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Distribution of aquatic macroinvertebrate communities in the arid ecosystems of the Jequetepeque Basin, Peru

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This study evaluated the influence of altitudinal gradients and anthropogenic pressures on the composition and distribution of aquatic macroinvertebrate communities in arid ecosystems of the Jequetepeque River basin, northern Peru. Ten sampling stations were established along the middle and lower reaches of the river, covering an altitudinal range between 1,009 and 29 m a.s.l., and sampling campaigns were conducted during the 2022 and 2023 dry seasons. Macroinvertebrates were collected using standard methods, while physicochemical water variables, including pH, temperature, dissolved oxygen, and electrical conductivity, were measured *in situ*. Organisms were identified to the genus level, and the data were analyzed using multivariate approaches (PCA and CCA). A total of 33 genera belonging to 24 families and 11 orders were identified, comprising 1,182 individuals, with Diptera and Ephemeroptera being the most representative orders. A clear ecological pattern was observed along the longitudinal river gradient, characterized by the dominance of sensitive taxa such as *Atopophlebia, Baetodes*, and *Leptonema* in the upper and middle reaches, associated with well-oxygenated conditions and moderate electrical conductivity. In contrast, downstream reaches showed a progressive replacement by more tolerant taxa, including *Melanoides, Biomphalaria*, and *Corbicula*, correlated with increased electrical conductivity and a stronger influence of anthropogenic activities, particularly agriculture and hydrological regulation associated with the Gallito Ciego dam. Multivariate analyses confirmed that altitude, electrical conductivity, and dissolved oxygen were the most influential variables structuring macroinvertebrate communities. Overall, these findings demonstrate that the studied biological assemblages can detect subtle and progressive changes in river environmental quality, even when physicochemical variables do not show statistically significant differences between sampling stations, highlighting the value of aquatic macroinvertebrates as bioindicators for environmental monitoring in arid and semi-arid fluvial ecosystems with limited technical infrastructure.

KEYWORDS

altitudinal gradient, anthropogenic pressures, aquatic macroinvertebrates, arid river systems, bioindicators, canonical correspondence analysis

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1 Introduction

Currently, knowledge of the diversity of aquatic ecosystems in arid and semi-arid regions of Latin America, particularly in northern Peru, remains limited. The lack of systematic monitoring hampers the identification of species that are exclusive to these ecosystems, in contrast to taxa with broader distribution ranges that overlap with arid habitats (Davies et al., 2012). In the department of Cajamarca, up to 21 ecosystems have been identified, with arid-type ecosystems being particularly prominent on the eastern and western slopes of the northern Peruvian Andes (Gonzáles, 2010). Nevertheless, the available information on aquatic communities in this region—including their distribution, structure, and ecological niches—remains fragmented. In this regard, data scarcity generates high levels of uncertainty and constrains the development of appropriate monitoring strategies, thereby limiting progress in the understanding of these ecosystems (Custodio and Chanamé, 2016).

Despite the recognized importance of aquatic macroinvertebrates for the management and assessment of ecological quality in fluvial ecosystems, studies addressing their diversity patterns in arid and semi-arid environments of Peru remain scarce. A total of 53 studies on macroinvertebrate communities in arid and semi-arid ecosystems of Peru have been compiled; however, only four have been conducted in the Cajamarca region, and these have focused primarily on water quality assessment, physicochemical variables, and the application of biotic indices (Arana et al., 2021). This limited spatial and thematic coverage highlights the need for approaches that integrate environmental and spatial variability of these communities at the basin scale.

In addition, there is growing concern regarding the impacts of climate change on lotic and lentic ecosystems in arid and semi-arid regions of northern Peru. In the Jequetepeque River basin, which connects the high-Andean headwaters of Cajamarca with the arid Pacific coastal zone, climate change is primarily manifested through increasing temperatures and greater irregularity in precipitation patterns, characterized by longer drought periods and the intensification of rainfall events concentrated over short time intervals. These conditions, together with flow regulation and anthropogenic pressures, increase hydrological variability and render this system particularly sensitive for assessing ecological responses to multiple environmental stressors. Changes in precipitation patterns, temperature, and the frequency of extreme events are significantly altering aquatic habitats, affecting the distribution and health of macroinvertebrate communities (Marquet et al., 2019). These impacts include alterations in flow regimes, degradation of water quality, and habitat loss, ultimately leading to changes in the composition and structure of biological communities (Kintz et al., 2009).

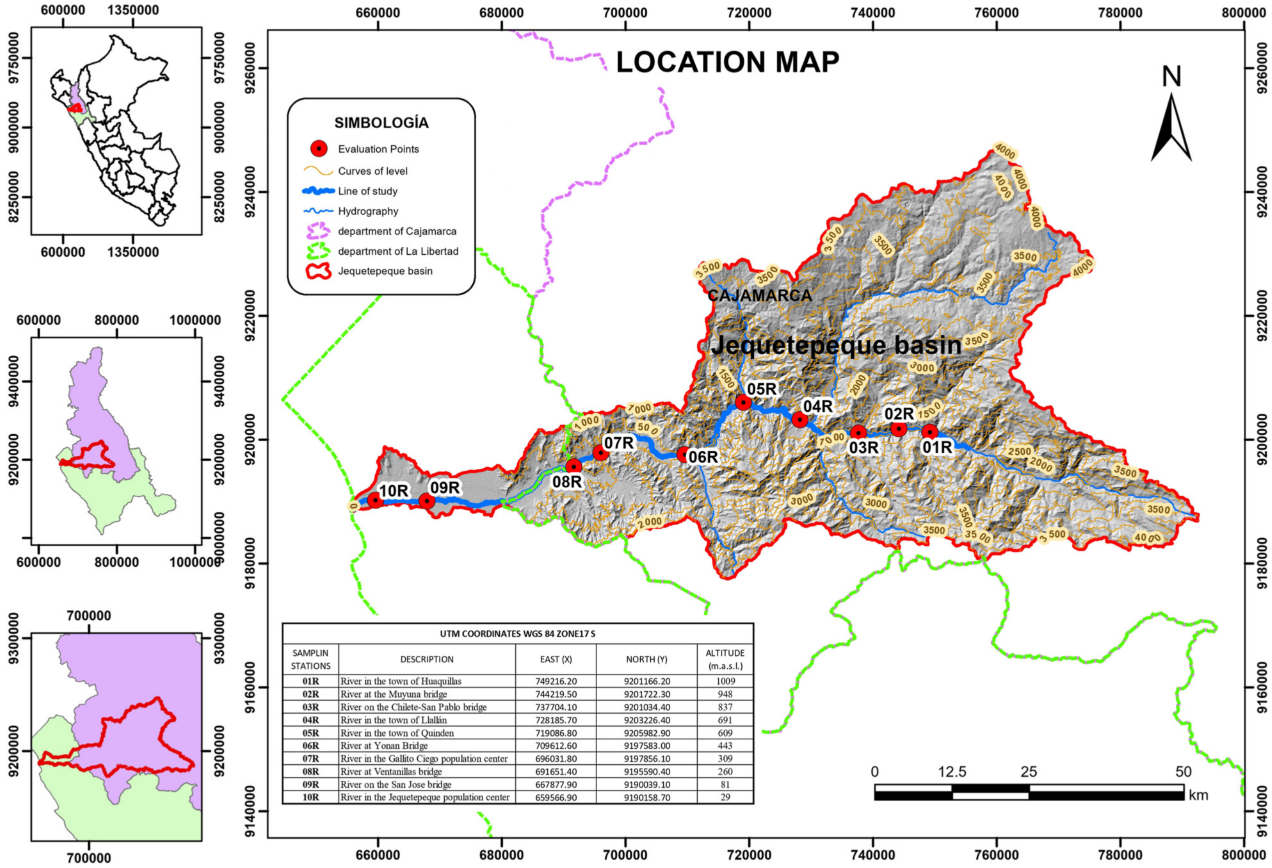
In this context, the limited availability of ecological information, combined with high environmental variability and the effects of climate change, constrains the understanding of diversity and distribution patterns of aquatic macroinvertebrates in arid and semi-arid ecosystems of northern Peru. The dispersal of these communities represents a key process for interpreting their ecological dynamics and adaptive mechanisms in dry environments (Hankel et al., 2018) and may be influenced by abiotic and biotic factors, as well as by the degree of connectivity between ephemeral and permanent water bodies (Hanson et al., 2010). Within this framework, the objective of the present study was to evaluate the spatial distribution of aquatic macroinvertebrate communities in arid ecosystems of the Jequetepeque River basin and their relationship with key physicochemical parameters and ecological conditions of the system, under a scenario of climate change and multiple anthropogenic pressures, including livestock activities, agriculture, and water impoundment systems. We hypothesized that community composition varies progressively along the river's altitudinal gradient, responding primarily to increases in conductivity and the intensity of anthropogenic disturbances, with a replacement of sensitive taxa in upper reaches by more tolerant taxa in lower reaches. Additionally, we postulated that macroinvertebrate assemblages can detect subtle changes in the ecological quality of the fluvial system, even when physicochemical variables do not exhibit statistically significant differences among sampling stations. Overall, this study contributes to the understanding of spatial patterns and biological community responses in arid fluvial systems subjected to multiple environmental stressors, providing both conceptual and applied foundations for their management and conservation under conditions of increasing climatic uncertainty (Pineda and Cañón, 2023).

2 Materials and methods

The Jequetepeque River basin is located in the departments of Cajamarca and La Libertad and flows along 161.5 km, ultimately discharging into the Pacific Ocean (Peña et al., 2015). The basin exhibits a pronounced altitudinal gradient that strongly influences the ecological characteristics of the river. As altitude decreases along the longitudinal profile, habitat conditions such as water temperature, flow velocity, and riparian vegetation composition change, leading to spatial variation in the structure of aquatic communities and biodiversity (Flores and Huamantinco, 2017).

The Jequetepeque River basin is one of the most important hydrographic systems in northern Peru, supplying drinking water and supporting productive activities in surrounding towns, primarily through hydrological regulation by the Gallito Ciego dam. Several economic activities are carried out within the basin, notably agriculture, livestock grazing, and mining, which exert significant pressure on the local fluvial ecosystems (Moya et al., 2009).

In this context, ten sampling stations were established along the middle and lower reaches of the Jequetepeque River basin, within the departments of Cajamarca and La Libertad. All stations were georeferenced using a GARMIN GPS receiver (model 60CSx), as shown in Figure 1. Sampling was conducted during the dry season over two consecutive years: the first survey in September 2022 and the second in September 2023 (Figure 1).



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SAMPLIN STATIONS	DESCRIPTION	EAST (X)	NORTH (Y)	ALTITUDE (m.a.s.l.)
01R	River in the town of Huaquillas	749216.20	9201166.20	1009
02R	River at the Muyuna bridge	744219.50	9201722.30	948
03R	River on the Chilete-San Pablo bridge	737704.10	9201034.40	837
04R	River in the town of Llallán	728185.70	9203226.40	691
05R	River in the town of Quinden	719086.80	9205982.90	609
06R	River at Yonan Bridge	709612.60	9197583.00	443
07R	River in the Gallito Ciego population center	696031.80	9197856.10	309
08R	River at Ventanillas bridge	691651.40	9195590.40	260
09R	River on the San Jose bridge	667877.90	9190039.10	81
10R	River in the Jequetepeque population center	659566.90	9190158.70	29

FIGURE 1
Location map of the sampling stations in the middle and lower basin of the Jequetepeque River (Peru).

2.1 Sampling of aquatic macroinvertebrates

Sampling followed the methodology described by (Alomar, 2011). Three sampling points were selected along a 10 m longitudinal transect, ensuring that all present and dominant habitat types were represented. Aquatic macroinvertebrates were collected using the kick-sampling method with a D-frame net (sampling area: 0.056 m^2; mesh size: 250 µm). At each sampling point, the net was firmly positioned on the streambed and oriented upstream, while the substrate immediately upstream was manually disturbed by kicking for a standardized period of 30 s, allowing dislodged organisms to be transported by the current and retained in the net.

Additionally, macroinvertebrates associated with coarse substrates were collected through manual inspection and washing of submerged stones, woody debris, and roots in a bucket containing site water. A standardized sampling effort was applied at all sites by using a fixed inspection time and extracting organisms with entomological forceps. Particular attention was given before and during sampling to taxa with high escape capacity, such as Gyrinidae, Gerridae, and Hydrometridae, which were actively captured by visual search during the same time interval at each site to standardize sampling effort.

All organisms collected at each sampling point were preserved in plastic containers with 96% ethanol. *In situ* physicochemical parameters (pH, water temperature, electrical conductivity, and dissolved oxygen) were measured in the field using a portable multiparameter probe (HANNA HI 9829). Air temperature and relative humidity were also recorded at each sampling site using a thermohygrometer (BOECO SH-110).

In the Ecology Laboratory of the National University of Cajamarca, samples were sorted and macroinvertebrates were taxonomically identified to family and genus levels using updated taxonomic keys, and individuals were counted per taxon. All identifications were performed under a stereomicroscope (Olympus SZ5), following the keys provided by (Dominguez et al., 2006; Dominguez et al., 2009; Hamada et al., 2018). Taxonomic richness and abundance data were subsequently used for cartographic and statistical analyses.

2.2 Statistical analyses

Physicochemical data were square-root transformed prior to multivariate classification and clustering analyses in order to reduce the influence of extreme values and homogenize variances. Based on the transformed data, a dendrogram was constructed using Euclidean distance. The statistical significance of the resulting groups was assessed using the SIMPROF test ($p < 0.05$), applied to the dendrogram to identify significantly different clusters among sampling sites (Oyanedel et al., 2008). In addition, a principal

TABLE 1 **Physicochemical characteristics (mean ± standard deviation) of water at the Jequetepeque River sampling stations, Cajamarca (Peru).**

Station	Ph	EC (µS/cm)	DO (mg/L)	T (°C)	ΔT (°C)
01R	8.16 ± 0.26	570 ± 1.77	7.11 ± 1.27	24.2 ± 0.283	2.51 ± 1.27
02R	8.03 ± 0.21	495 ± 27.6	7.12 ± 0.53	29.4 ± 4.31	6.43 ± 4.20
03R	8.06 ± 0.29	474 ± 30.4	5.91 ± 0.06	29.5 ± 2.05	5.10 ± 2.55
04R	8.13 ± 0.74	401 ± 83.8	6.22 ± 0.13	29.1 ± 2.97	5.10 ± 3.68
05R	8.53 ± 0.33	419 ± 69.3	6.51 ± 0.21	29.6 ± 3.68	4.65 ± 6.44
06R	8.51 ± 0.09	474 ± 101	6.93 ± 0.82	30.2 ± 4.18	5.10 ± 7.21
07R	7.70 ± 0.92	249 ± 45.6	6.72 ± 0.46	30.0 ± 3.18	6.81 ± 0.16
08R	8.46 ± 0.04	247 ± 41.6	7.20 ± 0.665	28.3 ± 4.95	4.91 ± 1.57
09R	7.96 ± 0.29	514 ± 24.0	6.88 ± 1.14	27.8 ± 7.71	3.22 ± 4.12
10R	7.86 ± 0.17	754 ± 39.2	6.33 ± 0.552	23.1 ± 3.44	2.35 ± 3.32
p-value	0.39	0.05	0.39	0.54	0.9

EC, electrical conductivity; T, water temperature; DO, dissolved oxygen; ΔT, difference between air and water temperature; p-value = ANOVA probability value.

component analysis (PCA) was performed to synthesize environmental variables and identify those contributing most to the spatial variability of the system.

The representativeness of biological sampling was evaluated using taxa accumulation curves, following the approach proposed by (Jiménez and Hortal, 2003). Abundance data of the identified taxa were $\log_{10}(x + 1)$ transformed prior to conducting canonical correspondence analysis (CCA), with the aim of examining relationships between the most relevant environmental variables and the composition of freshwater macroinvertebrate communities. Additionally, physicochemical variables were compared among sampling sites using analysis of variance (ANOVA). Finally, non-parametric Spearman rank correlations ($p < 0.05$) were applied to evaluate relationships between water quality parameters and macroinvertebrate community attributes (taxonomic richness and abundance).

All statistical analyses were conducted using the vegan package (Oksanen et al., 2001) and FactoMineR (Lê et al., 2008) in the R environment version 3.5.1 (R Core Team, 2015), as well as the software PAST version 3.02.

2.3 Description of the mapping process

Thematic maps of location, life zones, and altitudinal gradient of the study area were produced using ArcGIS software version 10.8 through the ArcMap platform. The cartographic process aimed to integrate available spatial information with field-collected data, with particular emphasis on the spatial representation of aquatic macroinvertebrate sampling stations.

Cartographic data included geospatial layers obtained from official sources, such as the Geoserver of the Peruvian Ministry of the Environment (MINAM) and GeoGPSPerú, as well as complementary information acquired through SASPlanet and Google Earth Pro. Thematic field data corresponding to the ten sampling stations were integrated and spatially represented on the cartographic base of the Jequetepeque River basin.

All spatial data were processed using the UTM coordinate system, datum WGS84, zone 17S. For the topographic characterization of the study area, ASTER Digital Elevation Models (DEM) were used to generate derived layers, including contour lines, the main hydrographic network, and terrain hillshade models. These layers served as the basis for the altitudinal map, in which elevation bands were defined at 500 m above sea level intervals across the basin.

The location map was developed using high-resolution satellite imagery, whereas the life zones map was constructed from the shapefile corresponding to the Ecological and Economic Zoning (ZEE) of Peru, developed by INRENA–ONERN–MINAM. Each map was produced independently, integrating the layers required according to its specific thematic purpose.

Finally, maps were designed following criteria of clarity and interpretability, adjusting symbology, color schemes, scales, and labels. Essential cartographic elements, including legend, scale bar, north arrow, UTM coordinate grid, and title, were incorporated. Final products were exported in digital formats (PDF, PNG, or TIFF) for inclusion in the manuscript and Supplementary Material.

3 Results

3.1 Physicochemical characteristics

The values of the physicochemical parameters measured at each sampling station are presented in Table 1. Overall, the variables did not show significant differences among the evaluated stations, based on a total of 10 samples corresponding to two sampling campaigns conducted in 2022 and 2023 at the same sampling sites. pH values remained consistently within the alkaline range along the evaluated river reach. Electrical conductivity (EC) exhibited slight spatial variation, with the highest values recorded at station 10R (754 ± 39.2 µS/cm) and the lowest at station 07R (249 ± 45.6 µS/cm). Dissolved oxygen (DO) concentrations ranged from 5.91 ± 0.06 mg/L to 7.20 ± 0.665 mg/L, indicating

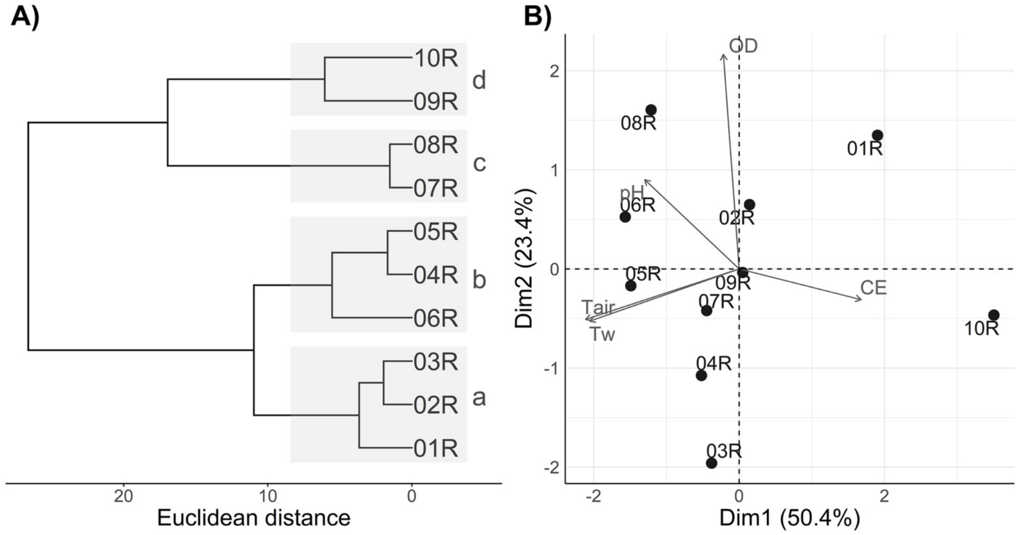

FIGURE 2
(A) Cluster dendrogram based on physicochemical variables from the sampling stations. **(B)** Principal Component Analysis (PCA) biplot based on physicochemical variables and sampling stations in the Jequetepeque River basin (Peru).

relatively homogeneous availability across stations. Water temperature (T) and the difference between water and air temperature (TΔ) did not show marked variation (Table 1).

The cluster analysis defined five groups. Stations 01R, 02R, and 03R formed one group ($p > 0.05$); stations 04R, 05R, and 06R, a second group; 07R and 08R, a third group; and stations 09R and 10R formed separate groups (Figure 2A). In the biplot of the principal component analysis (Figure 2B) of the relationship between physicochemical variables and sampling stations, the first two components explained more than 73.8% of the variability; these results are consistent with the cluster analysis. Stations 04R, 05R, and 06R exhibit higher pH and temperature values (Figure 2).

3.2 Composition of the aquatic macroinvertebrate community

The rarefaction curve (Figure 3) revealed a slight increase in taxa richness beyond the first 9 stations, suggesting that a large part of the species richness was collected in the study samples (Figure 3).

Table 2 presents the taxonomic classification and macroinvertebrate populations collected at the 10 sampling stations across the two campaigns conducted between 2022 and 2023.

During the two sampling campaigns, a total of 1,182 benthic macroinvertebrate individuals were collected, representing 33 genera across 24 families and 11 orders, distributed among the ten sampling stations (Table 2).

The most abundant family was Chironomidae, with 174 individuals, followed by Leptophlebiidae, with 127 individuals. In terms of taxonomic composition by order, Diptera accounted for 25% of the total organisms collected, whereas Ephemeroptera represented 17%.

A marked reduction in both total abundance and macroinvertebrate diversity was observed from stations 07R–10R. In contrast, station 05R recorded the highest number of individuals during both sampling campaigns. Additionally, a higher abundance of gastropods in the genera *Drepanotrema* and *Melanoides* was recorded at stations 09R and 10R.

Figure 4 shows that the highest genus-level diversity was recorded in the families Libellulidae, Leptophlebiidae, and Hydropsychidae, each representing 9% of the total genera. Analysis of the relative proportions of taxonomic groups revealed a clear spatial gradient across the sampling stations.

Ephemeroptera was the dominant group at upstream stations, reaching high relative abundances at stations 05R (81%), 02R (63%), and 04R (62%). In contrast, its representation decreased markedly toward downstream stations, with no records at stations 09R and 10R. Conversely, these downstream stations showed a significant increase in Caenogastropoda, accounting for 59% at station 09R and 43% at station 10R, and in Basommatophora, with 17% at station 09R and 22% at station 10R.

The order Diptera maintained a relatively constant presence along the longitudinal gradient, with a maximum relative abundance of 33% at station 03R and a minimum of 7% at stations 09R and 10R. Trichoptera exhibited intermediate proportions, with higher values at stations 06R (20%) and 03R (15%) (Figure 5B).

Canonical correspondence analysis (CCA) indicated that environmental factors strongly influenced the structure of aquatic macroinvertebrate communities. The first two canonical axes jointly explained 48.8% of the variance at the genus and family levels (Figure 5A) and 57.5% at the order level (Figure 5B). Altitude, pH, water temperature (Tw), and electrical conductivity (EC) were identified as the most influential variables shaping taxon distribution patterns.

Headwater and upper–middle reach stations (03R and 05R) were primarily associated with altitude and lotic flow conditions. At these stations, the presence of sensitive taxa was recorded, including

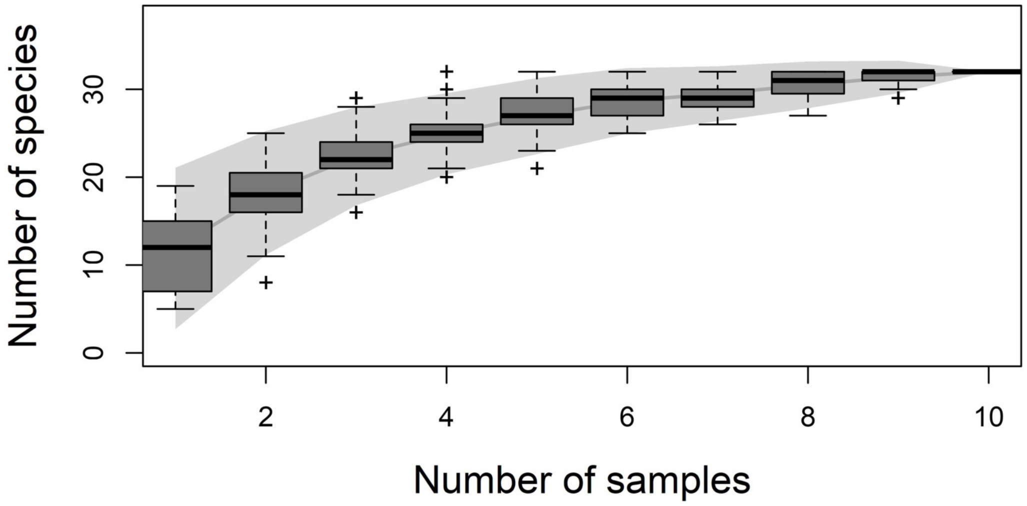

FIGURE 3
Species accumulation curve according to the number of samples collected in the Jequetepeque River basin during the 2022–2023 dry seasons (Peru).

TABLE 2 **Macroinvertebrate species and populations collected in the ten sampling stations and the two sampling campaigns.**

Class	Order	Family	Genus	Class	Order	Family	Genus
Gastropoda	Basommatophora	Physidae	*Physa*	Insecta	Ephemeroptera	Leptophlebiidae	*Atopophlebla*
Gastropoda	Basommatophora	Planorbidae	*Biomphalaria*	Insecta	Ephemeroptera	Caenidae	*Caenis*
Gastropoda	Caenograstropoda	Thiaridae	*Melanoides*	Insecta	Ephemeroptera	Leptophlebiidae	*Farrodes*
Insecta	Coleoptera	Elmidae	*Heterelmis*	Insecta	Haplotaxida	Haplotaxidae	*Drepanotrema*
Insecta	Coleoptera	Elmidae	*Cylloepus*	Insecta	Hemiptera	Mesovellidae	*Mesoveloidea*
Insecta	Coleoptera	Dytiscidae	*Acilius*	Insecta	Hemiptera	Naucoridae	*Pelocoris*
Insecta	Diptera	Simuliidae	*Simulium*	Insecta	Hemiptera	Gerridae	*Eurygerris*
Insecta	Diptera	Chironomidae	*Tanypodinae/chironominae/Metriocnemus*	Insecta	Melagoptera	Corydalidae	*Corydalus*
Insecta	Diptera	Tipulidae	*Tipula*	Insecta	Odonata	Libellulidae	*Miathyrla*
Insecta	Diptera	Limoniidae	*Antocha*	Insecta	Odonata	Libellulidae	*Dythemis*
Insecta	Diptera	Stratiomyidae	*Euparyphus*	Insecta	Odonata	Libellulidae	*Brechmorhoga*
Insecta	Diptera	Ephydridae	*Ochthera*	Insecta	Odonata	Aeshnidae	*Aeshna*
Insecta	Ephemeroptera	Leptohyphidae	*Haplohyphes*	Insecta	Trichoptera	Hydropsychidae	*Leptonema*
Insecta	Ephemeroptera	Leptohyphidae	*Asioplax*	Insecta	Trichoptera	Hydropsychidae	*Macrostemun*
Insecta	Ephemeroptera	Baetidae	*Baetodes*	Insecta	Trichoptera	Hydropsychidae	*Smicridea*
Insecta	Ephemeroptera	Leptophlebiidae	*Traverella*	Insecta	Trichoptera	Hydroptilidae	*Hydroptila*
				Bivalvia	Veneroida	Corbiculidae	*Corbicula*

the ephemeropterans *Atopophlebia* and *Baetodes*, as well as the trichopteran Leptonema. The latter was detected at the headwater station (01R) and at station 07R but was absent from middle-reach stations (05R and 06R) and from downstream stations (08R, 09R, and 10R).

In contrast, electrical conductivity was mainly associated with downstream stations (09R and 10R), where a higher abundance of tolerant taxa was recorded, including *Melanoides*, *Biomphalaria*, and *Corbicula*. A marked decrease in the occurrence of sensitive genera was also observed downstream of station 07R.

The orders Diptera and Coleoptera exhibited a broad distribution along the environmental gradient, with variable presence across most sampling stations, from headwaters to downstream reaches.

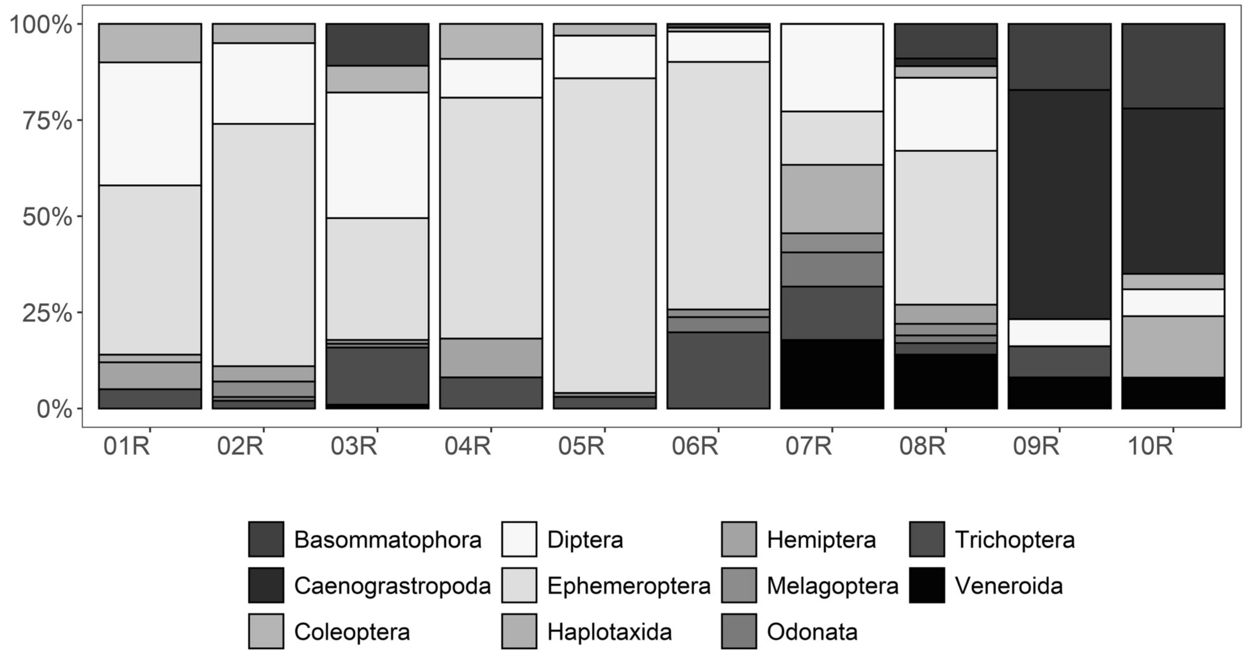

FIGURE 4
Relative abundance (%) of aquatic macroinvertebrate orders by sampling station in the Jequetepeque River basin during the 2022–2023 dry seasons (Peru).

Figure 6 shows the altitudinal distribution and relative abundance of the main genera of aquatic macroinvertebrates along the longitudinal gradient of the Jequetepeque River. The upper and middle reaches exhibited higher diversity and abundance of genera considered sensitive, whereas downstream reaches showed a progressive reduction in these taxa and an increase in the representation of more tolerant genera. This figure descriptively illustrates the spatial pattern previously identified at the order level and supports the results obtained through multivariate analyses.

4 Discussion

This study revealed a pronounced longitudinal and altitudinal gradient in the structure of macroinvertebrate communities in the Jequetepeque River, characterized by a progressive replacement of sensitive taxa in the upper and middle reaches by more tolerant taxa downstream. This turnover was evident at both order and genus levels, with a dominance of Ephemeroptera and Trichoptera at higher-altitude sites and an increasing prevalence of Diptera and tolerant mollusks in the lower reaches. Comparable patterns have been documented in various Neotropical river systems, including arid Andean rivers and Amazonian basins, where altitude and associated environmental conditions strongly structure the composition and richness of benthic assemblages (Ferru and Fierro, 2015; Castillo and Huamantinco, 2020; Barrera-Herrera et al., 2023; Arana et al., 2021; García-Ríos et al., 2020).

In the Jequetepeque River, biological structure exhibited systematic changes along the longitudinal gradient, even when physicochemical variables showed limited spatial variation, suggesting a progressive ecological degradation that is primarily detectable through biological responses rather than through point measurements of water quality.

The observed pattern is consistent with the typical longitudinal organization of arid and Andean rivers, where altitudinal and conductivity gradients exert primary control over benthic community structure. Studies in arid fluvial systems of the Southern Hemisphere indicate that upper reaches, under well-oxygenated and low-conductivity conditions, are dominated by Ephemeroptera, Trichoptera, and Coleoptera, whereas lower reaches support impoverished communities dominated by tolerant taxa (Ferru and Fierro, 2015; Castillo and Huamantinco, 2020). Similarly, in Andean rivers of Argentina, altitude, conductivity, and habitat type explain a large proportion of the spatial variation in macroinvertebrate composition and richness, particularly in arid systems characterized by strong environmental gradients (Scheibler et al., 2014; Paul et al., 2024).

In the Jequetepeque River, sensitive genera such as Atopophlebia, Baetodes, Leptonema, and Cylloepus were associated with higher-altitude and lower-conductivity sites, reflecting their dependence on oligotrophic and relatively conserved habitats (González et al., 2015; Ardila and Molina, 2021). While these results confirm the structuring role of natural gradients, the magnitude of the observed taxonomic turnover suggests the superposition of anthropogenic pressures that intensify this pattern in the lower reaches of the system.

The longitudinal structure of macroinvertebrate communities in the Jequetepeque River cannot be explained solely by natural processes. The Gallito Ciego dam represents the primary anthropogenic driver of downstream ecological alteration by disrupting longitudinal connectivity, regulating flow pulses, and modifying sediment and nutrient dynamics (Hanson et al., 2010). This hydrological regulation reduces flood frequency, limits benthic

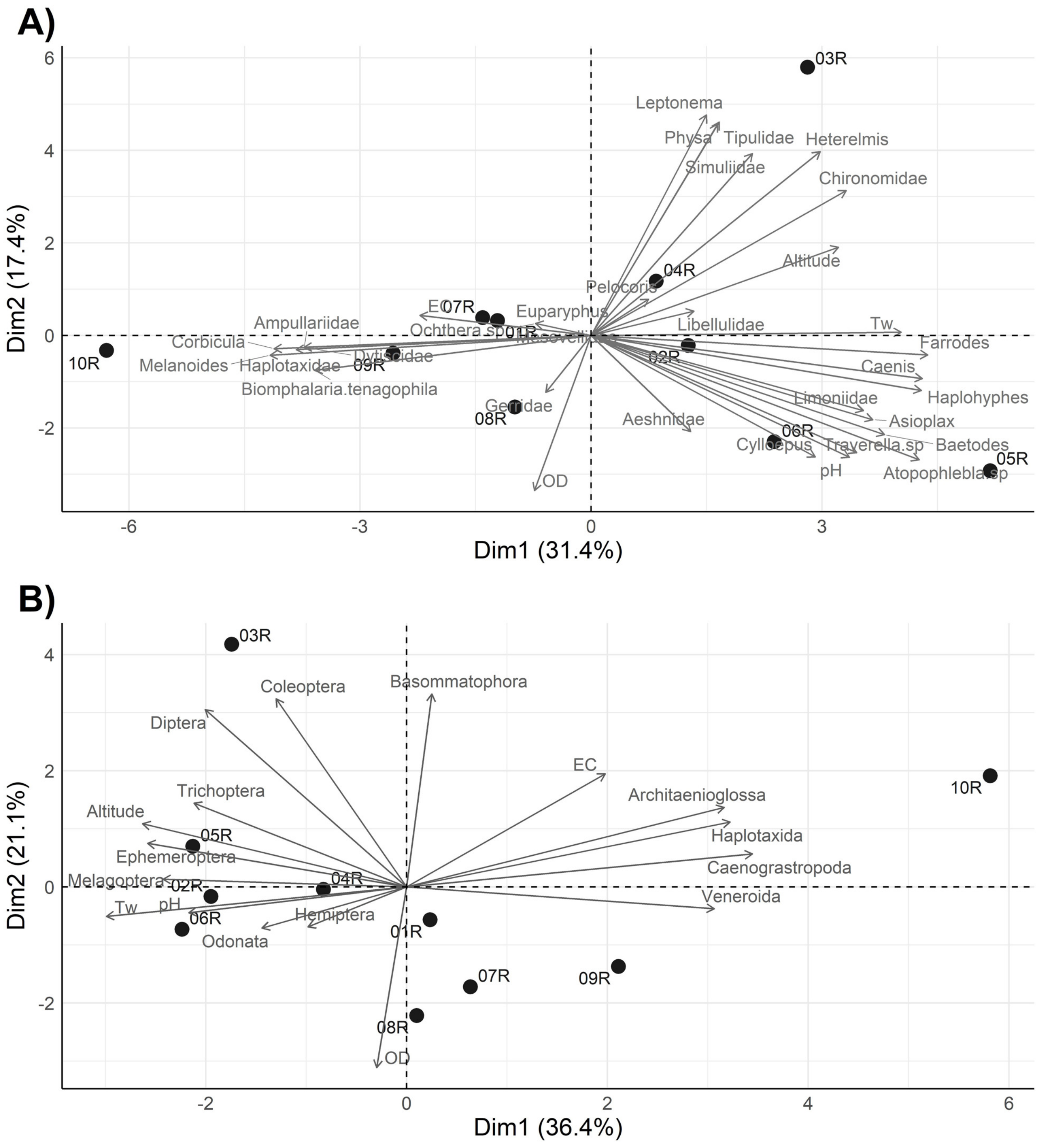

FIGURE 5
Canonical Correspondence Analysis (CCA) of aquatic macroinvertebrate communities in the Jequetepeque River basin (Peru), relating environmental variables to **(A)** genera and **(B)** orders.

habitat renewal, and homogenizes substrate composition, generating unfavorable conditions for sensitive taxa and strictly lotic specialists.

These processes directly explain the reduced diversity, abrupt decline in taxonomic richness, and progressive disappearance of strictly lotic genera downstream of station 07R, as well as the reduction of predators such as Corydalus, reflecting the structural and functional simplification typical of regulated rivers (González et al., 2015; Doychev, 2023). In contrast, station 05R exhibited higher abundance and diversity, associated with the influence of the Agua Blanca River (~3,200 m a.s.l.), which provides greater hydrological stability and more favorable conditions for the development of diverse benthic communities, partially attenuating the effects of downstream regulation. Similar patterns have been reported in regulated systems, where communities located downstream of large dams show lower taxonomic diversity and increased dominance of tolerant organisms (Brown et al., 2024).

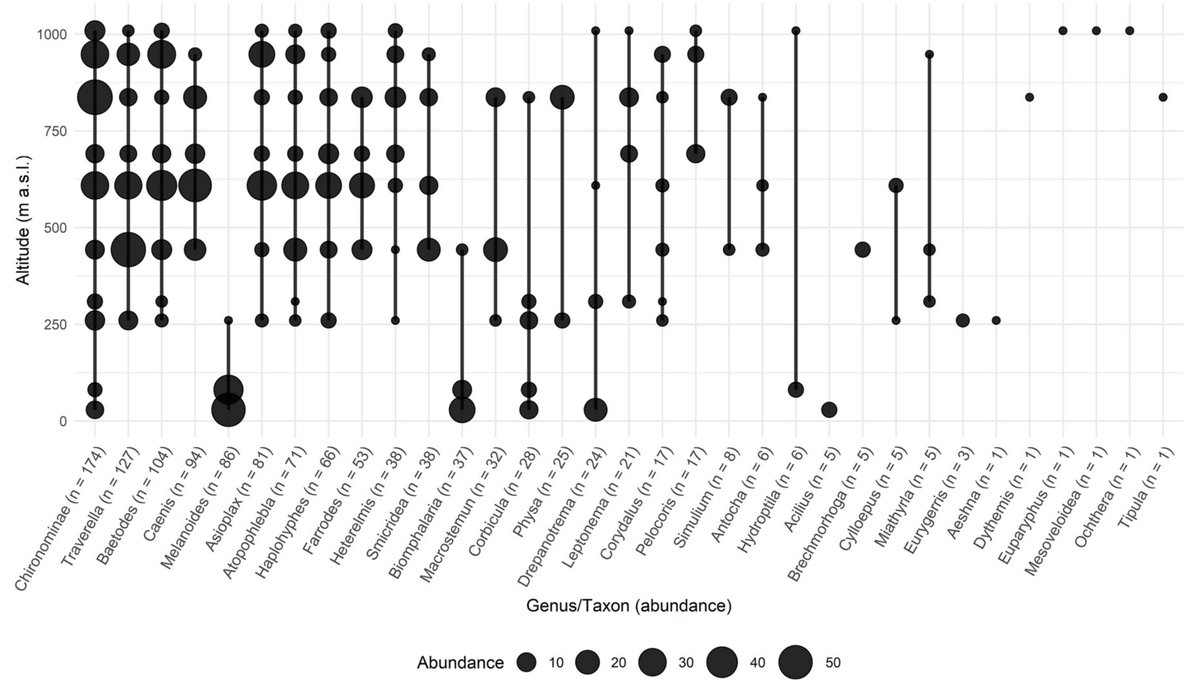

FIGURE 6
Altitudinal distribution and relative abundance of the main aquatic macroinvertebrate genera recorded along the Jequetepeque River during the dry season (2022–2023).

In addition to hydrological regulation, intensive agriculture in the middle and lower Jequetepeque River basin represents a second key anthropogenic driver that acts diffusely and persistently on benthic community structure. The progressive increase in electrical conductivity toward downstream reaches reflects a higher ionic load associated with fertilizer use, irrigation salts, agricultural runoff, and inputs from populated areas (Otero et al., 2012; Zárate-Martinez et al., 2024). This pattern is consistent with observations from arid and semi-arid rivers, where agricultural intensification increases dissolved ions and nutrients, altering macroinvertebrate composition and diversity (Jun et al., 2011; Fierro et al., 2021).

In the lower reaches, particularly at stations 09R and 10R, the high abundance of Melanoides, Biomphalaria, and Corbicula indicates the dominance of taxa highly tolerant to elevated concentrations of dissolved ions, organic loading, and reduced flows—conditions typical of regulated rivers impacted by agriculture (Salinas, 2010; Martínez and Serna, 2019; Pereira et al., 2016; Salguero et al., 2018; Rodríguez et al., 2021). These results confirm that increased conductivity and the proliferation of tolerant taxa reflect the combined impact of hydrological regulation and intensive agriculture on the ecological integrity of the fluvial system.

Aquatic macroinvertebrates demonstrated high sensitivity for detecting ecological changes that were not evident through conventional physicochemical parameters. Although variables such as pH, temperature, and dissolved oxygen showed limited spatial variation, the composition and structure of benthic communities consistently responded to the gradient of environmental alteration. The persistence of generalist groups such as Diptera and Coleoptera reflects their ecological plasticity and tolerance to variable hydrochemical conditions (Sierpe and Sunico, 2019; González et al., 2020), whereas the restricted distribution of more demanding taxa acts as an early indicator of habitat degradation (Ardila and Molina, 2021).

Studies in tropical Andean rivers have shown that macroinvertebrate assemblages discriminate gradients of multiple disturbance—including agriculture and hydrological regulation—more effectively than physicochemical parameters considered in isolation, reinforcing their value as integrative bioindicators for ecological monitoring in arid regions (Castillejo et al., 2024; Roldán, 2024).

This study was conducted during the dry season and focused on the middle and lower reaches of the Jequetepeque River; therefore, it does not capture hydrological variability associated with the rainy season nor ecological processes occurring in high-Andean headwaters. Macroinvertebrate composition, abundance, and functional structure can vary significantly between dry and wet seasons in response to changes in discharge, lateral connectivity, and habitat availability (Beche et al., 2005; Quesada-Alvarado et al., 2020). Consequently, assessments restricted to a single hydrological season may underestimate total biodiversity and fail to fully capture annual benthic dynamics.

Nevertheless, the observed patterns are consistent with alteration mechanisms documented in arid rivers regulated by dams and impacted by intensive agriculture, supporting the robustness of the ecological inferences. From a management perspective, the results highlight the need to implement macroinvertebrate-based biological monitoring programs that incorporate seasonal variability, as well as to evaluate environmental flow regimes that mitigate the effects of the Gallito Ciego dam. Taken together, these findings position macroinvertebrates as a key tool to guide adaptive management decisions and the conservation of upper and middle reaches of the

Jequetepeque River under scenarios of increasing anthropogenic and climatic pressure (Riato et al., 2023).

5 Conclusion

This study demonstrated that the distribution of aquatic macroinvertebrate communities in the arid Jequetepeque River basin is strongly structured by environmental and altitudinal gradients, as well as by the cumulative influence of anthropogenic pressures along the fluvial system. Despite the relative spatial stability of some physicochemical parameters, the composition and structure of benthic assemblages reflected progressive changes in the ecological quality of the river.

Upper and middle reaches were characterized by communities dominated by sensitive taxa associated with well-oxygenated, alkaline waters and moderate electrical conductivity, indicating favorable environmental conditions and lower anthropogenic disturbance. In contrast, downstream reaches exhibited a gradual replacement of these groups by more tolerant genera in response to increased electrical conductivity, reduced dissolved oxygen, and human activities, including intensive agriculture, soil removal, and hydrological regulation associated with the Gallito Ciego dam.

Multivariate analyses confirmed the separation of sampling stations according to their environmental characteristics, highlighting electrical conductivity, dissolved oxygen, and altitude as key variables structuring macroinvertebrate communities. The persistence of orders such as Diptera and Trichoptera along the gradient reflects high ecological plasticity, although with variations in richness and abundance associated with habitat quality.

Overall, the results demonstrate that aquatic macroinvertebrates are sensitive and reliable indicators of subtle changes in water quality, even when physicochemical variables do not show statistically significant differences. This underscores their usefulness as cost-effective environmental monitoring tools in arid and semi-arid regions with limited technical infrastructure.

Finally, this study provides a solid scientific baseline for the Jequetepeque River basin and contributes to reducing the existing knowledge gap regarding arid fluvial ecosystems in northern Peru. The findings provide valuable input for future ecological research and for the development of management and conservation strategies aimed at mitigating the effects of climate change and human activities on aquatic ecosystems.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

DS-Q: Conceptualization, Methodology, Investigation, Data curation, Formal Analysis, Writing – original draft, Writing – review and editing. MS-P: Conceptualization, Investigation, Writing – original draft, Writing – review and editing. DA-T: Formal Analysis, Writing – review and editing. JA-M: Data curation, Methodology, Writing – review and editing. AM-A: Methodology, Visualization, Writing – review and editing.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

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SUPPLEMENTARY FIGURE S1
Altitudinal distribution map of genera in the order *Trichoptera*.

SUPPLEMENTARY FIGURE S2
Altitudinal distribution map of genera in the order *Diptera*.

SUPPLEMENTARY FIGURE S3
Altitudinal distribution map of genera in the orders *Basommatophora*, *Veneroida*, *Caenogastropoda*, and *Haplotaxida*.

SUPPLEMENTARY FIGURE S4
Altitudinal distribution map of genera in the order *Ephemeroptera*.

SUPPLEMENTARY FIGURE S5
Altitudinal distribution map of genera in the orders *Coleoptera*, *Hemiptera*, *Megaloptera*, and *Odonata*.

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