

Article

Evaluating Ecological Integrity in Andean High-Mountain Streams Using a Multiplicative Water Quality Index: Roles of Seasonal Hydrology and Benthic Assemblages

Diego Fernando Moreno Pérez * , Germán Eduardo Cely Reyes and Pablo Antonio Serrano Cely

Faculty of Agricultural Sciences, Agronomic Engineering, Universidad Pedagógica y Tecnológica de Colombia (Uptc), Tunja 150003, Boyacá, Colombia; german.cely@uptc.edu.co (G.E.C.R.); pablo.serrano@uptc.edu.co (P.A.S.C.)

* Correspondence: diego.morenoperez@uptc.edu.co

Abstract

High-mountain lotic ecosystems in the tropical Andes are increasingly threatened by agricultural expansion and seasonal hydrological variability. This study evaluates structural water quality shifts and benthic macroinvertebrate community assembly across an environmental degradation gradient in the La Chorrera micro-basin (Boyacá, Colombia). A weighted multiplicative Water Quality Index (*mWQI*), originally developed in previous literature, was implemented and validated alongside biotic scores (BMWP/Col) and Canonical Correspondence Analysis (CCA) across 16 sampling points during contrasting wet and dry seasons. The results demonstrate that intense precipitation during the wet season introduces a volumetric dilution effect, maintaining high ecological quality scores (*mWQI* > 80.0) even in deeply modified agricultural sectors. Conversely, severe baseflow contraction during the dry season triggers pollutant concentration, driving total phosphorus to hyper-eutrophic peaks (9.20 mg/L) and forcing a complete mathematical collapse of the index (*mWQI* = 0.00). The CCA biplot confirmed that seasonal chemical filters combined with hypoxia (<60% oxygen saturation) eliminate highly responsive macroinvertebrate orders (Ephemeroptera, Plecoptera, Trichoptera), leading to absolute dominance of hypoxia-tolerant opportunists (Chironomidae and Oligochaeta). The benthic community shifted from physical stress (sedimentation) during the wet season to chemical stress (nutrient toxicity and oxygen depletion) during the dry season. The multiplicative framework effectively isolates localized ecological tipping points, providing a high-sensitivity baseline tool for targeted watershed restoration in tropical alpine regions.

Keywords: Andean streams; aquatic macroinvertebrates; BMWP/Col; ecological integrity; multiplicative water quality index; seasonal hydrology



Academic Editor: Davide Taurozzi

Received: 29 May 2026

Revised: 22 June 2026

Accepted: 26 June 2026

Published: 30 June 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

High-mountain and páramo ecosystems in the northern Andes act as critical ‘water towers,’ regulating the hydrological cycle and ensuring water supply for downstream populations and socio-economic activities [1]. However, these systems face stress due to the convergence of climate variability, non-linear precipitation patterns dictated by complex orography, and agricultural expansion [1,2]. In tropical mountain regions, the intensification of the hydrological cycle modifies precipitation patterns, causing distinct ecohydrological transitions between the dry and wet seasons that alter natural stream dynamics and accelerate constraints such as severe droughts and frosts in vulnerable

smallholder networks [2]. Water resource management has traditionally relied on physico-chemical or hydrological criteria independently [3]. Conventional Water Quality Indices (WQIs), such as the National Sanitation Foundation WQI (NSF-WQI), were originally developed for temperate zones and often exclude critical regional drivers like Total Phosphorus (TP) or Electrical Conductivity (EC) dynamics under tropical mountain conditions [3–5].

In the context of high-mountain lotic ecosystems, pH and Total Phosphorus (TP) were selected as core parameters. pH acts as a diagnostic indicator for the natural flushing of organic acids from Andean páramo soils—a process where the saturation of organic-rich Histosols and Andosols during rainfall events exports dissolved organic carbon and humic complexes into the stream network [6,7]. Simultaneously, TP serves as the principal limiting nutrient sensitive to anthropogenic loading from agricultural expansion and livestock activities, whose concentration in pristine conditions is typically negligible [7,8]. While conventional additive Water Quality Indices (WQIs) often fail to isolate these localized stressors due to the ‘mathematical eclipsing’ effect [4], multiplicative aggregation frameworks provide a more sensitive and robust approach [4,9]. Recent case reports have successfully validated these multiplicative frameworks in diverse aquatic environments, including the Huang River catchment and Brazilian Reservoirs and river [9–11].

In Andean lotic systems, agricultural runoff and livestock inputs introduce nutrient loads that disrupt the equilibrium of aquatic ecosystems, creating a need for modified indices (*mWQI*) tailored to regional environmental standards [1,5]. A significant knowledge gap exists regarding how seasonal hydrological shifts interact with anthropogenic land-use gradients to dictate the structure of aquatic communities [12]. While the wet season induces dilution effects for certain elements, it also accelerates the transport of non-point source pollutants through surface runoff, significantly impacting ecosystem resilience [13]. Biological indicators, specifically macroinvertebrate richness and tolerance indices like the BMWP/Col, provide a continuous record of ecological integrity, reflecting the toxicological and physical stress that chemical monitoring alone fails to capture [14].

The La Chorrera river micro-basin (Boyacá, Colombia), situated within the upper Chicamocha river system, serves as a highly suitable study scenario. This watershed exhibits an environmental intervention gradient spanning from well-preserved páramo zones to stream reaches heavily modified by agricultural activities. Assessing this gradient across contrasting seasonal regimes allows for a rigorous validation of how modified physico-chemical frameworks correlate with structural changes in benthic communities [12,13]. This study aims to develop and validate a modified Water Quality Index (*mWQI*) optimized for Andean micro-basins by integrating: (i) targeted physicochemical sub-indices (*q*) calibrated for pH and total phosphorus using regional ecological thresholds, (ii) a comparative analysis across seasonal periods (dry vs. wet season), and (iii) the statistical correlation of the *mWQI* with macroinvertebrate taxonomic richness [10,15]. It is hypothesized that macroinvertebrate community degradation along the land-use gradient is strongly driven by seasonal nutrient pulses and localized organic loading effects captured by the *mWQI*, demonstrating that ecological integrity is highly sensitive to seasonal runoff interactions rather than static baseline conditions.

2. Materials and Methods

2.1. Study Area

The research was conducted in the La Chorrera river micro-basin, a high-mountain lotic ecosystem located in the department of Boyacá, Colombia, situated within the upper catchment of the Chicamocha River system (between 5°37′53.35″ N and 73°7′52.19″ W) (Figure 1). The micro-basin encompasses a total drainage area of approximately 66.75 km² and spans a pronounced altitudinal gradient from 2688 to over 3826 m above sea level,

encompassing fragile tropical alpine peatlands (páramos) and high-Andean Forest remnants [16]. The regional climate is governed by a bimodal hydrometeorological regime, displaying two distinct wet periods (typically April–May and October–November) and two contrasting dry baseflow periods (December–March and June–September) [17]. The headwaters of the hydrographic network are partially nested within the La Cortadera Regional Natural Park, a strategically protected area dedicated to regional hydrological regulation and páramo ecosystem conservation [16].

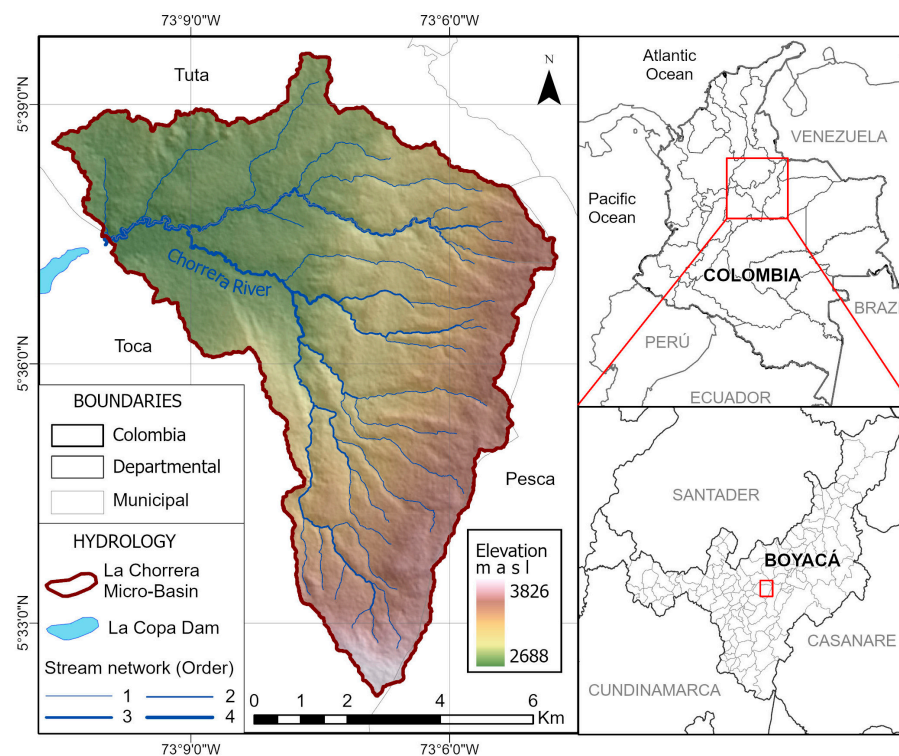


Figure 1. Geographical location of the La Chorrera river micro-basin in Boyacá, Colombia, displaying the altitudinal gradient and the regional hydrographic network. (The red boxes and lines indicate the geographic location and sequential magnification from the national level (Colombia) to the departmental level (Boyacá) and the specific study micro-basin.)

2.2. Landscape Characterization and Experimental Sampling Design

To systematically evaluate the spatiotemporal impact of human activities on water quality and biological community structures, an experimental sampling design was established across 16 strategic sampling points distributed along the mainstream and its primary tributaries. Land Use and Land Cover (LULC) dynamics within the drainage area were mapped and categorized following the Corine Land Cover (CLC) methodology adapted for Colombia [18]. This Geographical Information System (GIS) analysis allowed the spatial stratification of the 16 sampling nodes into three distinct experimental groups based on the dominant landscape matrix and the degree of anthropogenic environmental degradation (Figure 2):

- **GROUP I (Conserved Ecosystem; Points 1, 2, 3, 4, 7, 8):** Reference sampling points selected within or immediately adjacent to the protected boundaries of the Regional Natural Park. These reaches are characterized by pristine alpine conditions, where the surrounding landscape is predominantly composed of high-mountain grasslands (páramo) and undisturbed high-Andean forests.
- **GROUP II (Transitional Ecosystem; Points 5, 9, 11, 13, 14):** River reaches experiencing initial landscape fragmentation and a mixed land-use matrix. These sections serve as

an ecohydrological buffer zone where natural high-altitude vegetation patches coexist with low-intensity subsistence agriculture and extensive seasonal livestock grazing

- GROUP III (Agricultural Ecosystem; Points 6, 10, 12, 15, 16): Reaches situated in the lower valley of the micro-basin under intense anthropization. The adjacent landscape is extensively dominated by non-irrigated arable land for intensive crop production and managed pastures for dairy cattle, exhibiting a high degree of riparian vegetation removal and direct cattle access to the active stream channel.

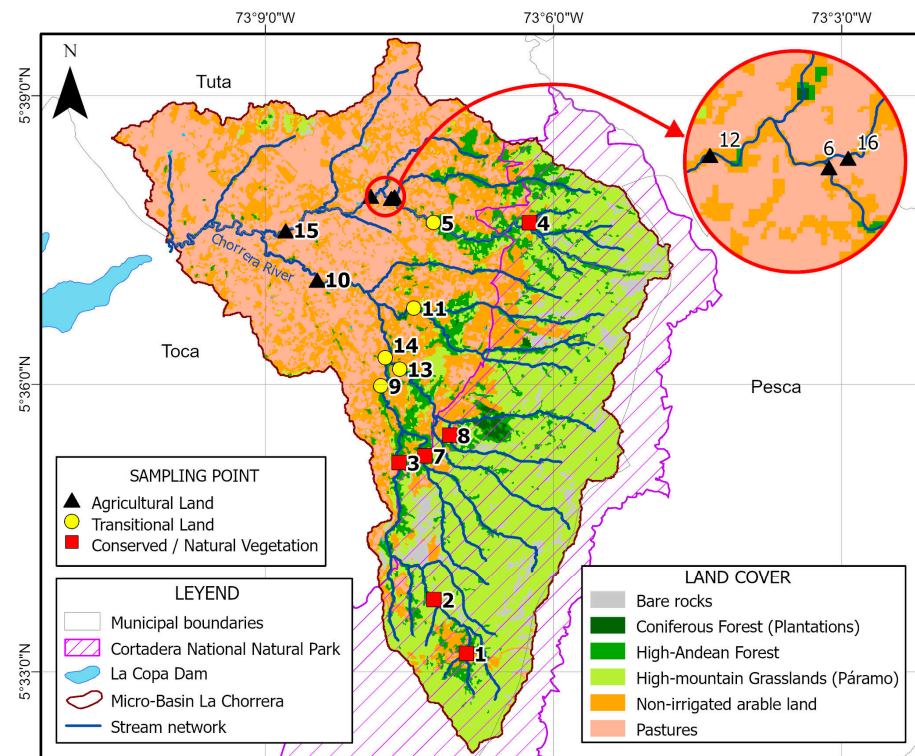


Figure 2. Spatial distribution of the 16 strategic sampling points and land use/land cover (LULC) classification within the La Chorrera river micro-basin drainage area (2018).

A total of 32 sampling events were conducted across the 16 strategic locations to capture the full hydrological gradient of the catchment. Sampling was performed during two intensive campaigns: the high-discharge wet season, conducted between 13 and 20 November 2019, and the low-flow dry season, carried out between 15 and 20 February 2020. These campaigns provided 16 samples per period (32 in total), ensuring a robust comparative assessment across contrasting seasonal regimes. At each point, water samples were collected for physicochemical analysis, and a standardized multi-habitat sampling approach was employed for benthic macroinvertebrates to ensure spatial representativeness.

The experimental framework cross-referenced this spatial gradient with temporal dynamics through surface water sampling campaigns conducted concurrently across the 16 sampling points during the preestablished contrasting wet and dry hydrometeorological periods. At each sampling point, instantaneous streamflow (Q , m^3/s) and physical hydraulic factors were determined in situ via the velocity-area profiling method using a calibrated digital flow meter. Immediately following flow measurements, physicochemical parameters were collected for subsequent laboratory evaluation under standardized protocols, including Dissolved Oxygen (DO%), 5-day Biochemical Oxygen Demand (BOD₅ mg/L O₂), Chemical Oxygen Demand (COD mg/L O₂), Total Suspended Solids (TSS), Total Kjeldahl Nitrogen (TKN), Total Phosphorus (TP mg/L), Electrical Conductivity (EC $\mu S/cm$), and pH. This integrated land-use and seasonal classification framework serves

as the structural baseline for evaluating how anthropogenic land-cover gradients alter physicochemical stressors and biological metrics across contrasting climate regimes [12,13].

Dissolved oxygen (DO) was recorded and reported as a percentage of saturation (% sat) rather than absolute concentration (mg/L). This unit is standardized in high-mountain aquatic research as it accounts for the significant, altitude-driven fluctuations in atmospheric pressure and water temperature, which otherwise skew absolute concentrations and hinder the comparability of water quality status across the altitudinal gradient [19,20]. Furthermore, expressing DO as a percentage of saturation provides a more reliable metric of the water's reaeration potential and metabolic status, as recognized in recent studies on high-mountain stream energetics and nutrient cycling [21,22].

2.3. Mathematical Framework and Formulation of the mWQI

To transform the multi-dimensional environmental data into a single, cohesive indicator highly sensitive to high-mountain agricultural stress, a modified Water Quality Index (*mWQI*) was developed utilizing a weighted multiplicative aggregation structure [4,10]. Compared to conventional arithmetic indexing configurations, the multiplicative framework eliminates the mathematical eclipsing effect, ensuring that a critical deflection in a single master parameter such as severe dry-season hypoxia or extreme hyper-eutrophic phosphorus pulses is accurately preserved and isolates localized ecological tipping points. The global *mWQI* scores were computed according to Equation (1):

$$mWQI = \prod_{i=1}^n q_i^{w_i} \quad (1)$$

where n represents the total number of physicochemical quality attributes selected for the structural core vector ($n = 7$), q_i constitutes the dimensionless, standardized sub-index value ranging from 0 to 100 calculated for the i -th parameter, and w_i denotes its assigned relative environmental weight. Electrical Conductivity (EC) was computed as an auxiliary sub-index (q_{EC}) to monitor baseline mineralization trends but was excluded from the multiplicative product to avoid over-penalizing the index in naturally low-conductivity alpine streams, remaining available exclusively for multivariate ordination analysis. The relative weights (w_i) within the multiplicative core were adjusted and mathematically normalized to satisfy the strict boundary condition $\sum w_i = 1.0$, distributed based on environmental responsiveness as follows: Dissolved Oxygen ($w_{DO} = 0.18$), 5-day Biochemical Oxygen Demand ($w_{BOD5} = 0.15$), Chemical Oxygen Demand ($w_{COD} = 0.13$), Total Suspended Solids ($w_{TSS} = 0.13$), Total Kjeldahl Nitrogen ($w_{TKN} = 0.14$), Total Phosphorus ($w_{TP} = 0.14$), and pH ($w_{pH} = 0.13$).

Following the calculation of the *mWQI*, the water quality status was classified based on the following thresholds, which categorize the index values into five distinct levels: Excellent ($mWQI > 0.90$), Good ($0.70 < mWQI \leq 0.90$), Fair ($0.50 < mWQI \leq 0.70$), Poor ($0.25 < mWQI \leq 0.50$), and Very Poor ($mWQI \leq 0.25$) [4]. This classification framework allows for a standardized interpretation of the ecosystem's ecological integrity, where higher values indicate lower anthropogenic stress and greater suitability for the maintenance of benthic macroinvertebrate assemblages.

Raw physicochemical concentrations collected in field campaigns were converted into their corresponding dimensionless sub-indices (q_i) using localized segment equations and regional mathematical interpolation curves optimized for Andean lotic systems, as detailed in Table 1.

Table 1. Mathematical transformation functions for individual mWQI sub-indices (q_i).

Parameter	Sub-Index Transformation (q_i)	Reference
BOD ₅	$q_{\text{BOD5}} = 100 \cdot e^{-0.05 \cdot \text{BOD5}}$	[23]
COD	$\text{IF} \left\{ \begin{array}{ll} \text{COD} < 20, & q_{\text{COD}} = 91 \\ 20 \leq \text{COD} \leq 25, & q_{\text{COD}} = 71 \\ 25 \leq \text{COD} \leq 40, & q_{\text{COD}} = 51 \\ 40 \leq \text{COD} \leq 80, & q_{\text{COD}} = 26 \\ \text{QOD} > 80, & q_{\text{COD}} = 12.5 \end{array} \right\}$	[24]
TSS	$q_{\text{TSS}} = 100 \cdot (1 - (-0.02 + 0.003 \cdot \text{TSS}))$	[24]
TKN	$\text{IF} \left\{ \begin{array}{ll} \text{TKN} \leq S_{\text{season}}, & q_{\text{TKN}} = 100 \\ \text{TKN} \geq S_{\text{season}}, & q_{\text{TKN}} = 100 \cdot \left(\frac{S_{\text{season}}}{\text{TKN}} \right) \end{array} \right\}$	Present study, (Concept adapted from [4])
TP	$\text{IF} \left\{ \begin{array}{ll} \text{TP} \leq 0.019, & q_{\text{TP}} = [90-100] \\ 0.019 < \text{TP} < 0.052, & q_{\text{TP}} = [70-50] \\ 0.052 < \text{TP} < 0.120, & q_{\text{TP}} = [50-25] \\ 0.120 \geq \text{TP}, & q_{\text{TP}} = [25-0] \end{array} \right\}$	Adapted from [25]
pH	$\text{IF} \left\{ \begin{array}{l} \text{pH} < 4, q_{\text{pH}} = 10 \\ 4 \leq \text{pH} \leq 7, q_{\text{pH}} = 100 \cdot (0.02628419 \cdot e^{\text{pH} \cdot 0.520025}) \\ 7 \leq \text{pH} \leq 8, q_{\text{pH}} = 100 \\ 8 \leq \text{pH} \leq 11, q_{\text{pH}} = 100 \cdot (0.02628419 \cdot e^{[(\text{pH}-8) \cdot (-0.5187742)]}) \\ \text{pH} > 11, q_{\text{pH}} = 10 \end{array} \right\}$	[24,25]
EC	$q_{\text{EC}} = 100 \cdot (1 - 10^{(-3.26 + 1.047 \cdot \text{Log}_{10} \text{EC})})$	[24,25]

To account for the distinct ecohydrological variability of tropical alpine systems, the transformation function for the Total Kjeldahl Nitrogen sub-index (q_{TKN}) incorporates a dynamic regional baseline threshold, denoted as S_{season} . This threshold is computed as the seasonal arithmetic mean of TKN concentrations recorded exclusively within the undisturbed reference points (Group I) during each respective hydrometeorological phase (wet versus dry season). The mathematical integration of this dynamic boundary layer is ecologically necessary to isolate and filter out the natural organic nitrogen flushing mechanisms typically triggered by high-volume precipitation events in pristine páramo peatlands [1]. By adjusting the baseline parameter according to the active climatic regime, the model prevents natural, non-anthropogenic humic and organic nitrogen pulses from introducing systemic bias or false degradation signals into the multiplicative aggregation framework, ensuring high diagnostic precision [4,12].

2.4. Benthic Macroinvertebrate Sampling and Biotic Indices

Benthic macroinvertebrates were collected concurrently with the physicochemical water sampling campaigns across the 16 strategic sampling points. To ensure structural representativeness and minimize microhabitat or substrate preference bias within the lotic riffle and pool systems, biological sampling was executed using a standardized Surber net with a sampling area of 0.09 m² and a 250 µm mesh size, utilizing three distinct field replicates per sampling point. Collected specimens were immediately preserved in situ in 96% ethanol and subsequently transferred to the laboratory. Taxonomic identification was performed down to the family level using specialized Neotropical taxonomic keys [14], a classification threshold widely deemed robust and highly representative for capturing macroinvertebrate community structural responses along steep anthropogenic land-use gradients [12,13].

Biotic and ecological integrity were quantified through three primary metrics: total taxonomic richness (S), community structural diversity, and organic pollution tolerance scores [14]. Internal complexity and family distribution within the benthic assemblages were evaluated using the Shannon–Wiener diversity index (H'), computed according to Equation (2) [14]:

$$H' = - \sum_{k=1}^S p_k \ln p_k \quad (2)$$

where S represents the total number of macroinvertebrate families identified at a specific sampling site, and p_i denotes the relative proportion of individuals belonging to the i -th family relative to the total abundance of the sample ($p_i = n_i/N$).

To evaluate the continuous response of the biological community against the localized agricultural intervention gradient, the Biological Monitoring Working Party index adapted for Colombia (BMWP/Col) was calculated [26]. This specific bioindication framework translates multi-metric ecosystem quality based on fixed sensitivity scores assigned to macroinvertebrate families according to their respiratory requirements, specialized branchial structures, and tolerance to organic degradation and low-flow stagnation [14,26]. The total biotic score was determined via Equation (3):

$$\text{BMWP/Col} = \sum_{j=1}^m s_j \quad (3)$$

where m represents the total number of families identified in the sample and s_j is the specific sensitivity score (ranging from 1 to 10) pre-assigned to the j -th macrobenthic family [26]. Higher accumulated scores indicate undisturbed, high-quality ecological conditions associated with highly sensitive taxa, specifically belonging to the Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders, whereas lower overall values indicate severely degraded or organic-enriched lotic systems dominated by hypoxia-tolerant, opportunistic assemblages [27].

2.5. Computational and Statistical Analysis

All computational procedures, piecewise sub-index transformations, and multivariate statistical modeling were implemented using Python (version 3.10) within the Google Colaboratory cloud-computing environment. Spatial and temporal variations in individual physicochemical stressors, biological attributes, and global index scores were reported as point-specific values alongside consolidated group metrics (Mean $\pm$ Standard Deviation) across the established landscape zones and seasonal configurations. Normality and homoscedasticity of the calculated sub-indices and biological matrices were verified using Shapiro–Wilk and Levene tests, respectively, to define subsequent parametric or non-parametric evaluation vectors.

To establish a comprehensive mathematical bridge between multivariate environmental stressors and benthic biological community assembly without assuming linear constraints, a Canonical Correspondence Analysis (CCA) was performed [28]. The biological response matrix (Y), composed of family-level absolute abundances, was utilized directly to preserve the chi-square distance metric intrinsic to the canonical ordination space, tracking community variations through a singular value decomposition (SVD) of the row- and column-weighted contingency matrix.

Canonical Correspondence Analysis (CCA) was implemented to evaluate the direct influence of environmental variables on benthic macroinvertebrate community structure. This method was selected over indirect ordination techniques due to its efficacy in modeling unimodal species responses across steep environmental gradients, a characteristic feature

of Andean high-mountain stream ecosystems [29,30]. By constraining ordination axes to environmental predictors, CCA provides a robust statistical framework for identifying the primary physicochemical drivers—specifically nutrient loading and seasonal hydrological variability—that governs benthic community composition [31,32]. This approach is widely utilized in freshwater biomonitoring to link biological integrity with environmental quality gradients. To evaluate the statistical robustness of the environmental drivers, the individual contribution of each physicochemical factor to the benthic community structure was assessed through marginal effects analysis. This univariate approach isolates the variance explained by each quality sub-index, with statistical significance determined via 999 Monte Carlo permutation tests. This procedure complements the multivariate ordination by identifying specific environmental parameters that exert measurable pressure on community composition, ensuring that the ecological interpretations derived from the canonical axes are statistically supported.

To maintain structural and conceptual symmetry with the developed aggregation framework, the explanatory abiotic matrix (X) incorporated the eight standardized, dimensionless quality sub-indices (q_{DO} , q_{BOD5} , q_{COD} , q_{TSS} , q_{TKN} , q_{TP} , q_{pH} , and q_{EC}) derived from the physicochemical and hydraulic configurations, rather than raw values. This standardized ecological approach mathematically homogenizes highly disparate units, prevents geometric distortions caused by extreme out-of-range nutrient pulses, and accurately captures non-linear biological thresholds that conventional raw vectors fail to isolate [15]. Cumulative dataset trends, Pearson correlation vectors, and ecological complexity indices were verified and compiled utilizing the core scientific Python ecosystem, including the *pandas*, *numpy* (version 1.22), *ecopy*, and *scipy* libraries.

3. Results

The monitoring and analytical assessment of the La Chorrera river micro-basin provided a comprehensive dataset mapping the complex interactions between spatial land-use gradients and seasonal hydrological forcing factors. The results are structured to evaluate: (i) the physicochemical and hydraulic variations of individual abiotic stressors under contrasting climatic regimes, (ii) the diagnostic performance and sensitivity of the developed multiplicative modified Water Quality Index (*mWQI*), and (iii) the ecological response patterns of the benthic macroinvertebrate communities. Statistical differences across the experimental intervention zones (Conserved, Transitional, and Agricultural) and seasonal configurations (wet versus dry periods) serve as the analytical foundation to validate watershed resilience under localized anthropogenic stress.

3.1. Spatial and Temporal Dynamics of Individual Abiotic Stressors

The structural evaluation of individual physicochemical and hydraulic parameters demonstrated that seasonal hydrodynamics act as the primary control factor governing pollutant concentration and volumetric dilution mechanisms within the high-mountain catchment [17]. The bimodal hydrometeorological regime of the Northern Andes establishes two contrasting operational phases: a high-discharge wet season characterized by intense surface runoff and non-point source particle flushing, and a low-discharge dry season driven by baseflow contraction and structural resource restriction [17].

The physical hydraulic characterization confirmed a sharp contrast in water volume availability along the altitudinal gradient (Table 2). During the high-discharge wet season, streamflow (Q) and flow velocity peaked across the lotic layout, providing a substantial volumetric dilution capacity. Conversely, the transition to the dry season induced a systemic baseflow constriction. This hydrologic depletion was particularly pronounced within the lower agricultural valley (Group III), where streamflow collapsed to critical baselines

($0.11 \pm 0.06 \text{ m}^3/\text{s}$), with absolute minimum flows dropping to $0.03 \text{ m}^3/\text{s}$ and velocity constricting to $0.27 \pm 0.12 \text{ m/s}$. This baseflow crisis converted previously continuous streams into a series of sluggish, semi-isolated pooling macro-habitats, establishing the boundary conditions that directly governed the subsequent concentration of chemical stressors.

Table 2. Seasonal and spatial variations of physicochemical and hydraulic parameters across different land-use groups.

	Parameter	WET		DRY	
		Media $\pm$ SD	Min, Max	Media $\pm$ SD	Min, Max
GROUP I (Conserved)	Streamflow (Q , m^3/s)	0.21 ± 0.13	0.07, 0.49	0.05 ± 0.03	0.01, 0.1
	Flow Velocity (m/s)	0.45 ± 0.23	0.22, 0.86	0.17 ± 0.08	0.03, 0.3
	BOD ₅ (mg/L O_2)	3.82 ± 1.69	1.9, 6	6 ± 3	0.01, 9
	COD ₅ (mg/L O_2)	11.92 ± 7.78	0.49, 25	17.25 ± 8	0.49, 24
	TSS (mg/L)	9.25 ± 5.51	0.49, 17	12.17 ± 3.98	5, 17
	TKN	10.13 ± 4.54	3.9, 17.4	5.92 ± 4.21	0.29, 12.04
	TP (mg/L)	0.01 ± 0	0.01, 0.01	0.11 ± 0.15	0.01, 0.42
	DO%	103.24 ± 3.71	95.73, 106.33	64.81 ± 2.67	60.2, 68.92
	EC ($\mu\text{S/cm}$)	6.63 ± 1.34	5.37, 9.47	7.51 ± 2.08	3.87, 10.1
	pH	6.18 ± 0.57	5.28, 6.97	6.56 ± 0.61	5.56, 7.33
	Parameter	WET		DRY	
		Media $\pm$ SD	Min, Max	Media $\pm$ SD	Min, Max
GROUP II (Transitional)	Streamflow (Q , m^3/s)	0.32 ± 0.12	0.11, 0.44	0.16 ± 0.14	0.07, 0.43
	Flow Velocity (m/s)	0.51 ± 0.2	0.14, 0.71	0.28 ± 0.06	0.21, 0.39
	BOD ₅ (mg/L O_2)	3.76 ± 2.26	1.9, 8	3.4 ± 2.57	0.01, 7
	COD ₅ (mg/L O_2)	8.8 ± 8.61	0.49, 24	14.3 ± 7.94	0.49, 24
	TSS (mg/L)	9.5 ± 5.52	0.49, 17	7.4 ± 3.5	4, 13
	TKN	3.04 ± 0.99	2, 4.2	3.58 ± 1.49	1.12, 5.6
	TP (mg/L)	0.01 ± 0	0.01, 0.01	0.1 ± 0.08	0.01, 0.21
	DO%	100.78 ± 3.39	94.81, 104.5	61.61 ± 9.83	49.73, 72.62
	EC ($\mu\text{S/cm}$)	11.75 ± 1.94	9.43, 14.17	14.21 ± 2.14	11.83, 17.54
	pH	6.62 ± 0.33	6.1, 7.13	6.86 ± 0.58	6.01, 7.6
	Parameter	WET		DRY	
		Media $\pm$ SD	Min, Max	Media $\pm$ SD	Min, Max
GROUP III (Agricultural)	Streamflow (Q , m^3/s)	0.21 ± 0.12	0.06, 0.43	0.11 ± 0.06	0.03, 0.21
	Flow Velocity (m/s)	0.4 ± 0.15	0.19, 0.61	0.27 ± 0.12	0.08, 0.41
	BOD ₅ (mg/L O_2)	6 ± 2.1	4, 10	4 ± 2.09	0.01, 6
	COD ₅ (mg/L O_2)	19.2 ± 2.99	17, 25	9.9 ± 7.42	0.49, 23
	TSS (mg/L)	36.8 ± 49.11	11, 135	6.79 ± 3.76	0.49, 10
	TKN	3.76 ± 2.97	0.29, 9.2	3.81 ± 1.97	0.03, 5.6
	TP (mg/L)	0.01 ± 0	0.01, 0.01	1.93 ± 3.64	0.07, 9.2
	DO%	95.41 ± 3.24	89.33, 98.5	65.44 ± 6.36	57.54, 72.57
	EC ($\mu\text{S/cm}$)	22.46 ± 9.38	12.23, 36.27	37.18 ± 11.06	21.73, 51.1
	pH	6.6 ± 0.16	6.34, 6.83	6.43 ± 0.32	5.85, 6.71

Organic matter and biochemical oxygen demand dynamics exhibited highly variable spatiotemporal patterns across the anthropized gradient. In the Conserved Ecosystem (Group I), Biochemical Oxygen Demand (BOD₅) and Chemical Oxygen Demand (COD) values shifted from $3.82 \pm 1.69 \text{ mg/L}$ and $11.92 \pm 7.78 \text{ mg/L}$ during the wet season to $6.00 \pm 3.00 \text{ mg/L}$ and $17.25 \pm 8.00 \text{ mg/L}$ during the dry season, respectively, indicating an initial concentration effect of natural humic compounds under reduced volumetric baseflows [1]. In the Transitional Ecosystem (Group II), BOD₅ and COD tracked values of $3.76 \pm 2.26 \text{ mg/L}$ and $8.80 \pm 8.61 \text{ mg/L}$ in the wet season, and $3.40 \pm 2.57 \text{ mg/L}$ and $14.30 \pm 7.94 \text{ mg/L}$ during the dry season. This induced a critical shift in the biodegradability

index (BOD_5/COD) of Group II, falling from 0.42 (wet) to 0.23 (dry), which mathematically demonstrates a significant accumulation of recalcitrant, non-biodegradable organic matter under low-flow conditions [33]. Conversely, the Agricultural zone (Group III) demonstrated severe anthropogenic organic loading, with BOD_5 and COD tracking values of 6.00 ± 2.10 mg/L and 19.20 ± 2.99 mg/L in the wet season, and 4.00 ± 2.09 mg/L and 9.90 ± 7.42 mg/L in the dry season. The calculated BOD_5/COD ratio in Group III shifted from 0.31 during the wet season to 0.40 during the dry season, confirming a transition from chemically stable agricultural runoffs carried by surface washing to raw, localized organic discharges linked to direct livestock access in the active stream channel.

Dissolved oxygen saturation (DO%) confirmed a widespread metabolic decline during the dry season across all intervention groups (Table 2). During the wet season, high streamflow and thermal stability maintained optimal oxygenation, with pristine headwaters reaching $103.24 \pm 3.71\%$ saturation, which slightly decreased to $100.78 \pm 3.39\%$ in Group II and $95.41 \pm 3.24\%$ in Group III. This high oxygenation is driven by physical reaeration caused by channel turbulence and lower water temperatures [18]. However, during the dry season, severe oxygen depletion occurred throughout the entire hydrographic network, with mean saturation levels collapsing to $64.81 \pm 2.67\%$ in Group I, $61.61 \pm 9.83\%$ in Group II, and $65.44 \pm 6.36\%$ in Group III. This widespread dry-season decline highlights that high-mountain lotic ecosystems undergo severe physical constriction when stream velocity and water depth decrease under seasonal hydrological shifts [27,34], magnifying the relative impact of sediment oxygen demand and heterotrophic consumption even in completely undisturbed zones.

Sediment and nutrient transport patterns were highly sensitive to non-point source agricultural runoff during precipitation events (Table 2). Total Suspended Solids (TSS) in the conserved headwaters remained low and constant (9.25 ± 5.51 mg/L in wet; 12.17 ± 3.98 mg/L in dry). In the agricultural reaches (Group III), however, TSS surged to a mean of 36.80 ± 49.11 mg/L during the wet season, exhibiting an absolute maximum peak of 135.00 mg/L. This massive sediment pulse represents intense mechanical erosion from non-irrigated arable lands undergoing active tillage. This erosive mechanism directly governed the dynamics of Total Phosphorus (TP). During the wet season, TP concentrations across all groups remained at oligotrophic baseline levels (0.01 ± 0.00 mg/L) due to high volumetric dilution. Nevertheless, during the dry season, the lack of dilution capacity triggered extreme nutrient concentration in the lower valley. In Group III, mean dry-season TP escalated to a hyper-eutrophic concentration of 1.93 ± 3.64 mg/L, with absolute maximum spikes reaching up to 9.20 mg/L. This critical nutrient accumulation reflects a continuous, unassimilated load of livestock waste and chemical fertilizer residues concentrated within a severely contracted water volume, posing an immediate risk of localized eutrophication and toxic heterotrophic proliferation [15].

Finally, Electrical Conductivity (EC) mapped the progressive enrichment of dissolved ions along the landscape degradation gradient (Table 2). While the conserved zone maintained stable, minimal ionic concentrations ranging from 6.63 ± 1.34 $\mu\text{S}/\text{cm}$ to 7.51 ± 2.08 $\mu\text{S}/\text{cm}$, matching the pristine reference baselines reported for high-altitude Andean streams [27], the agricultural sector (Group III) experienced significant enrichment, increasing from 22.46 ± 9.38 $\mu\text{S}/\text{cm}$ during the wet season to 37.18 ± 11.06 $\mu\text{S}/\text{cm}$ during the dry season. This progression confirms that localized agricultural expansion introduces a persistent mineral and dissolved solid load that accumulates during low-flow periods, permanently altering the natural chemical configurations of the micro-basin.

3.2. Evaluation of the Modified Water Quality Index (*mWQI*)

The structural application of the weighted multiplicative modified Water Quality Index (*mWQI*) isolated the seasonal and spatial stress gradients within the high-mountain catchment, avoiding the mathematical eclipsing vulnerabilities inherent to traditional arithmetic formulations [4,10]. The computed individual site scores revealed a profound shift in water quality profiles, driven by the structural interaction between landscape human intervention and seasonal hydrological contraction [15].

During the wet season, the hydrographic network displayed a generalized, homogeneous pattern of high environmental quality. As presented in Table 3, the Conserved Ecosystem (Group I) registered robust *mWQI* scores ranging from 80.08 (Site 1) to 93.95 (Site 2), indicating “Excellent” water quality conditions driven by stable baseline parameters. Concurrently, this high-quality status was maintained as the stream transitioned through anthropized areas. The Transitional zone (Group II) preserved scores ranging from 89.23 (Site 5) to 94.24 (Site 9), while the Agricultural reaches (Group III) exhibited high wet-season values, peaking at 91.33 at Site 10 and 90.09 at Site 6. This widespread homogenization during the high-flow phase is mathematically explained by the overriding effect of volumetric dilution. The elevated wet-season streamflow successfully assimilated diffuse nutrient inputs, keeping raw concentrations below critical impact thresholds.

Table 3. Spatial and temporal distribution of the calculated modified Water Quality Index (*mWQI*) scores across the 16 monitoring stations during contrasting climatic seasons.

Group	Sitio	<i>mWQI</i>	
		WET	DRY
GROUP I (Conserved)	1	80.08, Good	63.76, Fair
	2	93.95, Excellent	62.66, Fair
	3	91.62, Excellent	73.33, Good
	4	82.06, Good	88.08, Good
	7	88.1, Good	79.24, Good
	8	88.47, Good	70.18, Good
GROUP II (Transitional)	5	89.23, Good	72.44, Good
	9	94.24, Excellent	66.29, Medium
	11	93.05, Excellent	64.84, Medium
	13	94.04, Excellent	89.42, Good
	14	89.26, Good	77.91, Good
GROUP III (Agricultural)	6	90.09, Excellent	69.65, Medium
	10	91.33, Excellent	72.38, Good
	12	85.33, Good	77.06, Good
	15	88.2, Good	0, very Poor
	16	88.52, Good	65.55, Medium

Conversely, the dry season induced a severe fragmentation of water quality across the spatial gradient, shifting the catchment into critical degradation. Within the reference zone (Group I), sites experienced a noticeable drop (e.g., Site 1 falling to 63.76; Site 2 falling to 62.66). This dry-season shift in pristine areas represents the mathematical sensitivity of the multiplicative aggregating structure to the natural reduction in dissolved oxygen saturation. A critical localized exception was observed at Site 4, where the *mWQI* score increased from 82.06 in the wet season to 88.08 during the dry season (Table 3). This anomaly highlights the “páramo flushing effect,” where intense precipitation events mechanically wash natural humic acids and organic matter from high-altitude peat soils into the stream, temporarily increasing oxygen demand. During the dry season, the absence of surface runoff ceases this organic input, allowing headwater births to return to high baseline purity [1].

The most severe environmental breakdown was captured in the agricultural valley (Group III) during the dry phase, where the *mWQI* scores collapsed. Sampling points fell into degraded ranges, with Site 16 dropping to 65.55 and Site 6 sinking to 69.65. The absolute collapse of the ecosystem was recorded at Site 15, which escalated to a hyper-eutrophic TP value of 9.20 mg/L due to the combined pressure of untreated domestic wastewater discharges and intensive livestock access under restricted dry-season baseflow. Because the piecewise linear interpolation framework assigned a sub-index of $qTP = 0.0$ to this extreme concentration, the multiplicative aggregation model acted as a strict single-parameter bottleneck, dragging the global index score to zero. This response confirms the reliability of the *mWQI* for identifying ecological tipping points and tracking complex point and non-point source pollution crises that traditional sum-based models frequently eclipse.

3.3. Macroinvertebrate Community Response and Biotic Indices Dynamics

The spatial structure and temporal composition of benthic macroinvertebrate communities reflected a clear biological degradation pattern that closely corresponds to the physicochemical degradation gradient recorded along the watershed [26], and the BMWP/Col score for each site and season, are detailed in Table 4. These biological response metrics—specifically total taxonomic richness (*S*), the Shannon–Wiener diversity index (*H'*), and the Biological Monitoring Working Party score adapted for Colombia (BMWP/Col)—demonstrated that benthic assemblages are highly sensitive to the interaction between local agricultural land-use pressures and seasonal hydrological alterations [12,26].

Table 4. Individual biotic metrics per site.

	Site	Wet		Dry	
		<i>H'</i>	BMWP/Col	<i>H'</i>	BMWP/Col
GROUP I (Conserved)	1	1.98	72	1.16	20
	2	1.43	61	1.74	45
	3	1.53	38	1.23	42
	4	0.82	10	0.2	7
	7	1.87	45	1.2	17
	8	1.63	54	1.03	30
	Site	Wet		Dry	
		<i>H'</i>	BMWP/Col	<i>H'</i>	BMWP/Col
GROUP II (Transitional)	5	1.43	28	1.45	26
	9	1.45	38	1.45	32
	11	1.08	24	1.27	28
	13	0.87	22	1.27	23
	14	1.19	17	1.48	34
	Site	Wet		Dry	
		<i>H'</i>	BMWP/Col	<i>H'</i>	BMWP/Col
GROUP III (Agricultural)	6	1.7	16	0.53	9
	10	1.32	50	1.56	32
	12	1.76	24	0.96	23
	15	0.79	16	0.95	20
	16	1.06	24	1.45	13

In the Conserved Ecosystem (Group I), sampling points located within or adjacent to the National Park boundaries exhibited well-structured benthic communities with high biological complexity during the wet season. Reaches such as Site 1 and Site 2 achieved optimal ecological status, registering high BMWP/Col scores of 72 and 61, respectively, which correlate with intermediate-to-high structural diversity values ($H' = 1.98$ and 1.43).

These biological profiles reflect the presence of diverse, sensitive aquatic insect families belonging to the Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders. These specialized macroinvertebrates rely on high dissolved oxygen levels ($103.24\% \pm 3.71\%$) and undisturbed stone substrates.

However, within this same reference group, a notable exception occurred at Site 4, where biological indicators dropped significantly during both seasons (BMWP/Col = 10, $H' = 0.82$ in wet; BMWP/Col = 7, $H' = 0.20$ in dry). This localized restriction is governed by a shifting seasonal stressor matrix. During the wet season, the benthic community is primarily constrained by natural hydrochemical stress, evidenced by a critical pH deflection down to 5.28 driven by the intensive flushing of humic and fulvic acids from the adjacent organic páramo soils into the stream channel. Conversely, during the dry season, although the water matrix neutralizes to a pH of 7.33, the severe constriction of the volumetric baseflow triggers an acute physical habitat bottleneck. In these high-altitude headwaters dominated by prominent rocky substrates and coarse bed materials, the hydrological drawdown disconnects the lateral wetted perimeter and desiccates small shallow pools and marginal interstitial niches [34]. This physical desiccation eliminates the localized micro-habitats required for the attachment and survival of sensitive macroinvertebrate families, effectively preventing biological recovery despite the mitigation of the wet-season chemical acidity [27].

During the dry season, a generalized reduction in biological metrics occurred across nearly all sampling points in the reference zone. For instance, at Site 1, the BMWP/Col score fell from 72 to 20, while diversity decreased from 1.98 to 1.16. This temporal shift represents a seasonal community contraction. As baseflow declines ($0.05 \pm 0.03 \text{ m}^3/\text{s}$), the loss of available wetted perimeter and the reduction in water velocity cause an environmental bottleneck. This physical pressure leads to taxonomic drift and temporary habitat loss, which reduces the dominance of sensitive organisms even in watersheds with low human intervention [35].

As the river crosses into the Transitional zone (Group II) and Agricultural reaches (Group III), the biological communities exhibit severe simplification. In Group III, under high-flow wet conditions, most sampling points showed low biotic scores (e.g., Site 6: BMWP/Col = 16, $H' = 1.70$; Site 15: BMWP/Col = 16, $H' = 0.79$). This simplified structure is driven by a multi-stressor matrix where physical and chemical degradation operate concurrently. Mechanically, non-point source sediment loading (TSS: $36.80 \pm 49.11 \text{ mg/L}$) causes intense riverbed scouring and silts the benthic interstitial spaces. Chemically, the generalized decline in water quality—characterized by significant increments in organic matter (COD: $19.20 \pm 2.99 \text{ mg/L}$) and dissolved ions (EC: $22.46 \pm 9.38 \text{ }\mu\text{S/cm}$)—acts as a restrictive environmental filter. Even under high volumetric dilution, this chronic chemical degradation alters critical micro-habitat conditions, exceeding the physiological tolerance thresholds of stenotolerant, sensitive taxa and preventing their colonization [36].

The most severe biological collapse was recorded in the agricultural valley during the dry season, where Site 6 dropped to an absolute minimum score of BMWP/Col = 9 ($H' = 0.53$) and Site 16 fell to BMWP/Col = 13. This critical loss of biological integrity directly mirrors the hyper-eutrophic chemical state of the stream, driven by extreme phosphorus concentration ($1.93 \pm 3.64 \text{ mg/L}$) and localized organic pollution. Under these toxicological conditions, sensitive macroinvertebrate assemblages belonging to the EPT orders are eliminated and replaced by large numbers of pollution-tolerant assemblages, such as Chironomidae (Diptera) and Naididae (Oligochaeta). These tolerant organisms are biologically adapted to survive within degraded substrates under severe hypoxia [37], confirming that the combination of agricultural land use and dry-season baseflow restriction causes a significant loss of ecological resilience in Andean stream systems.

3.4. Multivariate Ordination and Ecological Stress Factor Analysis

To establish a comprehensive mathematical bridge between multivariate environmental stressors and the biological structures of the benthic communities, a Canonical Correspondence Analysis (CCA) was executed. The model isolated how the calculated individual physicochemical quality sub-indices (q_{DO} , q_{BOD5} , q_{COD} , q_{TSS} , q_{TKN} , q_{TP} , q_{pH} , and q_{EC}) operate alongside seasonal landscape variations to govern the distribution of macroinvertebrate family assemblages across the catchment. The summary statistics for the multivariate ordination are consolidated in Table 5.

Table 5. Canonical Correspondence Analysis (CCA) summary statistics.

Biostatistical Metric	Axis 1	Axis 2	Cumulative/Total
Eigenvalue (Autovalor)	0.4737	0.4293	—
Explained Variance per Axis (%)	24.44	22.15	—
Cumulative Explained Variance (%)	24.44	46.59	46.59%
Total System Inertia	—	—	1.9383
Constrained Inertia (Explained)	—	—	0.4314

The first two principal canonical axes captured a cumulative explained variance of 46.59% relative to the constrained inertia component (Table 5). In lotic macroinvertebrate community datasets—which inherently exhibit high stochastic noise, complex biological interactions, and sparse zero-matrices—an explained variance approaching 50% constitutes a highly robust and ecologically representative model configuration. Beyond the global ordination axes, the individual contribution of each environmental parameter to the community structure was assessed through a marginal effects analysis (Table 6). Results indicate that no single variable acts as an isolated primary driver—consistent with the high environmental complexity of these Andean systems—as each physicochemical factor explains a relatively low percentage of the total variance (<5%). Instead, the collective contribution of the environmental set (43.14% of explained inertia) underscores that the macroinvertebrate assemblage structure is governed by the synergistic interplay of multiple environmental stressors rather than by the isolated action of a single quality index.

Table 6. Marginal effects of physicochemical quality sub-indices on macroinvertebrate community structure.

Environmental Factor	Explained Variance (%)	F-Statistic	p-Value
q_{DO}	4.47	0.7	0.114
q_{TSS}	4.34	0.68	0.306
q_{TKN}	3.5	0.54	0.342
q_{COD}	3.34	0.52	0.375
q_{TP}	3.34	0.52	0.37
q_{pH}	3.23	0.5	0.436
q_{BOD5}	1.48	0.23	0.99

Axis 1 (24.44%) captures spatial landscape degradation and environmental quality gradient, tracking the transition from protected forests to anthropized agricultural areas, as visualized in the CCA biplot (Figure 3). Axis 2 (22.15%) isolates the temporal hydrometeorological seasonal dynamics, separating the high-flow wet season from the constricted baseflows of the dry season. The near-symmetrical explanatory power between both axes indicates that spatial anthropogenic intervention and temporal seasonal dynamics exert an equivalent ecological pressure on the macrobenthic structure of the high-mountain micro-basin.

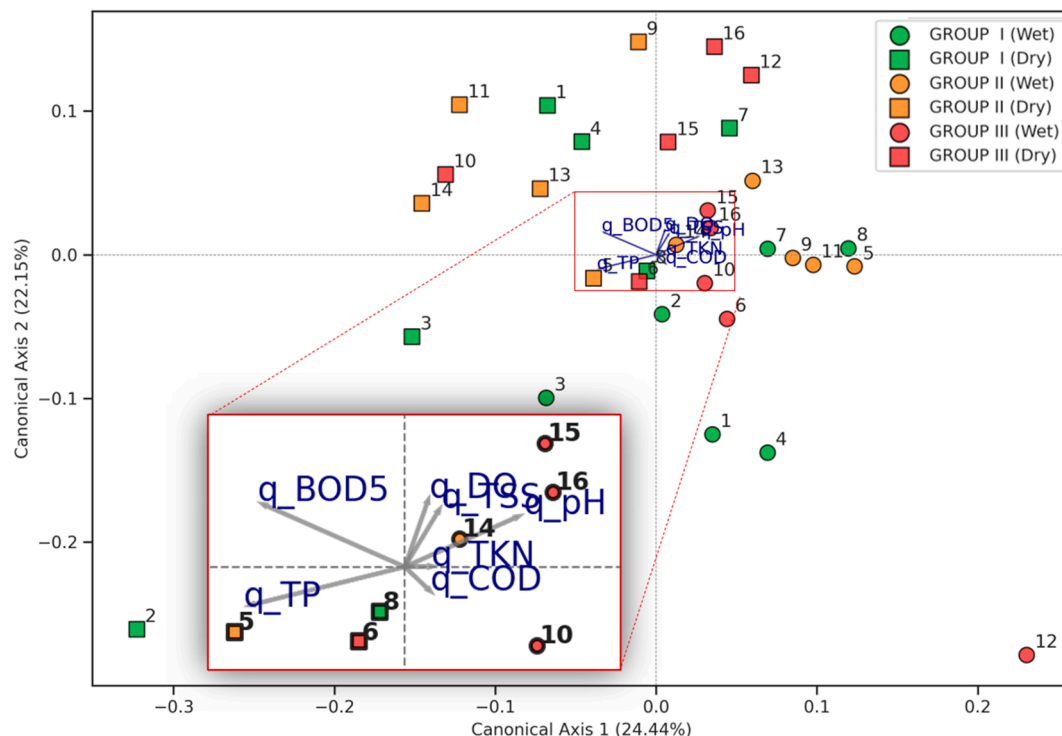


Figure 3. Canonical Correspondence Analysis (CCA) of benthic macroinvertebrate family abundance data constrained by physicochemical quality sub-indices (q_i) and streamflow vectors.

The multivariate biplot (Figure 3) revealed a clear segregation of sampling points governed by the conservation status and seasonal climate regimes. Spatial segregation was primary along Axis 1; during the wet season, the pristine headwater sites (GROUP I: Sites 1, 2, 3, 7, and 8) clustered in the positive quadrant, aligning with optimal quality vectors (q_{DO} , q_{pH} , and q_{EC}). In contrast, the transition to the dry season triggered a significant displacement of anthropized reaches along Axis 1, projecting the critical agricultural sites (GROUP III: Sites 12 and 16) into the upper right quadrant. Because environmental variables are expressed as sub-indices (q_i), the opposition between agricultural sites and the vectors for biochemical oxygen demand (q_{BOD5} , upper left) and total phosphorus (q_{TP} , lower left) mathematically demonstrates severe quality depletion. Within this degradation trajectory, sites 12 and 16 acted as primary multivariate indicators, mapping at the boundaries of the agricultural cluster. This indicates that nutrient and organic matter accumulation functions as a strict environmental filter, eliminating sensitive insect orders due to the chemical stress of hyper-eutrophication.

Finally, the spatiotemporal layout validates specific macroinvertebrate families as highly reliable biological indicators for high-altitude Andean monitoring. Sensitive taxa belonging to EPT orders—specifically Leptophlebiidae and Baetidae (Ephemeroptera), and Perlidae (Plecoptera)—were constrained by the positive vector coordinates of Axis 1, reflecting their affinity for optimal water quality, physical reaeration, and undisturbed lithic substrates. Conversely, pollution-tolerant families (Chironomidae and Naididae) displayed a strong positive affinity for the upper right quadrant under dry season baseflow restriction and hyper-eutrophic phosphorus loading, where they exploit fine, silted substrates under chronic hypoxia due to their specialized respiratory adaptations [38].

4. Discussion

The hydrodynamic and hydrochemical anomalies captured across the experimental landscape configurations underscore the profound influence of seasonal hydrometeo-

rological regimes on alpine lotic ecosystems [1]. A compelling phenomenon observed in the protected upper catchment (GROUP I) was the slight contraction of the modified Water Quality Index (*mWQI*) during the high-discharge wet season (80.08 at Site 1) compared to its counter-intuitive stability or partial recovery during the dry season (88.08 at Site 4). While classical limnological assumptions dictate that pristine headwaters maintain immutable reference conditions, high-altitude Andean streams are intrinsically coupled with the biogeochemical dynamics of surrounding peatlands, Histosols, and Andisols [1]. During intense convective precipitation events, the progressive saturation of the organic soil horizon triggers a localized subsurface and surface scouring process, known as the “páramo organic flushing effect”. This mechanical process drives a substantial export of dissolved organic carbon (DOC), humic complexes, and fulvic acids directly into first- and second-order lotic channels [39]. The sudden influx of allochthonous organic matter temporarily accelerates heterotrophic microbial activity, elevating the biochemical oxygen demand (BOD₅) and displacing the pH toward acidic ranges due to free proton dissociation from organic structures. Conversely, the onset of the dry season breaks this surface hydrologic connectivity. Riparian lateral input ceases, and the stream baseflow is sustained exclusively by deeper, well-filtered, and mineralized groundwater sources. This hydrogeological mechanism explains the physical clarification and baseline restoration observed at Site 4, highlighting that alpine headwaters display natural, cyclical fluctuations driven by landscape vertical connectivity, which environmental managers frequently misinterpret as anthropogenic degradation [40].

The critical response of the agricultural zone during the low-flow dry period—most notably at Site 15, where the *mWQI* score collapsed to a definitive 0.00—validates the mathematical necessity of the newly developed weighted multiplicative framework over standard additive formulations [4]. In conventional arithmetic quality indices, high multi-parameter stability mathematically offsets or masks a severe deficit in a single attribute. However, the multiplicative configuration ($\prod q_i^{w_i}$) functions as an environmental constraint model based on Liebig’s Law of the Minimum, where the global score is limited by the most degraded vital attribute [10]. The extreme concentration of Total Phosphorus (TP = 9.20 mg/L) recorded at Site 15 represents a critical ecological tipping point driven by the convergence of agricultural expansion and severe baseflow contraction ($Q \leq 0.11 \text{ m}^3/\text{s}$). During the dry season, the loss of dilution capacity is exacerbated by unregulated livestock access directly to the active channel. Cattle grazing induces stream bank destabilization, direct excreta deposition, and the mechanical resuspension of fine silts rich in adsorbed legacy phosphorus—a process commonly reported as a primary driver of nutrient loading in Neotropical agricultural landscapes [41]. When this extreme chemical state is processed through the piecewise linear interpolation framework, the sub-index falls to $q_{TP} = 0.0$. Because the multiplicative aggregation handles this score as an absolute zero factor, the global index drops to zero, overriding any mitigating factors from stable variables. This response aligns with the ecological realities of lotic eutrophication under summer baseflows. Excess orthophosphates break the strict stoichiometry of the Redfield Ratio (N:P), potentially triggering structural periphyton proliferation or cyanobacterial blooms and accelerating oxygen depletion at the sediment–water interface [42]. The developed *mWQI* does not simply over-penalize the ecosystem; it accurately reflects that a lotic habitat cannot sustain ecological resilience when a single master variable reaches ecotoxicological limits [4,10].

The structural reorganization of benthic macroinvertebrate communities along the catchment (Table 3) and their Canonical Correspondence Analysis (CCA) ordination (Figure 3) demonstrate that aquatic macrofauna are filtered by two distinct environmental pressures dependent on the seasonal hydrometeorological regime. During the wet season, the primary driver of biological degradation within Transitional (GROUP II) and

Agricultural (GROUP III) reaches is physical and mechanical: interstitial colmatation via terrigenous sediment fluxes [37,43]. Intense rainfall events over highly fragmented, non-irrigated agricultural terrains devoid of protective riparian buffers generate significant laminar erosion. This runoff delivers massive pulses of total suspended solids (TSS), reaching a maximum threshold of 135 mg/L at Site 12. In the lotic channel, high suspended solids exert an intense abrasive effect on the delicate branchial structures of sensitive macroinvertebrates [44]. As the water velocity drops in lower sections, these fine silts precipitate, filling the interstitial spaces between cobbles and gravels. This habitat degradation destroys the vital micro-refugia required by the highly sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders, a phenomenon widely recognized as a major stressor in degraded Neotropical streams [6,43]. This mechanical disturbance triggers a widespread behavioral drifting process, driving down the biotic scores (BMWP/Col) even when the turbulent stream flow maintains high dissolved oxygen levels [36,37].

In contrast, the dry season switches this environmental pressure into a chemical and metabolic filter driven by severe hypoxia and nutrient toxicity. As the baseflow contracts, the physical sediment input stops, but the accumulation and decay of organic material inside stagnant pools creates high sediment oxygen demand, heavily aggravated by the low-flow hydrologic alteration thresholds typical of alpine regimes. This process reduces dissolved oxygen saturation to critical boundaries (50.46% at Site 9 and 57.54% at Site 16). Under these low-oxygen conditions and higher water temperatures, highly responsive EPT groups are eliminated due to respiratory failure [39,45]. The empty ecological niches are rapidly colonized by pollution-tolerant taxa, specifically Chironomidae (Diptera) and Naididae (Oligochaeta). These tolerant organisms possess specialized evolutionary adaptations, such as high-affinity respiratory pigments (hemoglobin analogues) and anaerobic metabolic pathways, allowing them to dominate hypoxic substrates. The CCA biplot successfully captures this transition, illustrating that the Andean macrobenthic community undergoes a seasonal shift from mechanical habitat limitation in the wet season to critical chemical filtration during the dry season. This seasonal shift in environmental filtering mechanisms is statistically supported by our marginal effects analysis, which highlights the pervasive influence of low-flow nutrient loading (qTP and qCOD) as a persistent stressor across the catchment, reinforcing the observed seasonal biological turnover.

Ultimately, our findings reveal that the macrobenthic response to environmental stress in high-altitude Andean streams is not static, but rather a dynamic interplay between seasonal hydrologic energy and chemical concentrations. The integration of canonical ordination with marginal effects analysis confirms that the ecological integrity of these basins is governed by a shifting environmental filter: physical habitat limitation via sedimentation during the wet season, and metabolic toxicity driven by nutrient loading during low-flow baseflows. This suggests that the resilience of Andean macroinvertebrate communities is tied not only to mean annual water quality but to the maintenance of hydrologic connectivity and the mitigation of extreme seasonal fluctuations.

5. Conclusions

The integration of the newly developed weighted multiplicative modified Water Quality Index (mWQI) and benthic macroinvertebrate biomonitoring provided a highly sensitive and reliable framework for diagnosing environmental degradation thresholds along land-use and seasonal gradients in high-mountain Andean catchments. The structural evaluation of the lotic ecosystem successfully demonstrated that conventional additive indices often conceal localized environmental crises due to mathematical eclipsing. In contrast, the multiplicative aggregating framework effectively identified ecological tipping

points, establishing a precise baseline for tracking micro-basin resilience under localized anthropogenic stress.

The seasonal hydrodynamics of the catchment exerted a critical control mechanism over pollutant transport and biotic colonization. During the high-discharge wet season, intense precipitation triggered a volumetric dilution effect that homogenized water quality across the gradient, maintaining mWQI scores in optimal ranges even within agricultural reaches. However, the dry season induced severe baseflow contraction, causing systemic ecological breakdown. The hyper-eutrophic phosphorus concentrations caused by livestock access under restricted baseflows led to a mathematical collapse of the index at specific nodes. This behavior validates the sensitivity of the mWQI, which effectively utilizes single-parameter bottlenecks to reflect severe localized degradation that traditional models fail to isolate.

Biotic community arrays and Canonical Correspondence Analysis (CCA) validated the ecological relevance of the standardized sub-index approach. Benthic macroinvertebrates tracked the physicochemical degradation gradient with high taxonomic sensitivity. Undisturbed forest headwaters supported complex communities dominated by sensitive Ephemeroptera, Plecoptera, and Trichoptera (EPT) orders. Conversely, the intense nutrient loading and severe hypoxia recorded in agricultural reaches functioned as strict toxicological filters. These environmental barriers eliminated sensitive insect families and favored the dominance of pollution- and hypoxia-tolerant taxa (Chironomidae and Naididae).

These findings underscore that tropical alpine stream systems are highly vulnerable to the synergistic pressures of agricultural intensification and seasonal flow reduction. The developed multi-metric framework serves as a robust environmental management tool for water resource allocation and land-use planning. These results provide critical baseline criteria for designing targeted ecological restoration programs and protecting the hydrologic integrity of high-mountain watersheds facing increasing anthropogenic and climate-driven stress.

Future investigations could further enhance the robustness of the mWQI by evaluating its sensitivity across wider spatio-temporal scales, ensuring its applicability under varying hydrological extremes. Furthermore, future efforts could explore the functional ecological response of macroinvertebrate communities to assess metabolic changes in the watershed. Such research would complement our taxonomic findings, providing a more comprehensive understanding of the structural and functional resilience of Andean streams under anthropogenic and climate-driven pressure.

The findings of this study demonstrate that environmental management in high-mountain basins cannot rely on static water quality standards. Instead, monitoring programs must transition toward dynamic, multiplicative indices that account for the ‘limiting factor’ principle. By recognizing the seasonal shift from physical habitat degradation during wet periods to chemical toxicity during dry flows, basin authorities can implement targeted interventions—such as riparian buffer restoration for sediment control and livestock exclusion to mitigate nutrient pulses—thereby ensuring the ecological resilience of Andean aquatic ecosystems.

Author Contributions: D.F.M.P., G.E.C.R.; methodology, D.F.M.P.; validation, G.E.C.R. and P.A.S.C.; formal analysis, D.F.M.P.; investigation, D.F.M.P.; writing—original draft preparation, D.F.M.P.; writing—review and editing, D.F.M.P., G.E.C.R. and P.A.S.C.; supervision, G.E.C.R. and P.A.S.C.; project administration, G.E.C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Gobernación de Boyacá and Colciencias (currently Minciencias) under the framework of the “Convocatoria 733 de 2015” for high-level human capital formation in the Department of Boyacá.

Data Availability Statement: If scholars need more specific data, they can email the corresponding author. The data presented in this study are available on request from the corresponding author. The data are currently reserved for further analysis in ongoing research and are not yet publicly available.

Acknowledgments: The authors thank the Research Group in Integrated Management of Ecosystems and Biodiversity (XIUA-Uptc) for providing logistical and technical support during field sampling campaigns and subsequent laboratory analyses. During the preparation of this work, the authors used Gemini 3.5 Flash(Google), DeepSeek V3 and Consensus for the purposes of style correction, generation of Python code for data processing, results interpretation, and bibliographic search, review, and analysis. After using this tool. 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.

References

1. Buytaert, W.; Celleri, R.; De Bièvre, B.; Cisneros, F.; Wyseure, G.; Deckers, J.; Hofstede, R. Human impact on the hydrology of the Andean páramos. *Earth-Sci. Rev.* **2006**, *79*, 53–72. [\[CrossRef\]](#)
2. Vuille, M.; Carey, M.; Mitchell, K.R.; Horne, I.; Francou, B.; Bryan, R.; Viviroli, D.; Bury, J.; Postigo, W.A.; Sierra, R.; et al. Rapid decline of snow and ice in the tropical Andes—Impacts, uncertainties and challenges ahead. *Earth-Sci. Rev.* **2018**, *176*, 195–213. [\[CrossRef\]](#)
3. Garcia, C.A.B.; Silva, I.S.; Mendonça, M.C.S.; Garcia, H.L. Evaluation of Water Quality Indices: Use, Evolution and Future Perspectives. In *Advances in Environmental Monitoring and Assessment*; IntechOpen: Rijeka, Croatia, 2018; Chapter 2, pp. 21–36. [\[CrossRef\]](#)
4. Sutadian, A.D.; Muttill, N.; Yilmaz, A.G.; Perera, B.J.C. Development of river water quality indices a review. *Environ. Monit. Assess.* **2016**, *188*, 58. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Fathi, P.; Dorche, E.E.; Shahraki, M.Z.; Stribling, J.; Kashkooli, O.B.; Ofogh, A.E.; Bruder, A. Revised Iranian Water Quality Index (RIWQI): A tool for the assessment and management of water quality in Iran. *Environ. Monit. Assess.* **2022**, *194*, 504. [\[CrossRef\]](#) [\[PubMed\]](#)
6. Arízaga-Idrovo, V.; Pesántez, J.; Birkel, C.; Peña, P.; Mora, E.; Crespo, P. Characterizing solute budgets of a tropical Andean páramo ecosystem. *Sci. Total Environ.* **2022**, *835*, 155560. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Harden, C.P. Human impacts on headwater fluvial systems in the northern and central Andes. *Geomorphology* **2006**, *79*, 249–263. [\[CrossRef\]](#)
8. Patiño, S.; Hernández, Y.; Plata, C.; Domínguez, I.; Daza, M.; Oviedo-Ocaña, R.; Buytaert, W.; Ochoa-Tocachi, B.F. Influence of land use on hydro-physical soil properties of Andean páramos and its effect on streamflow buffering. *Catena* **2021**, *202*, 105227. [\[CrossRef\]](#)
9. Nguyen Van, H.; Nguyen Viet, H.; Truong Trung, K.; Nguyen Hai, P.; Nguyen Dang Giang, C. A comprehensive procedure to develop water quality index: A case study to the Huong river in Thua Thien Hue province, Central Vietnam. *PLoS ONE* **2022**, *17*, e0274673. [\[CrossRef\]](#) [\[PubMed\]](#)
10. Silva, P.L.C.; Borges, A.C.; Lopes, L.S.; Rosa, A.P. Developing a Modified Online Water Quality Index: A Case Study for Brazilian Reservoirs. *Hydrology* **2023**, *10*, 115. [\[CrossRef\]](#)
11. Lermontov, A.; Yokoyama, L.; Lermontov, M.; Machado, M.A.S. River Quality Analysis Using Fuzzy Water Quality Index: Ribeira do Iguaçu River Watershed, Brazil. *Ecol. Indic.* **2009**, *9*, 1188–1197. [\[CrossRef\]](#)
12. Zhang, M.; Yu, M.; Ding, S.; Li, Z. Adjustment of Effective Water Quality Evaluation Index for Subtropical Urban Rivers. *Environ. Manag.* **2025**, *75*, 2198–2208. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Rocha, F.C.; Andrade, E.M.; Lopes, F.B. Water quality index calculated from biological, physical and chemical attributes. *Environ. Monit. Assess.* **2015**, *187*, 4163. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Roldán-Pérez, G. Los macroinvertebrados y su valor como indicadores de la calidad del agua. *Rev. Acad. Colomb. Cienc. Exactas Fis. Nat.* **1999**, *23*, 375–387.
15. Luo, H.; Nong, X.; Xia, H.; Liu, H.; Zhong, L.; Feng, Y.; Zhou, W.; Lu, Y. Integrating Water Quality Index (WQI) and Multivariate Statistics for Regional Surface Water Quality Evaluation: Key Parameter Identification and Human Health Risk Assessment. *Water* **2024**, *16*, 3412. [\[CrossRef\]](#)
16. CORPOBOYACÁ. *Plan de Ordenación y Manejo de la Cuenca Hidrográfica del Río Alto Chicamocha (POMCA)—NSS (2403-01)*; Corporación Autónoma Regional de Boyacá: Tunja, Colombia, 2018; pp. 85–112. Available online: <https://www.corpoboyaca.gov.co/ventanilla/presentacion-resultados-pomca-rio-alto-chicamocha/> (accessed on 28 May 2026).

17. IDEAM. *Estudio Nacional del Agua (ENA)*; Instituto de Hidrología, Meteorología y Estudios Ambientales: Bogotá, Colombia, 2018; pp. 140–165.
18. IDEAM. *Leyenda Nacional de Cobertura de la Tierra: Metodología CORINE Land Cover Adaptada para Colombia Escala 1:100.000*; Instituto de Hidrología, Meteorología y Estudios Ambientales: Bogotá, Colombia, 2010; pp. 45–72.
19. Jacobsen, D.; Rostgaard, S.; Vásconez, J.J. Are macroinvertebrates in high altitude streams affected by oxygen deficiency? *Freshw. Biol.* **2003**, *48*, 2025–2032. [\[CrossRef\]](#)
20. Mortimer, C.H. The oxygen content of air-saturated fresh waters over ranges of temperature and atmospheric pressure of limnological interest. *Mitt. Int. Ver. Limnol.* **1981**, *22*, 1–23. [\[CrossRef\]](#)
21. Canadell, M.B.; Gómez-Gener, L.; Cléménçon, M.; Lane, S.N.; Battin, T.J. Daily entropy of dissolved oxygen reveals different energetic regimes and drivers among high-mountain stream types. *Limnol. Oceanogr.* **2021**, *66*, 1594–1610. [\[CrossRef\]](#)
22. Solár, J.; Tomaškovič, J. Physicochemical properties of mountain streams in the High and Western Tatras. *Environ. Monit. Assess.* **2023**, *195*, 1543. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Ministério do Meio Ambiente (MMA). *Índices e Indicadores de Qualidade da Água: Guia Técnico de Aplicação Regional*; Secretaria de Recursos Hídricos e Ambiente Urbano: Brasília, Brazil, 2012; pp. 44–68.
24. IDEAM. *Metodología de Cálculo del Índice de Calidad del Agua (ICA) para Corrientes Superficiales*; Instituto de Hidrología, Meteorología y Estudios Ambientales: Bogotá, Colombia, 2011; pp. 15–38.
25. Cude, C.G. Oregon Water Quality Index: A tool for evaluating water quality management effectiveness. *J. Am. Water Resour. Assoc.* **2001**, *37*, 125–137. [\[CrossRef\]](#)
26. Roldán-Pérez, G. *Bioindicación de la Calidad del Agua en Colombia: Propuesta para el uso del Método BMWP/Col*; Editorial Universidad de Antioquia: Medellín, Colombia, 2003; pp. 15–170.
27. Cabrera-García, S.; Goethals, P.L.M.; Lock, K.; Domínguez-Granda, L.; Villacís, M.; Galárraga-Sánchez, R.; Van der heyden, C.; Eurie Forio, M.A. Taxonomic and Feeding Trait-Based Analysis of Macroinvertebrates in the Antisana River Basin (Ecuadorian Andean Region). *Biology* **2023**, *12*, 1386. [\[CrossRef\]](#) [\[PubMed\]](#)
28. ter Braak, C.J.F. Canonical correspondence analysis: A new eigenvector method for multivariate direct gradient analysis. *Ecology* **1986**, *67*, 1167–1179. [\[CrossRef\]](#)
29. Keke, U.N.; Omoigberale, M.O.; Ezenwa, I.; Yusuf, A.; Bioseb, E.; Nweke, N.; Edegbene, A.O.; Arimoro, F.O. Macroinvertebrate communities and physicochemical characteristics along an anthropogenic stress gradient in a southern Nigeria stream: Implications for ecological restoration. *Environ. Sustain. Indic.* **2021**, *12*, 100157. [\[CrossRef\]](#)
30. Saal, I.; Bouchelouche, D.; Hamache, C.; Arab, A. Evaluation of the surface water quality in the Kebir-Rhumel catchment area (northeast Algeria) using biotic indices and physico-chemical analyses. *Environ. Sci. Pollut. Res.* **2021**, *28*, 46565–46579. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Makumbe, P.; Kanda, A.; Chinjani, T. The Relationship between Benthic Macroinvertebrate Assemblages and Water Quality Parameters in the Sanyati Basin, Lake Kariba, Zimbabwe. *Sci. World J.* **2022**, *2022*, 5800286. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Zhang, Y.; Yu, H.; Liu, M.; Liu, J.; Dong, W.; Xu, T.; Wang, Y.; Guo, Y. Analysis of Water Quality and Habitat Suitability for Benthic Macro-Invertebrates in the Majiagou Urban River, China. *Water* **2023**, *15*, 2269. [\[CrossRef\]](#)
33. Jouanneau, S.; Recoules, L.; Durand, M.J.; Boukabache, A.; Picot, V.; Primault, Y.; Lakel, A.; Sengelin, M.; Barillon, B.; Thouand, G. Methods for assessing biochemical oxygen demand (BOD): A review. *Water Res.* **2014**, *49*, 62–82. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Ríos-Touma, B.; Encalada, A.C.; Prat Fornells, N. Macroinvertebrate assemblages of an Andean high-altitude tropical stream: The importance of season and flow. *Int. Rev. Hydrobiol.* **2011**, *96*, 667–685. [\[CrossRef\]](#)
35. Dewson, Z.S.; James, A.B.W.; Death, R.G. A review of the consequences of decreased flow for instream habitat and macroinvertebrates. *J. N. Am. Benthol. Soc.* **2007**, *26*, 401–415. [\[CrossRef\]](#)
36. Fierro, P.; Valdovinos, C.; Lara, C.; Saldías, G.S. Influence of Intensive Agriculture on Benthic Macroinvertebrate Assemblages and Water Quality in the Aconcagua River Basin (Central Chile). *Water* **2021**, *13*, 492. [\[CrossRef\]](#)
37. Ntloko, P.; Palmer, C.G.; Akamagwuna, F.C.; Odume, O.N. Exploring Macroinvertebrates Ecological Preferences and Trait-Based Indicators of Suspended Fine Sediment Effects in the Tsitsa River and Its Tributaries, Eastern Cape, South Africa. *Water* **2021**, *13*, 798. [\[CrossRef\]](#)
38. Figueroa Eche, L.M.; Arenas Ibarra, J.A. Effect of Seasonality on the Assembly of Macrobenthos in a High Andean River. *Acta Biol. Colomb.* **2023**, *28*, 271–282.
39. Sánchez-Murillo, R.; Romero-Esquivel, L.G.; Jiménez-Antillón, J.; Salas-Navarro, J.; Corrales-Salazar, L.; Álvarez-Carvajal, J.; Boll, J.; Brooks, E.S.; Rounsard, O.; Sáenz-Segura, F.; et al. DOC transport and export in a dynamic tropical catchment. *J. Geophys. Res. Biogeosci.* **2019**, *124*, 1665–1679. [\[CrossRef\]](#)
40. Garzón Sánchez, H.; Loaiza Usuga, J.C.; Vélez Upégui, J.I. Hydrological Response to Predominant Land Use and Land Cover in the Colombian Andes at the Micro-Watershed Scale. *Land* **2024**, *13*, 1140. [\[CrossRef\]](#)

41. Tampo, L.; Kaboré, I.; Alhassan, E.H.; Ouéda, A.; Bawa, L.M.; Djaneye-Boundjou, G. Benthic Macroinvertebrates as Ecological Indicators: Their Sensitivity to the Water Quality and Human Disturbances in a Tropical River. *Front. Water* **2021**, *3*, 662765. [\[CrossRef\]](#)
42. Smith, V.H. Eutrophication of Freshwater and Coastal Marine Ecosystems: A Global Problem. *Environ. Sci. Pollut. Res.* **2003**, *10*, 126–139. [\[CrossRef\]](#) [\[PubMed\]](#)
43. Helson, J.E.; Williams, D.D. Development of a macroinvertebrate multimetric index for the assessment of low-land streams in the neotropics. *Ecol. Indic.* **2013**, *29*, 167–178. [\[CrossRef\]](#)
44. Laini, A.; Viaroli, P.; Bolpagni, R.; Cancellario, T.; Racchetti, E.; Guareschi, S. Taxonomic and functional responses of benthic macroinvertebrate communities to hydrological and water quality variations in a heavily regulated river. *Water* **2019**, *11*, 1478. [\[CrossRef\]](#)
45. Dick, J.J.; Soulsby, C.; Birkel, C.; Malcolm, I.; Tetzlaff, D. Continuous Dissolved Oxygen Measurements and Modelling Metabolism in Peatland Streams. *PLoS ONE* **2016**, *11*, e0161363. [\[CrossRef\]](#) [\[PubMed\]](#)

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.