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Impact of Water Quality and Sediments on the Riparian Vegetation of Andean Lake

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Abstract

This study evaluates the quality of water and sediments in a high-altitude Andean lake designated as a RAMSAR wetland of international ecological importance called Guamuéz Lake (Laguna de la Cocha). The analysis focuses on their effects on riparian vegetation, particularly on *Schoenoplectus californicus* (Bulrush), a keystone species in the lacustrine ecosystem. Water and sediment samples were collected from areas under varying levels of anthropogenic pressure, including zones with and without visible degradation. Results indicate that agricultural runoff, aquaculture, and domestic wastewater discharges are major drivers of spatial and seasonal variability in water quality. Elevated biochemical oxygen demand (BOD5) and chemical oxygen demand (COD) were observed during the rainy season, suggesting increased organic matter input. Sediment analyses showed that impacted areas had higher concentrations of metals such as iron and manganese and significantly elevated microbial loads. Microbiological analysis of sediments revealed a 440% increase in total microbial colonies at impacted sites compared to unaffected ones, with fecal coliforms (FC) and total coliforms (TC) increasing by 191% and 513%, respectively. This suggests that wastewater contamination promotes anaerobic conditions detrimental to *S. californicus* root systems, possibly contributing to vegetation dieback. The findings underscore the importance of including sediment quality assessments in aquatic ecosystem monitoring, as key indicators of riparian vegetation decline may not be evident through water analysis alone. These results call for integrated and sustainable watershed management practices to mitigate human impact and preserve the ecological integrity of this internationally recognized wetland system.

Keywords: Water Quality; Lacustrine Sediments; Riparian Vegetation; Bulrush; *Schoenoplectus californicus*; Guamuéz Lake; Microbial Contamination; RAMSAR Wetland.

1. Introduction

High-altitude lake ecosystems play a vital role in hydrological regulation and in supporting human settlements in environmentally sensitive regions such as the high Andean systems [1, 2]. Their ecological significance lies in the biodiversity they host and the wide range of ecosystem services they provide, including water supply, fisheries, flood regulation, nutrient retention, energy generation, transportation, and recreation. These services confer substantial

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cultural and socioeconomic value to these systems [3, 4]. In this context, the Ramsar Convention has acknowledged the relevance of these wetlands by designating them as sites of international importance, underscoring the critical need for their conservation and sustainable management [5, 6].

Despite their recognized value, anthropogenic pressures on wetland watersheds are increasing due to population growth and the expansion of agriculture, aquaculture, and tourism activities [7, 8]. These interventions introduce significant loads of nutrients, organic matter, heavy metals, and pathogenic microorganisms, leading to water quality degradation and the onset of eutrophication and pollution processes [9, 10]. Benthic sediments function as long-term sinks and secondary sources of such contaminants. Under specific environmental conditions, these substances can be remobilized into the water column, thereby extending and intensifying their ecological impacts [11]. The coupling of sediment and water pollution constitutes a major threat to the resilience and ecological integrity of high-altitude lake ecosystems [12].

Within these lacustrine systems, riparian vegetation plays a dual role as both a structural and ecological component of the littoral zone and as a sensitive bioindicator of water quality dynamics [13]. Its functional relevance includes shoreline stabilization, retention of suspended solids, and natural filtration of pollutants entering aquatic environments [14]. In Andean wetlands, species such as *Schoenoplectus californicus* (locally known as totora or bulrush) are particularly important due to their role in nutrient and heavy metal cycling [15, 16], as well as their cultural and economic significance for local communities [17]. However, in Lake Guamuéz (Laguna de la Cocha), a Ramsar-designated wetland located in southwestern Colombia, a concerning and progressive desiccation of *S. californicus* populations has been documented. This deterioration has prompted several hypotheses, including alterations in the lake's hydrological regime and intensified anthropogenic pressures that have impacted water and sediment quality. This condition is illustrated in Figure 1, where intact stands of *S. californicus* are contrasted with desiccation-impacted stands.

Figure 1. a) Unaffected Bulrush (S. californicus) b) Desiccation-impacted Bulrush (S. californicus)

A significant gap in current knowledge limits the understanding of the specific interactions between benthic sediment quality and the physiological performance of riparian macrophytes such as *S. californicus*. Most previous studies have primarily focused on water column analysis as the principal indicator of contamination [16, 18], thereby underestimating the critical role of sediments as reservoirs of organic matter, nutrients, heavy metals, and microbiological contaminants. These substances accumulate in the rhizosphere and may induce chronic toxicity or sublethal stress responses that are not always detectable through surface water monitoring alone. This limitation constrains a comprehensive assessment of the processes driving ecological degradation in high-altitude wetlands.

To address this research gap, the objective of the present study was to conduct an integrated evaluation of water and sediment quality in Lake Guamuéz (Laguna de la Cocha). A specific focus was on assessing its relationship with the progressive degradation and desiccation of riparian vegetation, particularly, *S. californicus*. The aim was to generate new insights into the environmental drivers influencing the health and spatial distribution of riparian macrophytes in Andean wetland ecosystems, and to provide a scientific foundation for the development of evidence-based conservation and management strategies.

To meet this objective, the study employed a comprehensive methodological approach involving systematic sampling of water and sediments at strategically selected locations within Lake Guamuéz. The sampling sites encompassed areas exhibiting varying degrees of *S. californicus* desiccation, enabling spatial differentiation in environmental conditions. Samples were subjected to laboratory analyses for physicochemical, microbiological, and heavy metal parameters, facilitating detailed characterization of environmental quality in both matrices (water and sediment). The methodological procedures and corresponding results are presented in Sections 2 and 3. The resulting data were subsequently correlated with field-based assessments of riparian vegetation condition in order to identify statistically significant associations, which are discussed in Section 4. Finally, Section 5 synthesizes the main conclusions of this research and presents recommendations for the future conservation and sustainable management of Lake Guamuéz.

2. Material and Methods

The flow diagram (Figure 2) illustrates the methodological framework implemented to assess the degree of impact on *S. californicus* by analyzing water and sediment quality. The process begins with the evaluation of potential impacts on the species, followed by the sampling of two distinct zones: unimpacted and impacted areas. For each zone, both water quality and sediment quality parameters are measured to allow for a comparative assessment. The collected data from these analyses is then subjected to statistical and data analysis procedures to determine the relationship between environmental quality and the observed condition of the *S. californicus* populations.

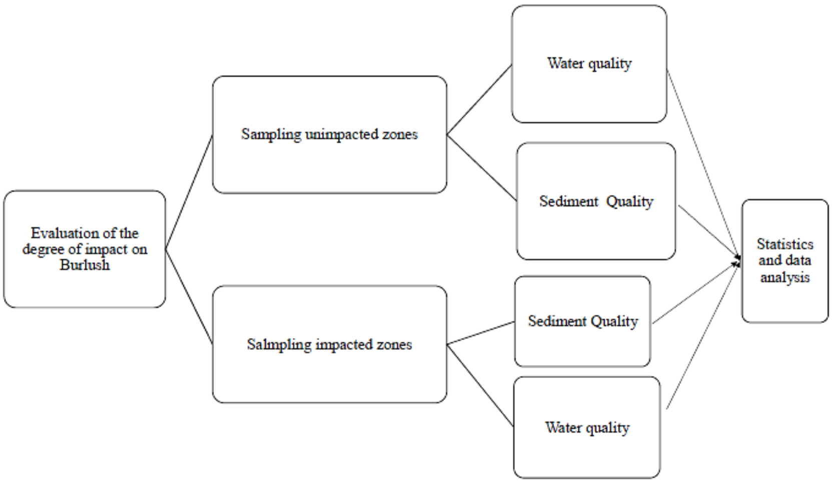

Figure 2. Flow diagram detailing the methodology employed for the evaluation of the impact of water quality and sediments on the bulrush (S. californicus)

2.1. Study Area

Guamuéz Lake, also known as Laguna de la Cocha, is a high-altitude Andean lake located on the eastern flank of the Los Pastos massif in southern Colombia, near the border with Ecuador. Situated at approximately 2,680 meters above sea level, it is the largest wetland in the Colombian Andes and spans an estimated 39,000 hectares. The lake lies within the coordinates 0°50' to 1°15' North latitude and 77°05' to 77°20' West longitude. Hydrologically, it forms part of the upper Guamuéz River basin, which feeds into the Putumayo and San Miguel Rivers, both key tributaries of the Amazon River. In 2021, Guamuéz Lake was officially designated as a Ramsar Wetland of International Importance, in recognition of its critical ecological role, its cultural and archaeological significance, and its provision of essential ecosystem services in a sensitive high-altitude environment.

To determine the degree of *S. californicus* degradation, a survey was conducted at 13 sampling points, following the methodology proposed in the carrying capacity study for Guamuéz Lake [19]. Figure 3, presents the geographical positioning of Colombia, specifically highlighting the department of Nariño and the location of Guamuéz Lake. The sampling points within the lake are also indicated, showing the specific areas where data were collected for the study.

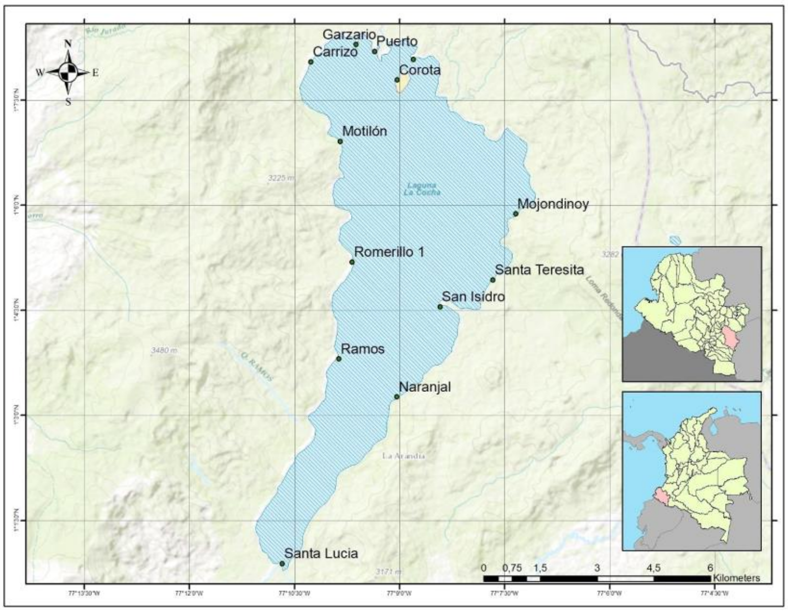

Figure 3. Location of Guamuéz Lake, and Sampling points

The evaluation of *S. californicus*, followed a modified version of the direct assessment methodology proposed by Mendoza [20], which emphasizes in situ observation of ecological and biological indicators within aquatic ecosystems. Key variables analyzed included species abundance, coloration, height, and morphological structure, providing a qualitative and comparative measure of vegetation health and potential degradation. To standardize observations, a semi-quantitative scale (from 0 to 3 was applied, where 0 = low impact, 1 = medium impact, and 3 = high impact) was applied, enabling systematic comparison of health status across individual plants and zones. This evaluation combined qualitative criteria (e.g., visual assessment of foliar damage, discoloration) with quantitative measurements (e.g., percent vegetation cover or reduction in height relative to a reference standard). Findings were further validated by comparison with non-degraded control areas. For water and sediment sampling, the number of sites was reduced to ten due to logistical and analytical constraints. As a result, sampling points 8 (San Isidro), 10 (Ramos), and 13 (Garzario) were excluded from the final sampling design.

2.2. Water Quality Parameters

To assess water quality, sampling was conducted during two distinct climatic periods: the high-rainfall season (April-May 2023) with an average precipitation of 162.7 mm, and the low-rainfall season (February-March 2024) with an average precipitation of 110.9 mm [21]. In-situ parameters were measured using a multiparametric probe, while laboratory analyses were carried out following standardized methods [22], which are detailed below (Table 1).

Table 1. Physicochemical and Microbiological Characterization of Sediments

Parameter	Units	Standardized Method
pH	u	SM 4500-H^+ B.
Total Alkalinity	mg $CaCO_3$ / L	SM 2320 B.
BOD5	mg O_2 / L	SM 5210 B, SM 4500-O G
COD	mg O_2 / L	SM 5220 C
Fats and Oils	mg/L	SM 5520 D
Total Suspended Solids TSS	mg/L	SM 2540 D
Ammonia	mg/L N-NH_3	SM 4500-NH_3 H
Nitrate	mg/L N-NO_3	SM 4500-NO3 D
Nitrite	mg/L N-NO_2	SM 4500-NO2 B
Kjeldahl Nitrogen	mg/L N	SM 4500-Norg C
Chlorophyll	mg/m^3	SM 10200 H
Anionic Detergents	mg/L SAAM	SM 5540 H
Orthophosphates	mg/L	SM 4500-P E
Total Phosphorus	mg/L	SM 4500-P B, SM 4500-P E
Copper	mg/L	SM 3111 B
Iron	mg/L	SM 3500 Fe
Magnesium	mg/L	SM 3111 B
Potassium	mg/L	SM 3500 K
Sodium	mg/L	SM 3500 Na – B
Zinc	mg/L	SM 3111 B
Fecal Coliforms FC (E. Coli)	NMP/100 mL	SM 9223 B
Total Coliforms TC	NMP/100 mL	SM 9223 B
Transparency	m	Secchi Disk

2.3. Sediment Quality Parameters

The following table presents the set of parameters analyzed to evaluate the physicochemical and microbiological characteristics of lake sediments. These indicators provide critical insights into nutrient availability, metal concentrations, organic matter content, and microbial load factors that influence sediment quality and its interaction with riparian vegetation (Table 2).

Table 2. Analytical Parameters for the Physicochemical and Microbiological Characterization of Sediments

Parameter	Units	Method
pH	Unit	NTC 5264 200803-26
Oxidizable Organic Carbon	mg/L	NTC 5403. 2013
Organic Matter (OM)	mg/L	NTC 5403. 2013
Total Nitrogen (TN)	mg/L	NTC 5889
Available Phosphorus (P)	mg/L	NTC 5350
Cation Exchange Capacity (CEC)	cmol(+)/kg	NTC 5268
Exchangeable Calcium (Ca)	cmol(+)/kg	NTC 5349
Exchangeable Magnesium (Mg)	cmol(+)/kg	NTC 5349
Exchangeable Potassium (K)	cmol(+)/kg	NTC 5349
Exchangeable Acidity and Aluminum (Al)	cmol(+)/kg	NTC 5263
Available Iron (Fe)	mg/kg	NTC 5526
Available Manganese (Mn)	mg/kg	NTC 5526
Available Copper (Cu)	mg/kg	NTC 5526
Available Zinc (Zn)	mg/kg	NTC 5526
Available Boron (B)	mg/kg	NTC 5404

Microbiological analyses of the sediment samples were also performed using standardized techniques. These included colony-forming unit (CFU) counts in accordance with ISO 4833-1:2013 or Standard Method 9215, enumeration of molds and yeasts using the colony count method for products with defined water activity (ISO 21527-1:2008), and quantification of total and FE following ISO 9308-1:2014. These indicators provide essential information on the microbiological load and potential contamination levels in sediment matrices.

3. Results

The following section presents the results of the water quality assessment conducted at the 10 sampling points in Guamuéz Lake. This includes both in situ measurements and physicochemical and microbiological parameters analyzed in the laboratory. Sampling was performed during two distinct climatic periods (rainy season and low-rainfall or dry season) to evaluate seasonal variability in water quality. Of the 10 sampling sites, five were located in areas with visible degradation of *S. californicus***,** while the remaining five corresponded to zones where the vegetation remained unaffected. This sampling design allowed for a comparative analysis aimed at determining whether variations in water quality parameters are associated with the observed condition of riparian vegetation

3.1. Assessment of Bulrush (*Schoenoplectus californicus*) Condition in impacted and unaffected Zones

An evaluation of the condition of *S. californicus* was conducted at the designated sampling sites to determine the degree of degradation in both impacted and unaffected areas of Guamuéz Lake. The assessment followed a modified version of the methodology proposed by Mendoza [20], which involves direct field observation of key ecological indicators, including plant abundance, coloration, height, and structural integrity. A scale from 0 to 3 was applied, where 0 = low impact, 1 = medium impact, and 3 = high impact. This methodology enabled a comparative analysis of riparian vegetation health across varying environmental conditions. The results of this evaluation, indicating the impact level at each sampling point, are presented in Table 3.

Table 3. Degree of impact of *Schoenoplectus californicus* at Sampling Points

Point	Zone	Impact
1	Carrizo	Medium
2	Sindamanoy	High
3	Santa Lucia	Low
4	Corota	High
5	Mojondinoy	High
6	Santa Teresita	Medium
7	Romerillo 1	Medium
8	San Isidro	Medium
9	Naranjal	Low
10	Ramos	Low
11	Motilón	High
12	Puerto	High
13	Garzario	High

Of the 13 evaluated sampling points, 6 were classified as having high affectation, 4 as medium, and 3 as low, based on field observations of *S. californicus* condition. The spatial distribution and corresponding levels of impact at each site are shown in Figure 4, where the degree of degradation is represented using a color-coded scheme: red for high affectation, yellow for medium, and green for low. This visual representation highlights the points most severely impacted by anthropogenic pressures around the lake.

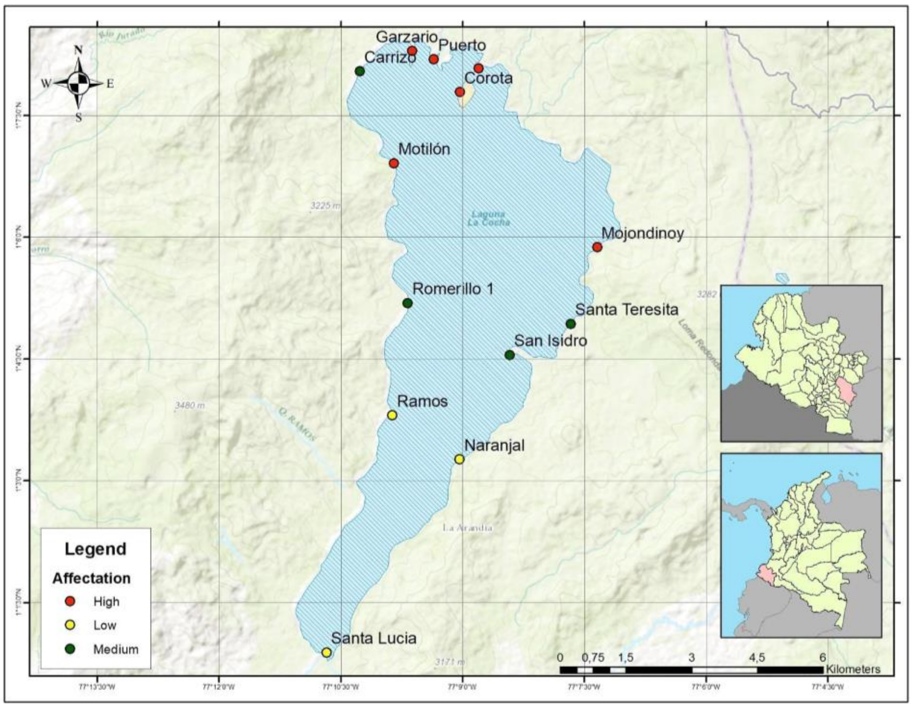

Figure 4. Spatial Distribution of *Schoenoplectus californicus* impact Levels

3.2. Water Quality Parameters

The following section presents the results of the water quality assessment conducted at the 10 sampling points in Guamuéz Lake. This includes both in situ measurements and physicochemical and microbiological parameters analyzed in the laboratory. Sampling was performed during two distinct climatic periods (rainy season and low-rainfall or dry season) to evaluate seasonal variability in water quality. Of the 10 sampling sites, five were located in areas with visible degradation of *S. californicus*, while the remaining five corresponded to zones where the vegetation remained unaffected. This sampling design allowed for a comparative analysis aimed at determining whether variations in water quality parameters are associated with the observed condition of riparian vegetation.

3.2.1. In Situ Water Quality Parameters

Figure 5 summarizes the results of in situ measurements of key water quality parameters collected at the ten sampling points across Guamuéz Lake. This figure presents the mean values of in situ measurements for key water quality parameters, temperature (°C), conductivity (µS/cm), dissolved oxygen (DO) concentration (mg/L), transparency (m), and pH, across the 10 evaluated sampling points, along with their respective standard deviations. The data were compared against the degree of *S. californicus* impact at each site, with locations classified as high, medium, or low based on observed levels of affliction.

This comparison allows for an evaluation of how varying water quality conditions may correlate with the degree of *S. californicus* impact. The spatial variation in these parameters reveals distinct patterns across zones with differing levels of contamination impact. Temperature was highest and most stable in the high-impact zone, while the medium-impact zone exhibited greater variability. Conductivity was slightly higher in the low-impact zone, suggesting possible ionic accumulation from runoff. Dissolved oxygen and pH showed the greatest variability in the medium-impact zone, likely reflecting localized biological or chemical processes. Transparency was lowest in the high-impact zone and peaked in the medium-impact zone due to a single elevated value. These results highlight the influence of contamination on water quality and underscore the importance of spatially informed monitoring strategies in lake ecosystems.

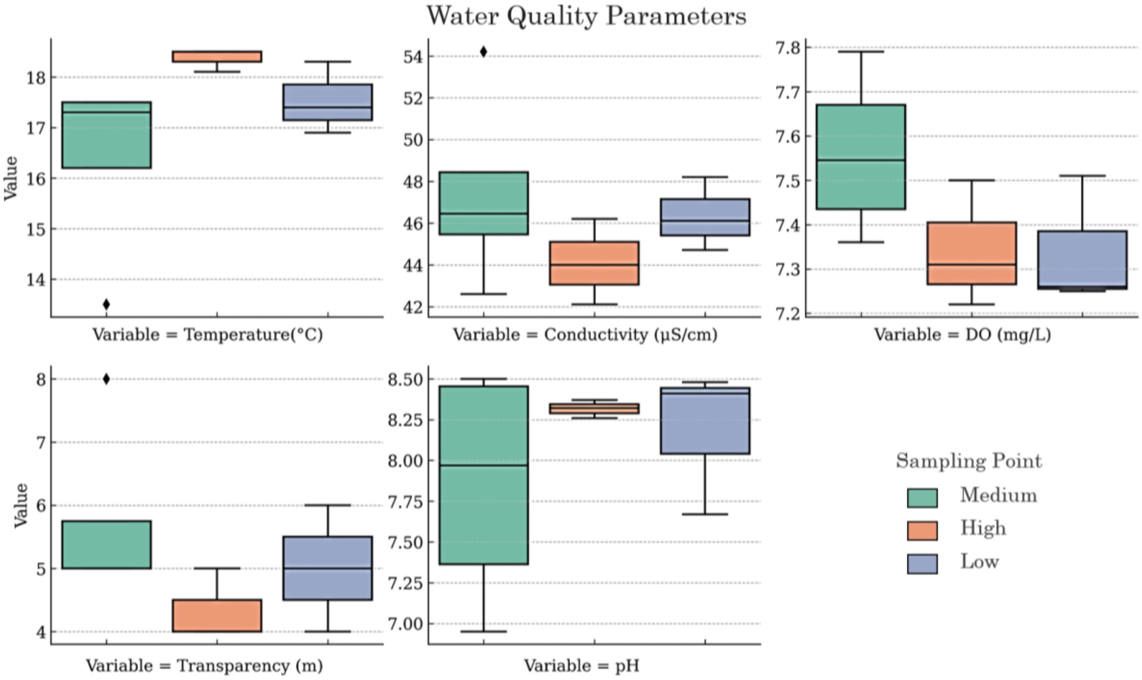

Figure 5. Comparison of In Situ Water Quality Measurements at Guamuéz Lake (Low, Medium, High Sites)

3.2.2. Physicochemical and Microbiological Parameters

Physicochemical and microbiological water quality parameters were analyzed based on samples collected from the 10 designated sampling points in Guamuéz Lake during two distinct hydrological periods: the rainy season (Sampling 1) and the low-rainfall or dry season (Sampling 2). This design allowed for the assessment of seasonal variability in water quality and potential changes in contamination levels. The results are presented in Figure 6, which displays the mean concentrations and standard deviations of key parameters across both sampling periods, highlighting seasonal differences in nutrients, organic matter, metals, and microbial indicators.

In general, the average values of many parameters are higher under “High impact” conditions compared to “Low impact” conditions. Parameters such as BOD5 and COD show slightly higher levels in “High impact”, which could be related to a greater presence of organic matter or easily biodegradable contaminants. Parameters such as nitrate, copper, iron, TC and FC show significantly higher concentrations in “High affectation”, indicating higher microbiological contamination, nutrients, salts, and dissolved minerals under these conditions.

To determine if there is a significant difference between the high and low impact zones of S. californicus, the non-parametric Mann-Whitney test was used, comparing water quality parameters between rainy and low-rainfall seasons. Significant differences (p 0.05) were observed for Fats and Oils (p = 0.0256), Total Suspended Solids (TSS) (p = 0.0091), Anionic Detergents (p = 0.007), Iron (p = 0.0002), Magnesium (p = 0.0002), Potassium (p = 0.0015), Sodium (p = 0.0028), and Fecal Coliforms (E. coli) (p = 0.0015), indicating seasonal variations influenced these parameters. Conversely, no significant differences ($p > 0.05$) were detected for Total Alkalinity (p = 0.9687), BOD_5 (p = 0.1617), COD (p = 0.2725), Nitrates (p = 0.5095), Total Phosphorus (p = 0.9675), Copper (p = 0.2885), or Zinc (p = 0.0741), suggesting these remained consistent across seasons. The results highlight specific contaminants (e.g., microbial, ionic, and particulate) that exhibit rainfall-driven dynamics, while conventional parameters showed minimal seasonal sensitivity.

A similar analysis was conducted for the physicochemical and microbiological parameters of water quality, comparing the 10 sampling points based on the level of riparian vegetation affectation. Specifically, points 1 to 5 correspond to areas with high affectation, while points 6 to 10 represent areas with low or no visible affectation. This comparison aimed to identify potential differences in water quality associated with the condition of S. californicus. The results of the analysis are displayed in Figure 7. Panel A presents the concentrations of key physicochemical parameters, including nutrients, organic matter, detergents, and metals, measured in surface water from zones with contrasting levels of riparian vegetation impact. Panel B shows the microbial contamination indicators, expressed as total coliforms (TC) and fecal coliforms (FC). Error bars represent the standard deviation (n = X). The data illustrates higher variability and elevated mean values in multiple parameters under high-impact conditions, indicating anthropogenic influence on water quality.

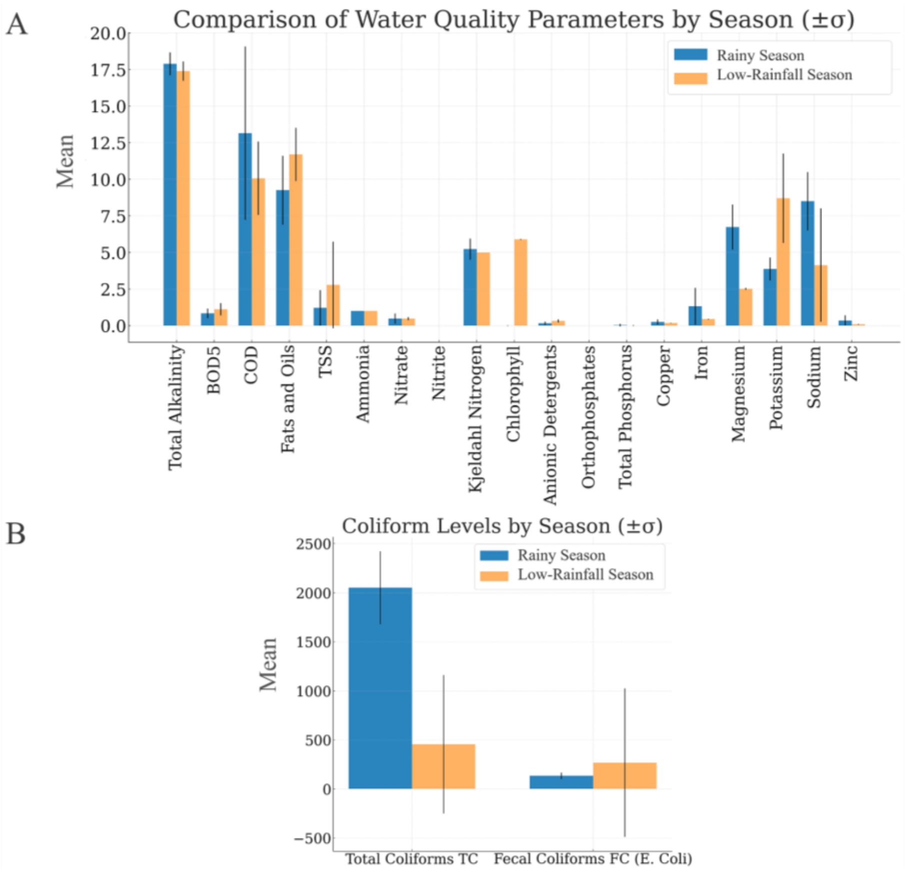

Figure 6. Physicochemical and microbiological water quality parameters (mean ± standard deviation) in Lake Guamuéz during the rainy season and low-rainfall season

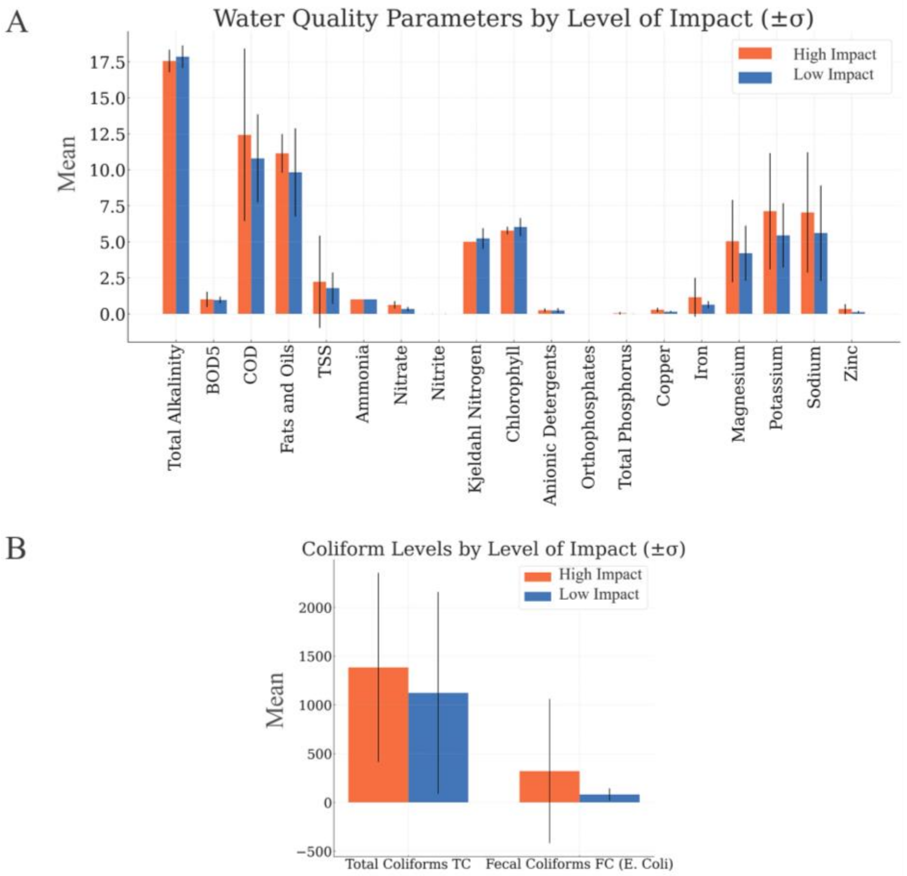

Figure 7. Comparison of physicochemical and microbiological water quality parameters (mean ± SD) between high- and low-impact zones in Lake Guamuéz

The following table supports the graphical results by providing detailed numerical values of each parameter, expressed as mean ± standard deviation, for both high- and low-impact zones. These quantitative data confirm the observed trends in the figure, highlighting consistent differences in water quality across the study sites. Notably, higher concentrations of COD, fats and oils, nitrates, and metals such as copper and iron were recorded in areas classified as highly impacted. Similarly, microbial indicators, particularly fecal coliforms, demonstrate increased variability and elevated mean values in those same zones. This evidence lends further support to the interpretation that anthropogenic activities are contributing to localized deterioration of water quality in riparian environments of Lake Guamuéz.

Table 4. Physicochemical and Microbiological Parameters (Mean and Standard Deviation) of Water Quality in Guamuéz Lake in High and Low Affectated Zones

Parameter	High impact (Mean ± σ)	Low Impact (Mean ± σ)
Total Alkalinity	17.56 ± 0.78	17.85 ± 0.78
BOD5	1.00 ± 0.53	0.96 ± 0.23
COD	12.43 ± 5.98	10.79 ± 3.06
Fats and Oils	11.14 ± 1.34	9.82 ± 3.06
TSS	2.23 ± 3.20	1.78 ± 1.09
Ammonia	1.00 ± 0.00	1.00 ± 0.00
Nitrate	0.62 ± 0.26	0.34 ± 0.15
Nitrite	0.00 ± 0.01	0.00 ± 0.01
Kjeldahl Nitrogen	5.00 ± 0.00	5.23 ± 0.72
Chlorophyll	5.78 ± 0.27	6.03 ± 0.63
Anionic Detergents	0.25 ± 0.12	0.24 ± 0.15
Orthophosphates	0.00 ± 0.00	0.00 ± 0.00
Total Phosphorus	0.04 ± 0.09	0.00 ± 0.01
Copper	0.28 ± 0.15	0.15 ± 0.05
Iron	1.15 ± 1.34	0.63 ± 0.25
Magnesium	5.05 ± 2.86	4.21 ± 1.91
Potassium	7.12 ± 4.04	5.45 ± 2.23
Sodium	7.04 ± 4.18	5.60 ± 3.31
Zinc	0.33 ± 0.35	0.12 ± 0.08
Total Coliforms TC	1383.28 ± 968.98	1122.19 ± 1035.61
Fecal Coliforms FC (E. Coli)	321.05 ± 739.80	80.59 ± 62.67

3.3. Assessment of Sediment Quality Parameters

3.3.1. Physicochemical Analysis of Sediment in Areas with High Impact and Low Impact of Bulrush

Table 5 presents the results of the physicochemical analysis of sediment collected from sampling points located in impacted and unaffected areas. These data provide insight into the sedimentary conditions that may be contributing to the observed degradation of riparian vegetation.

Applying the soil classification methodology of Osorio [23] for soil fertility analysis, acidity levels, and the methodology of Mora [24] for evaluating organic matter content (classified as very low, low, sufficient, high, and very high) and cation exchange capacity (determined in categories of very low, low, medium, medium-high, and high), the characterization of the sediments is presented in the Table 6.

Statistical analysis using SPSS software was conducted via independent Student's t-tests (assuming unequal variances) to compare sediment physicochemical parameters between *S. californicus*-impacted and unaffected zones in Guamuéz Lake, yielding no significant differences across all measured variables. For pH, organic matter (OM), phosphorus (P), cation exchange capacity (CEC), calcium (Ca), magnesium (Mg), potassium (K), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), and boron (B), all p-values exceeded $\alpha = 0.05$ (range: 0.26–0.95). This consistency (100% of parameters with $p > \alpha$) indicates no detectable influence of *S. californicus* presence on sediment quality characteristics.

Table 5. Physicochemical analysis of sediment collected from sampling points located in impacted and unaffected zones

Parameter	Impacted Mean	± σ	Unaffected Mean	± σ
pH	5.69	0.22	5.76	0.13
Organic Matter OM (%)	15.97	10.41	16.50	5.55
P (mg/kg)	14.96	18.41	5.35	3.44
CEC (cmol+/kg)	33.93	12.66	28.03	15.50
Ca (cmol+/kg)	13.52	8.43	12.73	0.76
Mg (cmol+/kg)	3.33	2.90	4.83	1.07
K (cmol+/kg)	0.45	0.28	0.55	0.17
Al (cmol+/kg)	0.18	0.05	ND	ND
Fe (mg/kg)	506.20	216.54	536.00	371.55
Mn (mg/kg)	57.92	42.99	56.43	27.79
Cu (mg/kg)	1.84	1.68	1.13	1.20
Zn (mg/kg)	1.60	1.64	0.74	0.71
B (mg/kg)	0.39	0.14	0.35	0.18
Total Nitrogen (%)	ND	ND	0.54	0.13
Oxidizable Organic Carbon (%)	ND	ND	9.57	3.25

Table 6. Sediment Classification in *Schoenoplectus californicus* impacted and unaffected Zones

Parameter	Impacted	Unaffected
Al	Very low	Very low
B	Low	Low
P	Low	Low
Zn	Low	Low
pH	Moderately acidic	Moderately acidic
Cu	Sufficient	Sufficient
CEC	Medium	Medium
OM	High	High
K	High	Very High
Ca	Very High	Very High
Mg	Very High	Very High
Fe	Very High	Very High
Mn	Very High	Very High

3.3.3. Microbiological Analysis of Sediments

As part of the sediment quality assessment, a microbiological analysis was performed to evaluate the presence and concentration of key microbial indicators. The analysis focused on fecal coliforms (FC), total coliforms (TC), and mesophilic microorganisms (MES), using colony-forming unit (CFU) counts as the quantification method. Table 7 presents the average concentrations of these microbial groups in both *S. californicus*-impacted and unaffected sampling points, providing insight into the microbiological status of the sediments and its potential relationship with riparian vegetation degradation.

Table 7. Microbiological analysis of sediment in S. californicus- impacted and unaffected Zones

Parameter	Impacted Points (CFU/g)	Unaffected Points (CFU/g)	Variation (%)
FC	131	45	191.11%
MES	143	53	170.19%
TC	141	23	513.04%
TOTAL	**654**	**121**	**440.50%**

The bar chart presents a comparative analysis of microbial concentrations (CFU/g) between impacted and unaffected points across four parameters: FC, MES, TC, and TOTAL, Figure 8. The X-axis displays parameters, while the Y-axis indicates the CFU/g values. Blue bars correspond to the impacted points, and red bars to the unaffected points. Each bar is annotated with its respective CFU/g value, facilitating a clear visual interpretation of the magnitude and variation between the two categories across all parameters. It also highlights the magnitude of increase in microbial presence associated with riparian vegetation degradation by *S. californicus*.

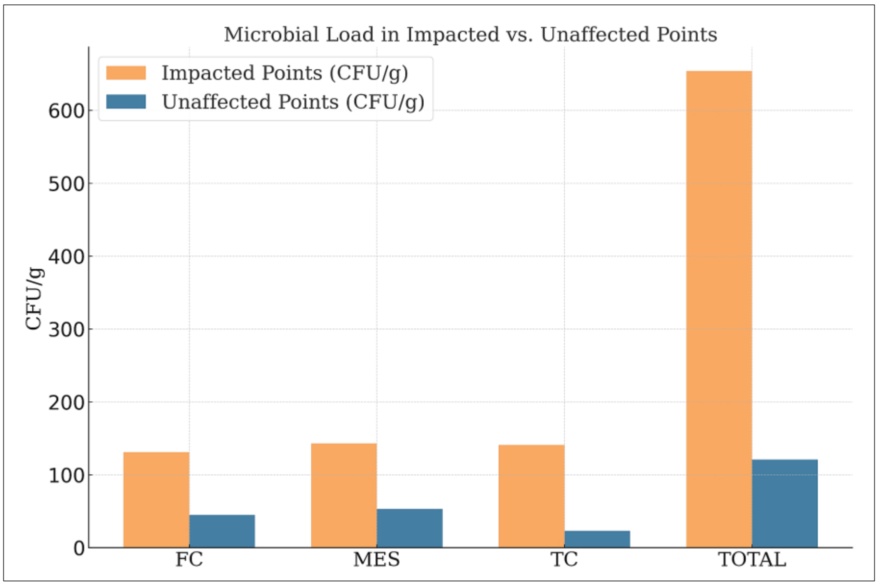

Figure 8. Microbiological analysis of sediment in Bulrush-affected and unaffected zones of Guamuéz Lake

4. Discussion

4.1. Assessment of Bulrush (*Schoenoplectus californicus*) Condition in Impacted and Unaffected Zones

Based on the field assessment of *S. californicus* condition, the following results were obtained regarding the levels of impact across the 13 evaluated sampling points: 6 sites (46.2%) were classified as having high impact, 4 sites (30.8%) showed medium impact, and 3 sites (23.1%) exhibited low impact. The high-impact category represents the largest proportion, indicating a significant degree of degradation in nearly half of the surveyed locations. As shown in Figure 4, the sites with the highest levels of impact correspond to areas with the greatest population density and higher tourist use, suggesting a direct relationship between human activity and the degree of ecological degradation. It is important to note that in the high-impact areas, sanitary conditions and wastewater treatment are not adequately addressed, as most of these locations are dispersed and lack wastewater treatment systems, or the existing systems are rudimentary. This spatial distribution highlights the riparian zones under varying degrees of ecological pressure, emphasizing the need for targeted management in these high-impact areas.

4.2. In Situ Water Quality Parameters

According to the in situ water quality measurements, several key parameters were analyzed to characterize the physicochemical conditions of Guamuéz Lake across the ten sampling sites.

Water temperature ranged from 13.5 °C to 18.5 °C. The lowest values were recorded near the inflow of the Encano River, the lake's main tributary originating from the Bordoncillo paramo where lower temperatures are attributed to altitude and surface runoff processes [25, 26]. In contrast, higher temperatures were observed in zones with limited water circulation or stagnation, where increased solar exposure contributes to thermal accumulation.

Electrical conductivity values varied between 42.1 and 54.2 µS/cm, consistent with low mineralization typically found in high-altitude water bodies. These conditions result from predominant inputs of rainfall and runoff from relatively unaltered areas with limited human influence [27, 28]. This contrasts with lowland lakes, where increased evaporation and mineral dissolution generally lead to higher conductivity values [27].

Dissolved oxygen (DO) concentrations ranged from 7.22 to 7.79 mg/L, values close to saturation under atmospheric pressure at approximately 2,760 meters above sea level [25]. These levels are considered adequate for supporting aquatic life [29, 30], typically falling within the range of 20 - 90% oxygen saturation for healthy ecosystems [31, 32].

Water transparency was measured between 4 m and 8 m, indicating relatively low turbidity and a low trophic state, characteristic of high-altitude lakes where limited phytoplankton productivity is common [33]. These values are consistent with previous studies in Guamuéz Lake [34], and position it between extremely oligotrophic lakes (e.g., 19.5 m transparency [35]) and eutrophic systems with much lower clarity (e.g., 0.81 m [36]).

Finally, pH levels ranged from 6.95 to 8.50, reflecting slightly alkaline conditions. This is typical for Andean lakes where phosphorus limitations restrict phytoplankton growth, while nitrogen fixation by cyanobacteria helps sustain productivity [37]. However, pH values exceeding 8.5 may affect microbial dynamics by increasing bacterial mortality, which could influence biogeochemical processes within the lake [38].

4.3. Physicochemical and Microbiological Water Quality Parameters

The comparative summary of physicochemical and microbiological water quality parameters in Guamuéz Lake across the rainy and low-rainfall seasons, as presented in Table 7, reveals consistent patterns for several indicators. Specifically, the analysis of total alkalinity shows values ranging from 16.83 to 19.8 mg/L during the Rainy Season, with an average of 17.89 mg/L, and from 15.98 to 17.86 mg/L during the Low-Rainfall Season, averaging 17.39 mg/L. The slight variation observed between sampling sites in both periods suggests a relatively homogeneous distribution of alkalinity throughout the lake, regardless of seasonal changes. This stability may reflect the buffering capacity of the lake’s water and its limited exposure to sources of acidification or external chemical inputs.

The data for organic matter in terms of BOD5 in Guamuéz Lake range from 0.31 to 1.39 mg/L, with an average of 0.84 mg/L in the rainy season. They also include between 0.56 and 1.92 mg/L, with an average of 1.12 mg/L during the low-rainfall season. In terms of COD, values range from 6.39 to 25.57 mg/L in the rainy season and from 6.98 to 14.3 mg/L in the low-rainfall season. Variations are observed between the different sampling points during both seasons, which could indicate point sources of contamination or differences in the local characteristics of the lake. This is due to the presence of human settlements, agricultural activities, and aquaculture in the basin. In the rainy season, COD shows a higher dispersion with higher extreme values, while in the low-rainfall season, the values are more homogeneous with fewer elevated peaks. This suggests that, during the rainy season, the increased flow of the lake's tributaries may carry organic matter and contaminants from external sources, such as agricultural areas or human settlements. This would explain the elevated values at points such as Point 2, near the hotel zone “Sindamanoy” and trout farms, where there is a higher accumulation of organic matter in the water column, reaching a maximum value of 25.57 mg/L. In the dry season, with less runoff, more stable concentrations are observed without the extreme values seen in the rainy season.

Regarding the biodegradability index, which relates to the biodegradable fraction of organic matter, values range from 4.13 to 11.89 in the rainy season and from 4.05 to 20.05 in the low-rainfall season. Some points show considerably higher values, such as Point 2 (20.05) near populated areas and hotels and Point 4 (16.87) near Corota, where there is tourist influx. This could indicate the accumulation of more biodegradable organic matter. In biodegradability, Guamuéz Lake exhibits an important seasonal dynamic influenced by the rainfall regime. The index is more stable and generally lower in the rainy season due to dilution effects and possible contributions of recalcitrant organic matter. This is in contrast to the low-rainfall season where significant increases are observed at certain points, indicating the concentration of biodegradable organic matter in the absence of water renewal flow.

The presence of nitrogen in reduced and organic forms during both the rainy and low-precipitation seasons suggests continuous nutrient inputs through consistent contributions from agricultural runoff, livestock activities, untreated wastewater discharges, or sustained decomposition of organic matter in lake sediments [39]. These conditions result in stable concentrations of Total Kjeldahl Nitrogen and ammonia. Nitrate concentrations averaged 0.48 mg/L but exhibited greater variability during the rainy season ($\sigma = 0.35$), likely due to episodic runoff events introducing fertilizers or other oxidized nitrogen compounds into the system. Nitrite was detected only during the rainy season (0.01 mg/L), indicating transient nitrification processes likely stimulated by increased microbial activity and oxygen fluctuations associated with elevated organic loading.

Parameters such as fats and oils and TSS have relatively lower and more homogeneous levels during the rainy season due to dilution, dispersion, and higher water renewal rates. In the low-rainfall season, a more significant accumulation of these compounds is observed, with higher values at specific points, due to reduced circulation and increased water residence time.

The seasonal differences in water quality parameters, assessed using the Mann–Whitney U test, revealed statistically significant variations between the rainy and low-rainfall seasons for several key indicators. Notable differences were observed in fats and oils**,** TSS**,** anionic detergents, and concentrations of certain metals, including iron**,** magnesium**,** potassium, and sodium, as well as in FC levels. These differences can be attributed to seasonal hydrological dynamics. During the rainy season, increased precipitation contributes to the dilution of surface pollutants**,** such as fats and oils, while simultaneously enhancing runoff and soil erosion, which introduces greater loads of suspended solids and microbiological contaminants into the lake. Moreover, rainfall events facilitate the mobilization and transport of mineral elements from the surrounding watershed, thereby increasing concentrations of metals like iron and sodium in the aquatic environment. The chlorophyll concentration during the period of reduced precipitation was 5.9 µg/L. This value suggests a moderate level of phytoplankton productivity in the lake. Chlorophyll concentrations in freshwater lakes can vary widely depending on factors such as nutrient availability, temperature, and light. A chlorophyll value of 5.9 µg/L typically indicates a mesotrophic state, where the lake has a moderate amount of nutrients, supporting a healthy balance of aquatic life without excessive algal blooms [34].

Significant differences were found between the samples from the two seasons (rainy and low-rainfall) for parameters such as Fats and Oils, TSS, Anionic Detergents, Iron, Magnesium, Potassium, Sodium, and FC. During the rainy season, the increase in precipitation can lead to the dilution of contaminants, such as fats and oils, as well as influence soil erosion and the runoff of suspended materials. Additionally, rainfall can affect the presence of heavy metals (iron, magnesium, potassium, and sodium) by increasing the transport of these minerals from the watersheds to the lagoon. Regarding FC, the bacterial load increases due to the runoff of domestic wastewater. The chlorophyll concentration was evaluated at all points and found to be in the range of 5.78 - 6.03 µg/L, indicating a mesotrophic state across all evaluated locations. This range suggests moderate levels of nutrients in the lake, supporting a balanced aquatic ecosystem with no excessive algal blooms. Chlorophyll concentrations within this range typically point to a healthy environment where phytoplankton growth is moderate and well-controlled. This finding highlights the lake's stable nutrient dynamics, particularly during periods of reduced precipitation when water flow and nutrient dilution are lower [34].

On the other hand, parameters with a p-value greater than 0.05, such as Total Alkalinity, BOD5, COD, Nitrates, and Total Phosphorus, remain relatively stable during both seasons. Alkalinity and oxygen demand do not vary drastically because, although rainfall can alter water chemistry, these indicators are less susceptible to seasonal variations. Moreover, nitrates and phosphorus tend to be influenced by the use of fertilizers in agriculture, trout farming, or the proximity to populated areas, which are constant regardless of rainfall. They do not allow for significant dilution during the rainy season, unlike other parameters. This highlights the importance of implementing sustainable agricultural practices that reduce the release of fertilizers into lakes, such as controlled release and reduced irrigation. This can be a key strategy to improve water quality in Guamuéz Lake and significantly mitigate eutrophication, while simultaneously promoting sustainability and agricultural productivity [40].

As explained in section 3.2.2, significant differences were identified for copper ($p = 0.009$) and nitrates ($p = 0.015$) between areas with high and low impact of *S. californicus*. In the case of copper, elevated concentrations in highly unaffected zones may be attributed to the decrease in riparian vegetation, as species such as *S. californicus* act as natural filters that retain and stabilize heavy metals in the sediment. When this vegetation is lost or degraded, the metals are more likely to be mobilized into the water column, increasing their concentration [41]. Similarly, nitrate levels tend to be higher in desiccated areas due to the reduction in plant uptake, which limits the removal of dissolved nutrients. This can intensify eutrophication processes, contributing to ecological imbalance within the aquatic system [42].

The other parameters did not show significant differences between the two zones, indicating that, despite having differences in averages, the difference is not statistically significant. Therefore, other factors, such as precipitation or biological activity in the unaffected riparian zones, help maintain the stability of these parameters [43].

According to the literature, riparian zones primarily receive nutrients through sediments transported by water (Mg, Pb, Mn, Fe) and organic material (litter, branches) deposited during floods. The vegetation specializes in conditions of low nutritional availability, developing strategies to capture nutrients in underdeveloped soils, such as shallow root systems or microbial symbiosis [44]. Additionally, it is known that riparian vegetation intercepts nitrates and heavy metals, preventing their entry into water bodies and preserving ecosystem quality. However, this process can be quite slow, as these substances can remain for many decades before being absorbed [45].

Mountain lakes generally exhibit superior water quality compared to non-mountainous lakes in terms of physical, chemical, and biological indicators, reflecting their lower anthropogenic impact and remote nature. Human activities nearby, such as urban, agricultural, and recreational settlements, along with intrinsic characteristics of mountain watersheds like steep slopes, high runoff, and low hydraulic conductivity of the soil, increase impacts such as the influx of nutrients and other pollutants, or physical changes and disturbances in the littoral zones. The combination of human pressures and the characteristic geography of mountain lakes highlight the need for conservation strategies that protect riparian vegetation and mitigate the transfer of pollutants into water bodies. This ensures the preservation of the critical ecosystem services that mountain lakes provide [46].

4.4. Sediment Parameters of *S. californicus*-impacted and Unaffected Areas

The analysis aims to identify potential differences in sediment composition that may be associated with the observed degradation of *S. californicus*. By comparing these two contrasting conditions, it is possible to better understand the role of sediment quality in the health and stability of riparian vegetation.

4.4.1. Physicochemical Characteristics of Sediments in *S. californicus* Impacted and Unaffected Areas

According to Table 5, the analysis of sediments at high-impact points in Guamuéz Lake reveals a complex interaction between soil quality and the chemical characteristics that influence the ecosystem. In these areas, the high organic matter content, combined with very high levels of potassium, calcium, magnesium, iron, and manganese, promotes nutrient retention and provides a solid foundation for biomass development, as supported by studies that emphasize the crucial role of these elements in sediment fertility [47, 48]. However, the low availability of phosphorus, zinc, and boron presents critical challenges for biological productivity, which could hinder optimal growth of S. californicus, a key species in the ecological regulation of these environments, as highlighted in research on aquatic ecosystems [49].

According to Table 6, the moderately acidic pH also affects nutrient availability and influences the behavior of certain metals like iron and manganese. At elevated concentrations, these metals can pose toxicity risks to plants and aquatic organisms [50]. Overall, the sediments at impacted sites exhibit moderate to high fertility; however, interventions are needed to improve the availability of phosphorus and zinc, and to manage the effects of acidity and metal concentrations. These measures, in line with sustainable wetland management practices [36], are essential for ensuring the long-term stability and sustainability of areas affected by S. californicus, as well as preserving the ecological equilibrium of the lagoon.

The analysis of sediments at points with unaffected *S. californicus* zones in Guamuéz Lake, reflects a balance between strengths and limitations in terms of physicochemical quality. Previous studies have shown that high levels of organic matter and nutrients such as potassium, calcium, and magnesium are positive indicators for sediment fertility and ecosystem stability, as observed in research conducted in the Laguna Bella wetland. Similar patterns in nutrient and metal dynamics were identified [51]. However, the low availability of phosphorus, zinc, and boron, along with a moderately acidic pH, may limit biological productivity. This phenomenon also reported in studies on lagoon systems such as Bajo Alcatraz-Mata Redonda in Venezuela, where the influence of acidity and metals on sediment quality was emphasized [50]. These findings highlight the need to monitor and manage these parameters to ensure the sustainability of the ecosystem and the healthy development of aquatic vegetation.

The analysis of the physicochemical parameters of sediments at points impacted and unaffected by *S. californicus* in Guamuéz Lake reveals key similarities and differences that influence the ecosystem dynamics. In both cases, the levels of aluminum (Al), boron (B), phosphorus (P), and zinc (Zn) are consistently low, indicating a general limitation in the availability of these essential nutrients for plant development. This could restrict biological productivity in both types of sediments, as observed in studies on the influence of micronutrients in aquatic ecosystems [52].

The moderately acidic pH is uniform in both cases, suggesting that acidity conditions could be affecting the availability of certain nutrients and the mobility of metals such as iron (Fe) and manganese (Mn). These metals, present at very high levels in both types of sediments, can be beneficial in small quantities, but their excess, combined with acidity, could create toxicity for plants and aquatic organisms, as documented in recent research [53].

The medium cation exchange capacity (CEC) and the high organic matter (OM) content are consistent in both cases, favoring nutrient retention and sediment structure. However, a notable difference is observed in the potassium (K) levels, which are high at impacted points and very high at unaffected points. This contrast could influence the ability of plants to withstand stress and maintain their vigor, as noted in studies on nutrient dynamics in wetlands [54].

In Table 6 it can be observed that 33.3% of the physicochemical parameters indicate a high level of nutrient availability at unaffected points, while at impacted points, this value is 26.7%. The nutrients with high availability include: exchangeable calcium (Ca), exchangeable magnesium (Mg), available iron (Fe), available manganese (Mn), Organic Matter and exchangeable potassium (K). There are no universally established toxicity thresholds specifically for *S. californicus* (bulrush) regarding metals such as calcium (Ca), magnesium (Mg), manganese (Mn), or organic matter. However, various environmental and ecological studies on other species indicate that while iron is essential for plant growth, at very high concentrations, it can be toxic. In general, iron concentrations exceeding 1-10 mg/L in water can have adverse effects on some aquatic plant species, although these values depend on ecosystem conditions such as acidity and the presence of other compounds. Exposures to iron levels greater than 1 mg/L can lead to necrosis, plant death, disintegration of colonies, and root loss in species like *Spirodela polyrrhiza*. Additionally, iron concentrations at elevated levels can interfere with chlorophyll synthesis, protein and carbohydrate production, and nutrient absorption [55].

Manganese, in particular, can become toxic at concentrations above 1 mg/L in aquatic environments, leading to negative effects such as impaired root development and reduced photosynthesis. Additionally, organic matter accumulation in sediments can influence metal bioavailability and oxygen availability in the rhizosphere, further impacting plant health. These values are highly dependent on ecosystem conditions, such as pH, sediment composition, and the presence of other chemical compounds [56].

On the other hand, when analyzing the low availability of nutrients, it is evident that 26.7% of the parameters at both impacted and unaffected points show low nutrient availability. These nutrients include: available boron (B), available phosphorus (P), and available zinc (Zn). This situation suggests the possibility of a nutritional imbalance, potential toxicity, or even environmental contamination in the sediments of the lagoon [57].

When analyzing pH at impacted points (5.69) and unaffected points (5.76), it is observed that the soil is moderately acidic. The literature generally recommends an ideal pH range for most cultivated plants between 6.0 and 7.0. Therefore, the moderate acidity in the soil pH may contribute to low soil fertility, as it can affect the availability of essential nutrients for *S. californicus* growth. This moderate acidity can be linked to the process of eutrophication, which occurs when an excess of nutrients, primarily nitrogen and phosphorus, enters the water body. Eutrophication can lead to the overgrowth of aquatic plants and algae, resulting in high chlorophyll levels exceeding 5 mg/L, which, upon decomposition, release acids that can lower soil pH, making it more acidic. Despite the high levels of nutrients such as calcium (Ca), magnesium (Mg), and manganese (Mn) in the soil, the acidification resulting from eutrophication may limit the effective absorption of other essential nutrients, negatively impacting bulrush plant growth [51].

4.4.2. Microbiological Analysis of Sediments

Table 7 shows a notably high presence of FC microorganisms in the sediment samples from *S. californicus*-impacted points, as indicated by elevated CFU counts. While unaffected areas also exhibit the presence of these microbial indicators, the concentrations are significantly lower. This disparity suggests a potential link to anthropogenic pollution, as the impacted zones are primarily located in densely populated areas and frequented tourist sites. In these locations, the absence of wastewater treatment infrastructure leads to the direct discharge of domestic and recreational waste into the lagoon, contributing to the microbial contamination of sediments and potentially impacting the health of riparian vegetation.

It can be observed that the presence of microorganisms at impacted points is high, with a percentage variation of 440% compared to the unaffected points. Thus, the presence of microorganisms in the *S. californicus* can primarily be attributed to the discharge of wastewater at the impacted points, which influences the high organic matter content and nutrients that stimulate microbial growth (TC +513%). This amount of microorganisms, along with the decomposition of organic matter, consumes oxygen, generating anaerobic conditions in the sediments, which could suffocate the *S. californicus* roots, reduce its growth or killing it. It could also favor the growth of sulfate-reducing bacteria, releasing toxic substances such as hydrogen sulfide (H_2 S). The overall increase in microorganisms (Total +440%) could disrupt the sediment balance, competing for resources or releasing metabolites that harm the Bulrush, and favoring the eutrophication of the lagoon [58].

5. Conclusions and Recommendations

This study shows that, while the water quality in Guamuéz Lake did not show significant differences between zones with and without *S. californicus* impact, the sediment analyzes did reflect relevant variability, particularly in the microbiological load. A 440% increase in the presence of microorganisms was observed in the sediments of the areas with high impact, suggesting a strong relationship between microbiological contamination and the deterioration of riparian vegetation. The *S. californicus* impact was found to be linked to areas with a higher influence of untreated wastewater discharges (from population and tourism) and aquaculture activity, promoting the formation of anaerobic environments, reducing oxygen availability, and favoring the proliferation of sulfate-reducing bacteria. This explains why there is a higher presence of microorganisms and plant deterioration in the "impacted" areas of Guamuéz Lake. Fecal contamination exacerbates the problem, but the main damaging mechanism is sediment eutrophication.

There is a significant seasonal influence on the variability of certain water quality parameters in Guamuéz Lake, especially those related to organic matter, metals, and microorganisms. The rainy season shows greater dispersion in values for COD, fats and oils, TSS, and the presence of FC. This suggests that increased precipitation intensifies the runoff of nutrients and contaminants from external sources, including agricultural areas and human settlements. In contrast, during the low-rainfall season, parameter stability is higher, reflecting a reduced influence of runoff on water quality. Although no statistically significant differences exist in water quality parameters between high and low *S. californicus* impact zones, variability patterns are observed in certain key parameters. The BOD5 and COD show higher values in the impacted zones, suggesting greater accumulation of organic matter in these areas.

The sediment analysis reveals metal accumulation in Guamuéz Lake, with iron (Fe) and manganese (Mn) concentrations reaching potentially toxic levels for aquatic vegetation. The measured Fe content exceeds known phytotoxicity thresholds that typically induce oxidative damage and impair root development in wetland plants under acidic, waterlogged conditions. Similarly, the elevated Mn levels surpass concentrations known to cause leaf chlorosis and cellular dysfunction. While copper and zinc remain within safe ranges, the combined effects of high Fe-Mn bioavailability in acidic sediments likely create synergistic stress that could hinder *S. californicus* growth. Although this species possesses adaptive tolerance mechanisms like metal exclusion and root oxidation, the persistent exposure to these metallic stressors may ultimately compromise its physiological performance and ecosystem functions in this environment. These findings highlight the need for monitoring metal bioavailability and their long-term ecological impacts in the lake's wetland system.

While others, such as available boron (B), available phosphorus (P), and available zinc (Zn), have low nutrient availability levels. This situation suggests the possibility of nutritional imbalance, potential toxicity, or even environmental contamination in the lagoon sediments.

The moderately acidic pH (5.69-5.76) in Guamuéz Lake's sediments, combined with elevated Fe and Mn levels, creates suboptimal conditions for *Schoenoplectus californicus* growth. While this species shows metal tolerance, the acidic environment likely reduces nutrient availability despite high Ca/Mg concentrations. These conditions may result from eutrophication processes, where nutrient overload leads to algal blooms and subsequent pH-lowering decomposition. The findings suggest that managing eutrophication could improve sediment quality and support healthier *S. californicus* populations.

This is corroborated by the analysis of microorganisms (TC, FC, MES), where the total percentage differences are greater, with a 440% variation in impacted points compared to unaffected points. This suggests a relationship between wastewater discharges, agriculture, and livestock, and the impact on *S. californicus*, potentially leading to hypoxia, H_2S or ammonium toxicity, and microbial competition.

The study highlights that impacts on riparian vegetation are not always detectable through water column analysis alone. Sediment quality, particularly with respect to microbial activity and nutrient dynamics, plays a critical role in the ecological condition of lacustrine systems. These findings reinforce the importance of integrated watershed management strategies that consider both point and non-point source pollution, and support the incorporation of sediment monitoring in aquatic ecosystem assessments to inform effective conservation and restoration of riparian zones.

The standardized methodology developed in this study, which integrates synchronized water and sediment sampling, multi-parameter analysis (physicochemical, trace metals, microbiological), and comparative statistical modeling (Mann–Whitney U test, t-tests), provides a robust and replicable framework for the assessment of high-Andean lake ecosystems. to mitigate impacts on sediment quality in high-altitude lake environments, sustainable management practices should be implemented in sectors such as tourism and aquaculture. This includes the continuous monitoring of key indicators such as pH, nutrient concentrations, and metal levels; controlling nutrient inputs; preventing the discharge of untreated wastewater; promoting responsible ecotourism; and restoring aquatic vegetation to reduce eutrophication. Moreover, management strategies must be adapted to local ecological and altitudinal conditions, applying established toxicity thresholds to regulate anthropogenic activities and safeguard sediment integrity and overall ecosystem health.

6. Declarations

6.1. Author Contributions

Conceptualization, L.S. and G.C.; methodology, L.S. and G.C.; formal analysis, L.S. and G.C.; investigation, L.S., G.C., M.B., M.P., A.B., J.C., D.A., A.B., and L.L.; data curation, L.S. and G.C.; writing—original draft preparation, L.S. and G.C.; writing—review and editing, L.S. and G.C. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

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