzing lotic and lentic ecosystems independently. For the 9 lotic sites (rivers), no statistically significant correlation was found between the Palmer Index and the absolute anthropogenic area ($r = 0.41$, $p = 0.275$). In stark contrast, for the 9 lentic ecosystems (lakes), a strong, positive, and statistically significant correlation was found between the Palmer Index and the absolute anthropogenic area ($r = 0.76$, $p = 0.016$) (Figure 5).

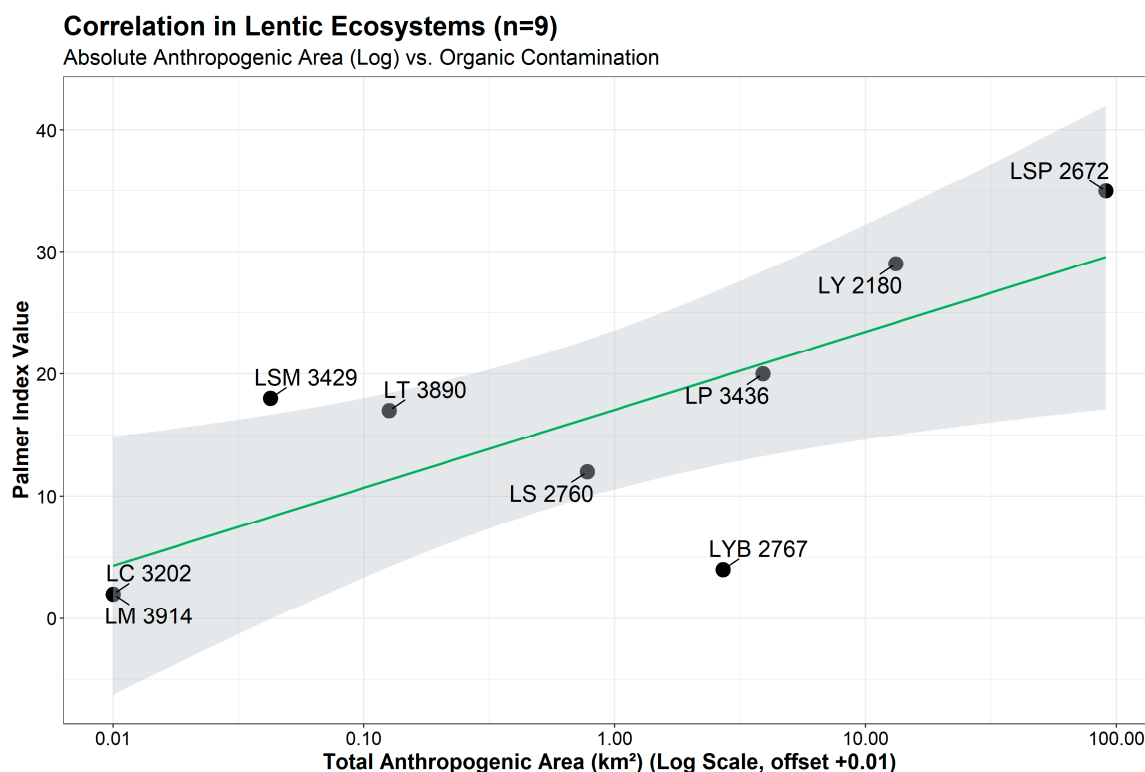


Figure 5. Relationship between absolute anthropogenic area (log-transformed) and Palmer Index values in lentic ecosystems ($n = 9$). Each point represents a lake, labeled with its site code and elevation (m.a.s.l.). The solid line shows the fitted linear regression, and the shaded band indicates the 95% confidence interval.

3.5. Community Composition

The Mantel test revealed no significant correlation between geographic distance and community dissimilarity (Jaccard; $r = -0.019$, $p = 0.517$), indicating the absence of spatial structure in phytoplankton assemblages across the 18 sites. Thus, communities from distant basins were not more dissimilar than those in geographical proximity.

Hierarchical clustering based on Jaccard similarity revealed three major assemblage groups (cophenetic correlation = 0.81) (Figure 6). The analysis distinguished a well-defined and statistically significant cluster of high-Andean lagoons (LSM 3429, LM 3914, LY 2180, LSP 2672, LP 3436 and LT 3890), with internal similarities of 22–47% (SIMPROF $p < 0.01$). Despite its lower altitude, LY 2180, grouped consistently with the high-altitude lakes, suggesting convergence in compositional characteristics.

A second significant cluster ($p < 0.05$) comprised mid-low-altitude rivers (RC 1070, RZ 890, RP 2260, RQ 1500, RA 1625, RM 5 and RS 720), forming a relatively homogeneous fluvial assemblage (20–40% similarity). Within this group, the lagoons LYB 2676 and LS 2760 clustered sequentially with the rivers ($\approx 18\%$ and $\approx 16\%$ similarity, respectively; SIMPROF $p < 0.05$), indicating transitional conditions and partial overlap in taxa typical of lotic environments.

Finally, LC 3202 and RAA 3400 appeared as isolated entities, while RAQ 2465 formed an independent branch at intermediate similarity levels ($\approx 25\%$), reflecting unique assemblages under distinct environmental or geomorphological conditions.

The habitat-based PERMANOVA revealed significant differences in species composition between lentic and lotic sites ($F = 1.89$, $p = 0.008$), explaining 10.6% of the variation. Multivariate dispersion was homogeneous between habitats ($F = 0.13$, $p = 0.72$), indicating that differences reflect centroid shifts rather than changes in within-group variability.

The environmental PERMANOVA accounted for 33.9% of community variation ($F = 1.23$, $p = 0.055$).

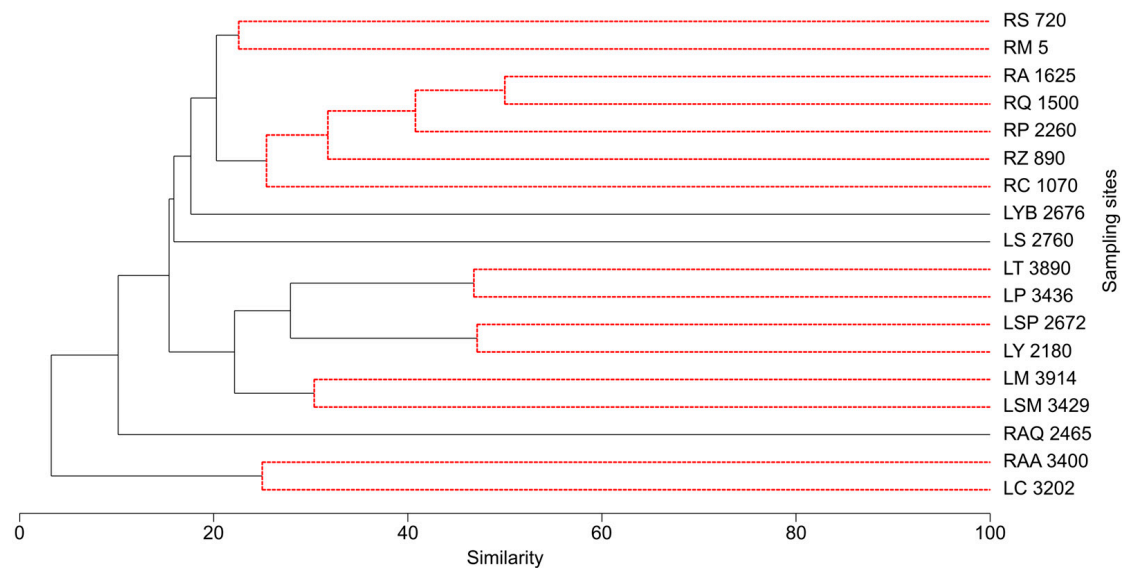


Figure 6. Hierarchical cluster analysis based on Jaccard similarity index of phytoplankton communities from 18 Andean lentic and lotic sampling sites. Red dashed lines indicate clusters that were not statistically significant according to the SIMPROF test ($p > 0.05$).

Although marginally non-significant, this model suggests that a larger fraction of community variation is associated with physicochemical differences than with the simple lentic–lotic distinction. Variation partitioning showed that temperature, conductivity, pH and DO together explained 27.3% of variation, with Palmer contributing an additional unique fraction (7.8%). Only a small fraction of variance was shared between Palmer and the physicochemical variables, indicating that the two sets of predictors capture distinct ecological processes.

3.6. Canonical Correspondence Analysis (CCA)

The Canonical Correspondence Analysis (CCA) provided an exploratory ordination in which broad physicochemical gradients were visually represented in relation to phytoplankton assemblages, with the first two axes explaining 68.5% of the total constrained variance (Figure 7). Permutation tests showed that the CCA model was not statistically significant ($F = 0.84$, $p = 0.50$), and neither individual axes (CCA1 $p = 0.45$; CCA2 $p = 0.69$) nor environmental variables (all $p > 0.10$) explained community structure under permutation-based inference. Nevertheless, the ordination provided ecologically coherent patterns consistent with results from complementary analyses.

Axis 1 (39.8%) summarized variation aligned with gradients of temperature (T), electrical conductivity (EC), and pH. Sites with higher T, EC, and pH were displaced to the left of the ordination, whereas colder, less conductive, and lower-pH waters plotted to the right. This pattern aligns with site groups known to differ in human impact, as warmer and more mineralized waters corresponded to human-impacted environments.

Axis 2 (28.7%) separated sites according to dissolved oxygen (DO), distinguishing lotic systems with higher DO and lower EC (bottom of the plot) from lentic Andean lakes (top), characterized by lower oxygen and higher conductivity. In the upper-left quadrant, the lakes LYB and LY stood out with high pH and conductivity, both affected by anthropogenic disturbance and associated with *Microcystis aeruginosa* and *Merismopedia glauca* eutrophication indicators. The lower-left quadrant grouped the most impacted rivers often associated with species such as *Euglena* sp. and *Closterium acerosum*, typical of

habitats with organic matter, while the upper-right contained the coldest, least conductive high-Andean lakes. The site RAA, located at the far right of Axis 1, was ecologically distinct, with cold waters closely associated with *Cosmarium trilobulatum* and *Closterium glacile*.

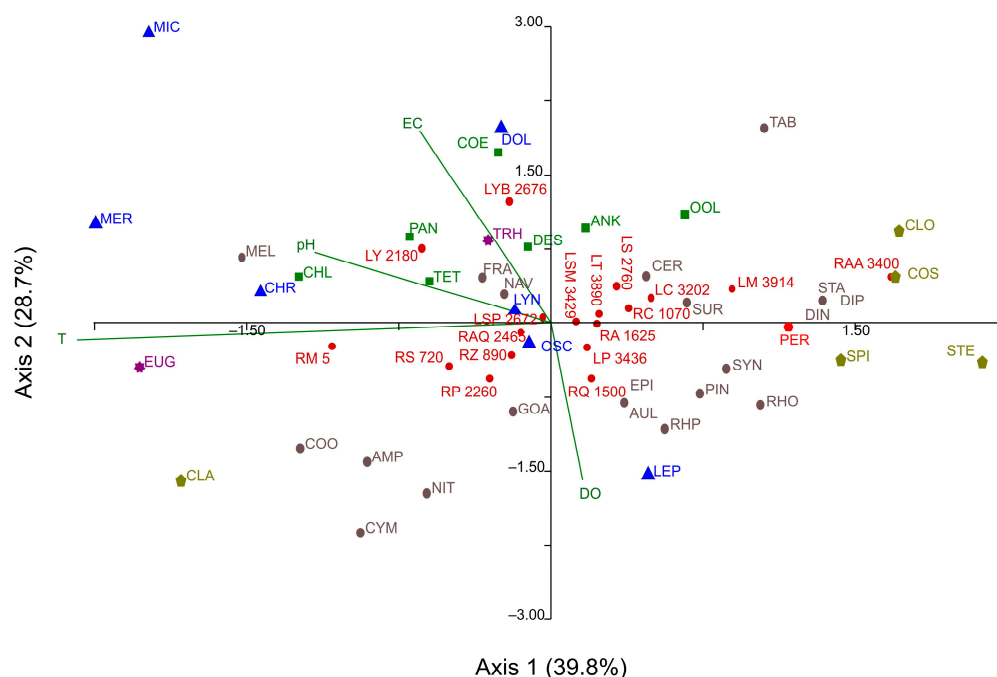


Figure 7. Canonical Correspondence Analysis (CCA) of phytoplankton assemblages and environmental variables across 18 Andean lentic and lotic sites (red dots). Green arrows indicate environmental gradients of temperature (T), electrical conductivity (EC), pH, and dissolved oxygen (DO). Blue triangles: Cyanobacteria phylum; green squares: Chlorophyta phylum; golden pentagons: Charophyta phylum; gray dots: Heterokontophyta phylum; violet stars: Euglenophyta phylum; red hexagon: Dinoflagellata phylum. All abbreviations are defined in Table A1 (Appendix A).

4. Discussion

Our findings reveal ecological patterns across Andean freshwater ecosystems, highlighting consistent associations between local physicochemical conditions and phytoplankton community composition. Despite the wide geographic and altitudinal variation in the study sites, community organization was not spatially structured, indicating that high dispersal potential allows taxa to overcome geographic isolation within the region. Instead, hydrodynamics and anthropogenic pressures emerged as the main factors associated with assemblage composition, leading to a marked lentic–lotic differentiation and to contrasting responses to land use. These broad patterns contribute to a more integrated understanding of phytoplankton community dynamics in tropical mountain waters and provide an ecological framework for interpreting future bioassessment efforts in the Andes.

4.1. Phytoplankton Diversity

The diversity patterns observed across Ecuadorian inland waters are consistent with emerging regional assessments of phytoplankton in the Tropical Andes. Recent studies show that high-elevation lakes tend to host rich assemblages dominated by desmids and diatoms, reflecting the influence of cold, dilute, low-ionic environments on community structure [42–44]. Our findings agree with classical limnological observations from Andean and tropical mountain lakes, where stable thermal regimes and low conductivity favor the persistence of sensitive Charophyta and Bacillariophyta taxa [45–47].

Conversely, water bodies exposed to agricultural and urban pressures exhibited a shift toward chlorophytes and bloom-forming cyanobacteria. The detection of potentially toxic

genera such as *Dolichospermum*, *Microcystis*, and *Raphidiopsis* aligns with global evidence showing that nutrient enrichment and reduced transparency promote cyanobacterial dominance and increase the risk of harmful algal blooms [48]. Similar transitions have been reported in Andean lakes subjected to watershed disturbance and untreated wastewater inputs [43,47].

The presence of numerous taxa not previously recorded for Ecuador highlights a persistent gap in phytoplankton taxonomic knowledge at the national scale. As noted in recent syntheses, much of Ecuador's freshwater microflora remains undocumented, and new records often reflect limited historical sampling rather than true biogeographical rarity [42–44]. In this context, the present study substantially expands the documented phytoplankton diversity of Ecuador, providing the most comprehensive national reference currently available across contrasting lentic and lotic ecosystems. This expanded taxonomic baseline strengthens phytoplankton-based bioassessment frameworks and improves the detection of early ecological shifts associated with land-use change and climate warming.

4.2. Ecological Differentiation Between Lentic and Lotic Environments

The results demonstrate a clear ecological separation between lentic and lotic ecosystems across continental Ecuador. Lakes consistently supported richer and more distinct phytoplankton assemblages than rivers, reflecting fundamental hydrodynamic contrasts between standing and running waters. Lakes provide stable thermal, chemical, and light regimes that favor habitat diversification and phytoplankton development [49,50], while rivers are characterized by turbulent flow, short residence times, and strong physical disturbance that constrain the establishment of planktonic taxa and shape community composition [51–53]. Such lentic–lotic differences have also been documented in other tropical mountain regions.

Geographical distance and basin identity did not explain community differences: sites from distinct drainage systems, even across Pacific and Amazonian slopes, harbored similar assemblages whenever environmental conditions converged. This pattern indicates high dispersal capacity of phytoplankton via wind, aerosols, and aquatic fauna, with local physicochemical gradients acting as the primary filters of community assembly [54,55]. The absence of distance–decay likewise suggests that dispersal is sufficient to overcome geographic isolation at the spatial scale of this study [56], reinforcing the predominance of environmental filtering over spatial constraints in Ecuadorian freshwaters. These findings support a unified ecological interpretation of phytoplankton community organization across Andean lentic and lotic systems.

4.3. Human Pressure as a Secondary Structuring Gradient

Beyond habitat type, anthropogenic disturbance emerged as an additional structuring factor of phytoplankton community composition. High-altitude lakes with minimal human influence (La Mica, Caricocha, Toreadora) were characterized by cold, diluted waters supporting Charophyta and diatom-dominated communities. Conversely, lakes located in populated or agricultural basins (Yahuarcocha, San Pablo, Yambo) exhibited distinct assemblages dominated by Chlorophyta and Cyanobacteria, including potentially toxic genera. These patterns align with previous reports of eutrophication in Andean lakes driven by nutrient loading from agriculture, livestock activities, and untreated wastewater [43,57,58]. Rivers exhibited more heterogeneous responses to disturbance, reflecting their dynamic hydrology and the predominance of localized stressors in shaping community structure.

4.4. Applicability and Limitations of Palmer's Organic Pollution Index

Palmer's Index effectively identified sites with high organic pollution, as reflected by pollution-tolerant genera. These locations contained high abundances of classical pollution-tolerant genera such as *Oscillatoria*, *Scenedesmus*, *Chlamydomonas*, and *Euglena*, confirming the utility of the index as a rapid screening tool.

However, Yambo Lake illustrates an important limitation of the index. Despite being one of the most eutrophic lakes in Ecuador, the index underestimated its trophic status. Yambo receives little direct organic loading yet exhibits elevated nutrient and ion concentrations due to its endorheic nature, evaporation-driven concentration, and long residence times [59]. Because Palmer's Index was designed to detect organic pollution, it does not respond to inorganic nutrient enrichment, natural geochemical concentration, or other eutrophication pathways common in Andean lakes. It should therefore be complemented with nutrient measurements, conductivity, and information on cyanobacterial functional groups [44,60]. These limitations highlight the need to integrate both biological and physicochemical indicators when assessing the ecological state of Andean watersheds.

4.5. Influence of Land Use: Strong in Lakes, Weak in Rivers

Lakes and rivers exhibited contrasting responses to land-use pressure. In lakes, higher Palmer scores tended to occur in basins with greater anthropogenic land cover, indicating that lentic systems integrate cumulative watershed pressures and function as sinks for sediments, nutrients, and organic matter [58,61]. This tendency reflects the long residence times, stratification regimes, and depositional dynamics characteristic of Andean lakes [62].

In contrast, no correlation emerged for rivers, reflecting the fact that water quality in mountain streams is often shaped by local, short-term drivers rather than catchment-scale gradients [63]. In lotic systems, steep gradients, high velocities, rapid flushing, and substrate instability act as dominant environmental filters. Under these conditions, local point-source discharges exert a stronger influence, whereas basin-scale effects are comparatively reduced. This pattern aligns with the hydromorphological complexity of Andean rivers [64] and with classical limnological observations that turbulence, shear stress, and rapid substrate turnover constrain the persistence of benthic algae and phytoplankton [17].

Together, these tendencies highlight the need for ecosystem-specific monitoring and management strategies. Lakes respond primarily to cumulative, basin-scale pressures, whereas rivers require targeted control of localized discharges and the integration of hydromorphological assessments when interpreting biological responses in tropical mountain environments.

4.6. Environmental Patterns and Community-Level Associations

Broad environmental contexts were reflected in patterns of community composition, although these associations were more subtle than the differentiation imposed by habitat type and land use. Although the CCA did not reach statistical significance, the ordination provided an exploratory visualization of how community composition varied across broad physicochemical contexts. These patterns were consistent with results from complementary multivariate analyses and with known ecological affinities reported in the literature. Higher conductivity, temperature, and pH characterized disturbed low- and mid-altitude sites, whereas dissolved oxygen differentiated lotic from lentic systems. Sensitive desmids characterized pristine, cold, diluted high-Andean lakes, whereas chlorophytes, euglenoids, and cyanobacteria dominated disturbed sites [65,66]. These patterns are consistent with those identified by other multivariate analyses and reinforce the ecological interpretation of phytoplankton responses to major environmental gradients [67,68]. Accordingly, taxa are interpreted as bioindicators based on their recurrent occurrence, documented ecological

affinities, and consistent associations with the environmental patterns and contexts identified in this study, rather than on quantitative dominance. Interpretations are therefore restricted to community-level responses rather than explicit chemical gradients.

4.7. Implications for Monitoring and Water Management

The present findings offer multiple practical implications for freshwater management in Ecuador and similar Andean regions:

- Lakes warrant priority monitoring, as their phytoplankton communities reflect cumulative basin-scale pressures and long-term changes in land use.
- Rivers require targeted control of point-source discharges, particularly industrial and urban effluents, as these exert a disproportionate influence on water quality.
- Palmer's Index is useful for rapid assessment, but should be complemented with nutrient measurements, conductivity, and cyanobacterial functional indicators, especially in endorheic or geochemically atypical lakes.
- The recurrent detection of potentially toxic cyanobacteria (*Microcystis*, *Dolichospermum*, *Raphidiopsis*) highlights the need for regular toxin monitoring using molecular or biochemical methods.
- Phytoplankton proved to be robust bioindicators, supporting their integration into national water-quality assessment frameworks and future monitoring programs in the Andes.

Together, these insights establish a coherent ecological baseline for phytoplankton bioassessment in the Tropical Andes and reinforce the need for monitoring approaches tailored to the contrasting dynamics of lakes and rivers.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w18040496/s1>, Table S1: Presence of phytoplankton taxa across sampled aquatic ecosystems.

Author Contributions: Material preparation, sample collection, and laboratory analysis were performed by A.A.-M. The first draft was written by A.A.-M., M.C. and I.T. Editions were made by I.T. and K.V. performed the spatial analysis. A.A.-M., K.V. and I.T. participated in writing and revising the final article. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Universidad Tecnológica Indoamerica through the Project: "Etnobiología para la Conservación de la Diversidad Biocultural y la Gobernanza de Ecosistemas Acuáticos en Ecuador". Funding number: INV-0001-003.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Acknowledgments: We acknowledge the staff at BioCamb for their valuable support and for providing access to laboratories and instrumentation. We also thank Gabriela E. and Steven G. for their collaboration in transporting and collecting samples at the different study sites. Our deepest gratitude goes to Nelson Gallo, whose teachings and encouragement were fundamental in shaping the work on microalgae and cyanobacteria in Ecuador. During the preparation of this manuscript, the authors used GenAI for language revision and editing. The authors have reviewed and edited the output and take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Presence-absence of phytoplankton and associated codes.

	Code	LY	LSP	LS	LYB	LC	LSM	LP	LT	LM	RM	RS	RZ	RC	RQ	RA	RP	RAQ	RAA
Cyanobacteria	<i>Calothrix</i> sp.							x	x										
	<i>Chroococcus</i> sp.	CHR	x					x	x		x								
	■ <i>Cyanosarcina</i> sp.							x	x								x		
	<i>Cylindrospermum</i> sp.			x			x				x								
	<i>Dichothrix</i> sp.								x										
	* <i>Dolichospermum</i> sp.	DOL	x	x			x		x										
	■ <i>Gomphosphaeria</i> sp.								x		x								
	<i>Leptolyngbya</i> sp.	LEP		x				x						x				x	
	<i>Lyngbya</i> sp.	LYN	x	x				x						x				x	
	<i>Merismopedia glauca</i>	MER	x	x					x		x								
	* <i>Microcystis aeruginosa</i>	MIC	x	x	x	x					x								
	<i>Nostoc commune</i>							x	x									x	
	<i>Oscillatoria</i> sp.	OSC	x	x	x			x	x		x				x	x	x	x	
	<i>Pseudanabaena</i> sp.			x														x	
	* <i>Raphidiopsis</i> sp.		x																
	■ <i>Stigonema</i> sp.								x										
	<i>Synechocystis</i> sp.			x															
Heterokontophyta	<i>Amphora</i> sp.	AMP		x			x	x	x		x	x						x	
	<i>Aulacoseira</i> sp.	AUL		x			x	x	x			x							
	<i>Ceratoneis</i> sp.	CER		x		x	x	x	x	x		x			x	x	x		
	<i>Cocconeis placentula</i>	COO		x				x			x	x				x	x		
	<i>Cymbella</i> sp.	CYM					x	x			x	x	x		x		x		
	<i>Dinobryon</i> sp.	DIN		x			x	x	x	x									
	<i>Diploneis</i> sp.	DIP		x				x	x	x									
	<i>Epithemia</i> sp.	EPI		x			x	x	x			x							
	<i>Fragilaria</i> sp.	FRA	x	x		x		x	x	x	x	x	x	x	x	x	x		
	<i>Gomphonema acuminatum</i>	GOA		x	x		x		x		x	x	x		x	x	x		
	<i>Gyrosigma</i> sp.			x		x				x									
	<i>Melosira</i> sp.	MEL	x	x			x			x	x		x						
	<i>Navicula</i> sp.	NAV	x	x	x	x		x	x	x		x	x	x	x	x	x	x	
	<i>Nitzschia sigmoidea</i>			x					x										
	<i>Nitzschia</i> sp.	NIT		x				x	x		x				x		x		
	<i>Pinnularia</i> sp.	PIN		x			x	x	x				x		x	x	x		
	<i>Pseudostaurastrum limneticum</i>					x													
	<i>Rhoicosphenia</i> sp.	RHO		x				x		x					x				
	<i>Rhopalodia</i> sp.	RHP		x			x	x	x				x		x		x		

Table A1. Cont.

		Code	LY	LSP	LS	LYB	LC	LSM	LP	LT	LM	RM	RS	RZ	RC	RQ	RA	RP	RAQ	RAA
Heterokontophyta	<i>Stauroneis</i> sp.	STA		x					x	x	x									
	<i>Surirella</i> sp.	SUR	x	x				x	x	x	x				x	x	x	x		
	<i>Synedra</i> sp.	SYN		x	x			x	x	x				x				x		
	<i>Synura</i> sp.			x			x													
	<i>Tabellaria</i> sp.	TAB				x	x	x		x	x						x			
Charophyta	■ <i>Actinotaenium curtum</i>						x	x												
	<i>Closterium acerosum</i>	CLA		x			x	x				x								
	<i>Closterium acutum</i>			x		x					x									
	<i>Closterium diana</i>		x	x																
	<i>Closterium glaucum</i>	CLO		x	x					x	x									
	<i>Closterium kuetzingii</i>			x																
	<i>Closterium moniliferum</i>			x									x							
	■ <i>Closterium parvulum</i>							x			x									
	<i>Closterium striolatum</i>			x																
	<i>Closterium venustum</i>		x	x																
	■ <i>Cosmarium bioculatum</i>										x									
	<i>Cosmarium botrytis</i>										x									x
	■ <i>Cosmarium formosulum</i>																			x
	■ <i>Cosmarium gonioides</i>																			x
	■ <i>Cosmarium humile</i>																			x
	<i>Cosmarium impressulum</i>						x													x
	■ <i>Cosmarium punctulatum</i>							x		x	x									
	■ <i>Cosmarium pyramidatum</i>										x									
	■ <i>Cosmarium quadratum</i>						x				x									x
	■ <i>Cosmarium quadrifarium</i>																			x
	■ <i>Cosmarium regnellii</i>						x				x									
	<i>Cosmarium subspinosum</i>			x				x	x		x									
	■ <i>Cosmarium trilobulatum</i>	COS					x	x			x									x
	<i>Elakatothrix gelatinosa</i>			x							x		x							
	■ <i>Euastrum bidentatum</i>						x	x												x

Table A1. Cont.

	Code	LY	LSP	LS	LYB	LC	LSM	LP	LT	LM	RM	RS	RZ	RC	RQ	RA	RP	RAQ	RAA
Charophyta	■ <i>Euastrum denticulatum</i>																		x
	<i>Hyalotheca</i> sp.		x																
	■ <i>Micrasterias americana</i>						x			x									
	<i>Micrasterias laticeps</i>		x	x															
	<i>Micrasterias truncata</i>			x															
	■ <i>Penium margaritaceum</i>					x	x												
	■ <i>Pleurotaenium trabecula</i>						x			x									
	<i>Spirogyra</i> sp.	SPI		x	x	x			x					x	x	x			
	■ <i>Stauroastrum furcigerum</i>								x										
	■ <i>Stauroastrum manfeldtii</i>		x						x	x									
	■ <i>Stauroastrum spongiosum</i>								x										
	■ <i>Stauroastrum subavacula</i>								x										
	<i>Staurodesmus dejectus</i>						x			x									
	<i>Staurodesmus extensus</i>	STE		x		x		x		x									
	■ <i>Staurodesmus gibberulus</i>					x													
	<i>Xanthidium octocorne</i>					x	x			x									
Chlorophyta	<i>Acutodesmus acuminatus</i>		x	x															
	<i>Acutodesmus bernardii</i>			x			x												
	<i>Ankistrodesmus fusiformis</i>	ANK	x	x			x	x	x										
	<i>Ankistrodesmus spiralis</i>		x	x															
	■ <i>Ankyra judayi</i>		x							x									
	■ <i>Asterococcus</i> sp.							x											
	<i>Botryococcus braunii</i>									x	x								
	<i>Bulbochaete</i> sp.									x	x								
	<i>Chlamydomonas</i> sp.	CHL	x	x			x					x					x		
	■ <i>Chlorococcum</i> sp.							x									x		
	<i>Coelastrum indicum</i>	COE	x	x			x		x										
	<i>Coelastrum microporum</i>		x	x								x							
	<i>Comasiella arcuata</i>						x			x	x								
	<i>Desmodesmus communis</i>	DES	x	x	x			x				x							

Table A1. Cont.

		Code	LY	LSP	LS	LYB	LC	LSM	LP	LT	LM	RM	RS	RZ	RC	RQ	RA	RP	RAQ	RAA
Chlorophyta	<i>Dictyosphaerium pulchellum</i>		x	x																
	<i>Eudorina elegans</i>		x	x									x							
	<i>Gloeocystis</i> sp.									x										
	■ <i>Golenkinia</i> sp.		x							x										
	■ <i>Gonium pectorale</i>		x																	
	■ <i>Haematococcus</i> sp.							x												
	<i>Kirchneriella lunaris</i>							x												
	<i>Lagerheimia ciliata</i>										x									
	<i>Monactinus simplex</i>		x					x				x								
	<i>Monactinus simplex</i> var. <i>Echinulatum</i>		x																	
	<i>Monoraphidium contortum</i>		x	x																
	■ <i>Monoraphidium griffithii</i>		x																	
	<i>Oedogonium</i> sp.				x					x										
	<i>Oocystis lacustris</i>	OOL	x	x	x			x	x		x									
	<i>Oocystis naegelii</i>		x	x																
	<i>Pandorina morum</i>	PAN	x	x			x							x					x	
	<i>Pseudopediastrum boryanum</i>		x	x				x												
	<i>Pediastrum duplex</i>		x	x																
	<i>Planktosphaeria gelatinosa</i>			x																
	■ <i>Scenedesmus javanensis</i>							x												
	■ <i>Sphaerocystis</i> sp.		x					x												
	<i>Tetraëdron minimum</i>	TET	x	x	x				x	x		x								
	■ <i>Tetraëdron tumidulum</i>										x									
	■ <i>Volvox aureus</i>		x								x									
Cryptista	<i>Cryptomonas</i> sp.		x	x																
Euglenophyta	<i>Euglena</i> sp.	EUG	x	x					x			x	x					x		
	<i>Lepocinclis</i> sp.		x	x								x								
	<i>Phacus</i> sp.		x	x																
	■ <i>Trachelomonas armata</i>		x																	
	<i>Trachelomonas hispida</i>	TRH	x	x			x		x											
	<i>Trachelomonas volvocina</i>		x					x												

Table A1. Cont.

	Code	LY	LSP	LS	LYB	LC	LSM	LP	LT	LM	RM	RS	RZ	RC	RQ	RA	RP	RAQ	RAA
Dinofl	<i>Ceratium</i> sp.	x																	
agellata	<i>Peridinium</i> sp.	PER	x				x	x	x	x									

LY: Yahuarcocha Lake; LSP: San Pablo Lake; LS: El Salado Lake; LYB: Yambo Lake; LC: Caricocha Lake; LSM: San Marcos Lake; LP: Papallacta Lake; LT: Toreadora Lake; LM: La Mica Lake; RM: Manta River; RS: Santiago River; RZ: Zamora River; RC: Copueno River; RQ: Quijos River; RA: Abanico River; RP: Pachanlica River; RAQ: Apaquí River; RAA: Agua Amarilla Stream. * Potentially toxic cyanobacteria. ■ New records. "x" indicates the presence of the taxon at the corresponding site.

References

- Bravo, E. *La Biodiversidad en el Ecuador*; Editorial Universitaria Abya-Yala: Quito, Ecuador, 2014.
- Steinitz-Kannan, M. The lakes in Andean protected areas of Ecuador. In *The George Wright Forum*; The George Wright Society: Denver, Colorado, 1997; pp. 33–43.
- Consejo Nacional de Recursos Hídricos. *Gestión de los Recursos Hídricos del Ecuador: Políticas y Estrategias*; Informe Ejecutivo: Quito, Ecuador, 2002.
- Lazo, P.X.; Mosquera, G.M.; McDonnell, J.J.; Crespo, P. The role of vegetation, soils, and precipitation on water storage and hydrological services in Andean Páramo catchments. *J. Hydrol.* **2019**, *572*, 805–819. [\[CrossRef\]](#)
- Naranjo-Silva, S. A hydropower development perspective in Ecuador: Past, present, and future. *La Granja* **2024**, *39*, 63–77. [\[CrossRef\]](#)
- Limburg, K.E. Aquatic ecosystem services. In *Encyclopedia of Inland Waters*; Elsevier: Amsterdam, The Netherlands, 2009; pp. 25–30.
- Aguirre, W.E.; Alvarez-Mieles, G.; Anaguano-Yancha, F.; Burgos-Morán, R.; Cucalón, R.V.; Escobar-Camacho, D.; Jácome-Negrete, I.; Jiménez Prado, P.; Laaz, E.; Miranda-Troya, K.; et al. Conservation threats and future prospects for the freshwater fishes of Ecuador: A hotspot of Neotropical fish diversity. *J. Fish Biol.* **2021**, *99*, 1158–1189. [\[CrossRef\]](#)
- Hernández-Falconi, A.V.; Castillo, M.M.; Mendoza-Carranza, M.; Jarquín-Sánchez, A.; Ramos-Reyes, R. Cambios en el uso del suelo afectan la calidad del agua y la concentración de clorofila en arroyos tropicales. *Hidrobiológica* **2023**, *33*, 59–72. [\[CrossRef\]](#)
- Liu, Y.; Jiang, X.; Li, D.; Shen, J.; An, S.; Leng, X. Intensive human land uses cause the biotic homogenization of algae and change their assembly process in a major watershed of China. *Sci. Total Environ.* **2023**, *871*, 162115. [\[CrossRef\]](#) [\[PubMed\]](#)
- Talib, A.; Randhir, T.O. Long-term effects of land-use change on water resources in urbanizing watersheds. *PLoS Water* **2023**, *2*, e0000083. [\[CrossRef\]](#)
- Nobre, R.L.G.; Caliman, A.; Cabral, C.R.; de Carvalho-Araújo, F.; Guerin, J.; Dantas, F.D.C.C.; Quesado, L.B.; Venticinque, E.M.; Guariento, R.D.; Amado, A.M.; et al. Precipitation, landscape properties and land use interactively affect water quality of tropical freshwaters. *Sci. Total Environ.* **2020**, *716*, 137044. [\[CrossRef\]](#)
- Lampert, W.; Sommer, U. *Limnology: The Ecology of Lakes and Streams*, 2nd ed.; Oxford university press: New York, NY, USA, 2007.
- Withers, P.J.; Neal, C.; Jarvie, H.P.; Doody, D.G. Agriculture and eutrophication: Where do we go from here? *Sustainability* **2014**, *6*, 5853–5875. [\[CrossRef\]](#)
- Elias, E.; Dougherty, M.; Srivastava, P.; Laband, D. The impact of forest to urban land conversion on streamflow, total nitrogen, total phosphorus, and total organic carbon inputs to the converse reservoir, Southern Alabama, USA. *Urban Ecosyst.* **2013**, *16*, 79–107. [\[CrossRef\]](#)
- Ptácnik, R.; Solimini, A.G.; Brettum, P. Performance of a new phytoplankton composition metric along a eutrophication gradient in Nordic lakes. *Hydrobiologia* **2009**, *633*, 75–82. [\[CrossRef\]](#)
- Esteves, F.A.; Suzuki, M.S. Comunidade Fitoplanctônica. In *Fundamentos de Limnologia*, 3rd ed.; Editora Interciência: Rio de Janeiro, Brasil, 2011; pp. 375–445.
- Reynolds, C.S. *The Ecology of Phytoplankton*; Cambridge University Press: Cambridge, UK, 2006.
- Green, A.J.; Lovas-Kiss, Á.; Reynolds, C.; Sebastián-González, E.; Silva, G.G.; van Leeuwen, C.H.; Wilkinson, D.M. Dispersal of aquatic and terrestrial organisms by waterbirds: A review of current knowledge and future priorities. *Freshw. Biol.* **2023**, *68*, 173–190. [\[CrossRef\]](#)
- Palmer, C.M.A. Composite rating of algae tolerating organic pollution. *J. Phycol.* **1969**, *5*, 78–82. [\[CrossRef\]](#) [\[PubMed\]](#)
- Escobar, M.J.; Terneus, E.; Yáñez, P. El plancton como bioindicador de la calidad del agua en zonas agrícolas andinas, análisis de caso. *Qualitas* **2013**, *5*, 17–37.
- Maila, M.; Pérez, E. Estudio preliminar del Componente Biológico Planctónico de Pasivos Mineros en la Micro-Cuenca del río Pilaló, Pujilí–Cotopaxi. *Cinchonia* **2016**, *14*, 151–170.

22. Jonah, U.E.; Archibong, I.J. Assessing the Water Quality of Akwa Ibom State North-West District, Nigeria, using Water Quality Indices and Palmer Pollution Index. *Ekológia* **2022**, *41*, 301–311. [\[CrossRef\]](#)
23. Khan, N.S.; Uddin, A.; Bari, J.B.A.; Tisha, N.A. Evaluating the potentiality of ancient ponds by Palmer's Algal pollution index, Noakhali, Bangladesh. *Evaluation* **2019**, *4*, 28–31.
24. Noel, S.D.; Rajan, M.R. Evaluation of organic pollution by Palmer's algal genus index and physico-chemical analysis of Vaigai river at Madurai, India. *Nat. Resour. Conserv.* **2015**, *3*, 7–10. [\[CrossRef\]](#)
25. Salem, Z.; Ghobara, M.; El Nahrawy, A.A. Spatio-temporal evaluation of the surface water quality in the middle Nile Delta using Palmer's algal pollution index. *Egypt. J. Basic Appl. Sci.* **2017**, *4*, 219–226. [\[CrossRef\]](#)
26. Bicudo, C.E.; Menezes, M. *Gêneros de Algas de Águas Continentais do Brasil: Chave para Identificação e Descrições*, 3rd ed.; RIMA: São Carlos, Brasil, 2017.
27. Coesel, P.F.M.; Meesters, K.J. *Desmids of the Lowlands: Mesotaeniaceae and Desmidiaceae of the European Lowlands*; KNNV Publishing: Amsterdam, The Netherlands, 2007.
28. Felisberto, S.A.; e Souza, D.B.D.S. Characteristics and diversity of cyanobacteria in periphyton from lentic tropical ecosystem, Brazil. *Adv. Microb.* **2014**, *4*, 1076–1087. [\[CrossRef\]](#)
29. Komárek, J. Phenotype diversity of the heterocytous cyanoprokaryotic genus *Anabaenopsis*. *Fottea* **2005**, *5*, 1–35.
30. Kim, H.S. New records of fresh-water green algae (Chlorophytes) from Korea. *J. Ecol. Environ.* **2013**, *36*, 303–314. [\[CrossRef\]](#)
31. Kim, Y.J. Taxonomic and ecological study of the families Hydrodictyaceae and Coelastraceae, order Chlorococcales, and Class Chlorophyceae in Korea. *J. Ecol. Environ.* **2013**, *36*, 421–437. [\[CrossRef\]](#)
32. Kim, Y.J. New records of genus *Scenedesmus* (Chlorophyceae) found in Korea. *J. Ecol. Environ.* **2015**, *38*, 213–227. [\[CrossRef\]](#)
33. Komárek, J.; Zapomělová, E. Planktic morphospecies of the cyanobacterial genus *Anabaena* = subg. *Dolichospermum* – 1. part: Coiled types. *Fottea* **2007**, *7*, 1–31. [\[CrossRef\]](#)
34. Rai, S.K.; Misra, P.K. Taxonomy and diversity of genus *Pediastrum* Meyen (Chlorophyceae, Algae) in east Nepal. *Our Nature* **2012**, *10*, 167–175. [\[CrossRef\]](#)
35. Rosini, E.F.; Sant'Anna, C.L.; Tucci, A. Cyanobacteria de pesqueiros da região metropolitana de São Paulo, Brasil. *Rodriguésia* **2013**, *64*, 399–417. [\[CrossRef\]](#)
36. Guiry, M.D.; Guiry, G.M. AlgaeBase. Available online: <https://www.algaebase.org> (accessed on 2 December 2025).
37. Clarke, K.R.; Gorley, R.N. *PRIMER v7: User Manual/Tutorial*; PRIMER-e: Plymouth, UK, 2015.
38. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2024.
39. Farr, T.G.; Rosen, P.A.; Caro, E.; Crippen, R.; Duren, R.; Hensley, S.; Kobrick, M.; Paller, M.; Rodriguez, E.; Roth, L.; et al. The Shuttle Radar Topography Mission. *Rev. Geophys.* **2007**, *45*, 361. [\[CrossRef\]](#)
40. Ministerio del Ambiente y Energía. Mapa Interactivo. Available online: <http://ide.ambiente.gob.ec/mapainteractivo/> (accessed on 6 June 2025).
41. Hammer, Ø.; Harper, D.A.T. *PAST: Paleontological Statistics Software Package for Education and Data Analysis; Version 4.03*; University of Oslo: Oslo, Norway, 2023. Available online: <https://www.nhm.uio.no/english/research/resources/past/> (accessed on 14 January 2026).
42. Guamán-Burneo, M.C.; González-Romero, N.; Santillán-Sarmiento, A. Microalgal Diversity in the Ecuadorian Tropical Andes and Its Association with Abiotic Factors. *Hydrobiology* **2025**, *4*, 28. [\[CrossRef\]](#)
43. Arévalo, A.; Cadena, M.; Ontaneda, D. Phytoplankton diversity and current trophic status of a high mountain lake in the province of Imbabura, Ecuador. *ACI Adv. Cien. Ing.* **2025**, *17*, 5235. [\[CrossRef\]](#)
44. Delgado-Fernández, E.; Cruz, D.; Ayavaca, R.; Benítez, Á.; Hernández, B. Microalgal Diversity as Bioindicators for Assessing and Sustaining Water Quality in the High Mountain Lakes of Quimsacocha, Azuay, Ecuador. *Sustainability* **2025**, *17*, 1620. [\[CrossRef\]](#)
45. Lewis, J.W.; Riehl, W. Phytoplankton composition and morphology in Lake Valencia, Venezuela. *Int. Rev. Ges. Hydrobiol.* **1982**, *67*, 297–322.
46. Catalan, J.; Donato, J. Perspectives for an integrated understanding of tropical and temperate high-mountain lakes. *J. Limnol.* **2016**, *75*, 215–234. [\[CrossRef\]](#)
47. Terneus-Jácome, E. Vegetación acuática y estado trófico de las lagunas andinas de San Pablo y Yahuarcocha, provincia de Imbabura, Ecuador. *Rev. Ecuat. Med.Cienc. Biol.* **2017**, *35*, 121–131. [\[CrossRef\]](#)
48. Huisman, J.; Codd, G.A.; Paerl, H.W.; Ibelings, B.W.; Verspagen, J.M.; Visser, P.M. Cyanobacterial blooms. *Nat. Rev. Microbiol.* **2018**, *16*, 471–483. [\[CrossRef\]](#)
49. Woolway, R.I.; Sharma, S.; Smol, J.P. Lakes in hot water: The impacts of a changing climate on aquatic ecosystems. *Bioscience* **2022**, *72*, 1050–1061. [\[CrossRef\]](#)
50. Jones, I.D.; Smol, J.P. (Eds.) *Wetzel's Limnology: Lake and River Ecosystems*, 4th ed.; Academic Press: London, UK, 2023.
51. Rodrigues, L.; Bicudo, D.D.C. Similarity among periphyton algal communities in a lentic-lotic gradient of the upper Paraná river floodplain, Brazil. *Braz. J. Bot.* **2001**, *24*, 235–248. [\[CrossRef\]](#)

52. Li, F.; Zhang, H.; Zhu, Y.; Xiao, Y.; Chen, L. Effect of flow velocity on phytoplankton biomass and composition in a freshwater lake. *Sci. Total Environ.* **2013**, *447*, 64–71. [[CrossRef](#)] [[PubMed](#)]
53. Song, Y. Hydrodynamic impacts on algal blooms in reservoirs and bloom mitigation using reservoir operation strategies: A review. *J. Hydrol.* **2023**, *620*, 129375. [[CrossRef](#)]
54. Tesson, S.V.; Skj  th, C.A.; Šantl-Temkiv, T.; L  ndahl, J. Airborne microalgae: Insights, opportunities, and challenges. *Appl. Environ. Microbiol.* **2016**, *82*, 1978–1991. [[CrossRef](#)]
55. Cochak, C.; Zanon, F.M.; Pineda, A.; Lansac-T  ha, F.M.; Jati, S.; Velho, L.F.M. Beta diversity of freshwater algal communities: Influence of different dispersal mechanisms. *Aquat. Sci.* **2024**, *86*, 26. [[CrossRef](#)]
56. Chiu, M.C.; Ao, S.; He, F.; Resh, V.H.; Cai, Q. Elevation shapes biodiversity patterns through metacommunity-structuring processes. *Sci. Total Environ.* **2020**, *743*, 140548. [[CrossRef](#)]
57. Portilla, K.; Velarde, E.; Decaestecker, E.; Teixeira de Mello, F.; Muylaert, K. Potential submerged macrophytes to mitigate eutrophication in a high-elevation tropical shallow lake a Mesocosm experiment in the Andes. *Water* **2022**, *151*, 75. [[CrossRef](#)]
58. Beltr  n-D  valos, A.A.; Salazar, C.; Kurbatova, A.I.; Echeverr  a, M.; Merino, A.; Otero, X.L. Sediment Chemistry and Ecological Risk Assessment in Andean Lakes of Central Ecuador: Influence of Trophic Status on Accumulation Patterns. *Sustainability* **2025**, *17*, 3397. [[CrossRef](#)]
59. Steinitz-Kannan, M.; Colinviaux, P.A.; Kannan, R. Limnological Studies in Ecuador 1. A Survey of chemical and physical properties of Ecuadorian lakes. *Arch. Hydrobiol.* **1983**, *65*, 61–105.
60. Im, J.K.; Sim, Y.B.; Byun, J.H.; Park, C.H.; Hwang, S.J.; Kang, T.G. The Seasonal Environmental Factors and Phytoplankton Composition of Lake Paldang, the Largest Water Source in South Korea. *Water* **2024**, *16*, 3504. [[CrossRef](#)]
61. Vyse, S.A.; Herzsuh, U.; Pfalz, G.; Pestryakova, L.A.; Diekmann, B.; Nowaczyk, N.; Biskaborn, B.K. Sediment and carbon accumulation in a glacial lake in Chukotka (Arctic Siberia) during the Late Pleistocene and Holocene: Combining hydroacoustic profiling and down-core analyses. *Biogeosciences* **2021**, *18*, 4791–4816. [[CrossRef](#)]
62. Aguilar, P.; Vila, I.; Sommaruga, R. Bacterioplankton zonation does exist in high elevation, polymictic Lakes. *Front. Microbiol.* **2022**, *13*, 764566. [[CrossRef](#)] [[PubMed](#)]
63. Khamis, K.; Blaen, P.J.; Comer-Warner, S.; Hannah, D.M.; MacKenzie, A.R.; Krause, S. High-frequency monitoring reveals multiple frequencies of nitrogen and carbon mass balance dynamics in a headwater stream. *Front. Water* **2021**, *3*, 668924. [[CrossRef](#)]
64. Habit, E.; Zurita, A.; D  az, G.; Manosalva, A.; Arriagada, P.; Link, O.; G  rski, K. Latitudinal and altitudinal gradients of riverine landscapes in Andean rivers. *Water* **2022**, *14*, 2614. [[CrossRef](#)]
65.   ahin, B.; Barinova, S. Assessment of Charophyta flora and ecological status in two high-mountain lakes (Rize, Turkey). *Transylv. Rev. Syst. Ecol. Res.* **2022**, *24*, 35–54. [[CrossRef](#)]
66. V  lez, M.I.; Salgado, J.; Delgado, M.; Pati  o, L.F.; Bird, B.; Escobar, J.H.; Fajardo, S. Humans and climate in ritualized landscapes, the case of Lake Tota in the eastern highlands of Colombia. *Holocene* **2024**, *34*, 1587–1597. [[CrossRef](#)]
67. Burdis, R.M.; Ward, N.K.; Manier, J.T. Phytoplankton assemblage dynamics in relation to environmental conditions in a riverine lake. *Aquat. Ecol.* **2025**, *59*, 467–485. [[CrossRef](#)]
68. Cao, H.; Zhang, K.; Deng, D.; Qi, H.; Li, J.; Cao, Y.; Jin, Q.; Zhao, Y.; Wang, Y.; Wu, Z.; et al. Environmental heterogeneity affecting spatial distribution of phytoplankton community structure and functional groups in a large eutrophic lake, Lake Chaohu, China. *Environ. Sci. Pollut. Res.* **2023**, *30*, 79001–79014. [[CrossRef](#)] [[PubMed](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.