Macroinvertebrate Communities and Ecological Quality of Springs under Anthropogenic and Thermal Influences in the Chili River Sub-Basin, Arequipa, Peru

Comunidades de Macroinvertebrados y Calidad Ecológica de Manantiales Bajo Influencias Antrópicas y Termales en la Subcuenca del Río Chili, Arequipa, Perú

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Highlights

- The Andean Biotic Index (ABI) revealed water quality ranging from good to very good, even under hydrothermal and anthropogenic influences.
- Forty-two aquatic macroinvertebrate families were recorded—the first report for Arequipa springs—with Chironomidae, Hydroptilidae, and Hyalellidae as dominant groups.
- Relationships between physicochemical parameters and macroinvertebrate composition revealed clear patterns linked to sampling stations and environmental features.

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ABSTRACT

Introduction. Springs are natural discharges of groundwater to the surface and represent strategic resources for water supply, biodiversity conservation, and social and economic well-being. Understanding their ecology is essential for establishing priorities for sustainable management and conservation. **Objective.** To characterize the structure of aquatic macroinvertebrate communities and assess water quality in three springs—one hydrothermal—of the Chili River sub-basin, Arequipa, Peru. **Materials and Methods.** A non-experimental, cross-sectional design was applied. Aquatic macroinvertebrates were sampled using a Surber net, and physicochemical parameters were measured *in situ* with a multiparameter probe. **Results.** A total of 42 aquatic macroinvertebrate families were recorded across the three springs. *Chironomidae* and *Hydroptilidae* dominated in Ojo del Milagro; *Hyalellidae* and *Glossosomatidae* in Yumina; and *Hydroptilidae* and *Naididae* in Yura. Significant differences were observed among springs in physicochemical and hydrological characteristics, as well as in the structural composition of macroinvertebrate communities. The mean Andean Biotic Index (ABI) scores indicated water quality ranging from good to very good. **Conclusions.** The composition and structure of macroinvertebrate communities differed significantly among the three springs, driven mainly by local physicochemical conditions and water use at each site.

RESUMEN

Introducción. Los manantiales son afloramientos naturales de agua subterránea en la superficie y constituyen recursos estratégicos para el suministro de agua, la conservación de la biodiversidad y el bienestar social y económico. Comprender su ecología es fundamental para establecer prioridades de manejo y conservación sostenibles. **Objetivo.** Caracterizar la estructura de las comunidades de macroinvertebrados acuáticos y evaluar la calidad de agua en tres manantiales—uno de ellos hidrotermal—de la subcuenca del río Chili, Arequipa, Perú. **Materiales y Métodos.** Se aplicó un diseño no experimental, transversal. Los macroinvertebrados acuáticos fueron muestreados mediante red Surber y los parámetros fisicoquímicos se midieron *in situ* con un equipo multiparámetro. **Resultados.** Se registraron un total de 42 familias de macroinvertebrados acuáticos en los tres manantiales. *Chironomidae* e *Hydroptilidae* dominaron en Ojo del Milagro; *Hyalellidae* y *Glossosomatidae* en Yumina; e *Hydroptilidae* y *Naididae* en Yura. Se observaron diferencias significativas entre los manantiales en las características fisicoquímicas e hidrológicas, así como en la composición estructural de las comunidades de macroinvertebrados. Los valores promedio del Índice Biótico Andino (ABI) indicaron una calidad de agua entre buena y muy buena. **Conclusiones.** La composición y estructura de las comunidades de macroinvertebrados difirieron significativamente entre los tres manantiales, influenciadas principalmente por las condiciones fisicoquímicas locales y el uso del agua en cada sitio.

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INTRODUCTION

Springs are natural discharges of groundwater to the surface and are of great importance for the development of a country, given their use as sources of drinking water as well as their role in supporting economic and social activities (1). Their natural quality depends largely on the geological conditions through which the water flows, since it may become enriched with minerals or contaminated by anthropogenic activities (2-3). One of the most widely used approaches to evaluate the ecological quality of aquatic ecosystems is the assessment of the abundance, diversity, and distribution of aquatic macroinvertebrates (4).

Aquatic macroinvertebrate communities comprise a large number of species belonging to different taxonomic groups, mostly arthropods, that depend on habitat availability and food resources, while playing key roles in the transformation of organic matter (5-6). Consequently, their dynamics in aquatic systems are influenced by a combination of factors such as the physicochemical properties of water, land use, and the chemical composition of leaf litter, which may include secondary toxic compounds that hinder macroinvertebrate colonization (6). Moreover, these organisms display varying levels of tolerance to pollution (7), which is reflected in the presence or absence of particular macroinvertebrate groups (8). This ecological variability has enabled the development of several water quality indices designed to indicate the ecological status of freshwater ecosystems (9). Among these indices, the Andean Biotic Index (ABI)—an adaptation used for high Andean regions—is rooted in the BMWP framework for bioassessment (10) and is used to evaluate the overall ecological condition of aquatic ecosystems (11).

In Peru, several studies conducted in rivers and lakes have demonstrated that water quality—defined by its level of purity or contamination—is a critical factor in water resource management and conservation strategies, and is assessed through physical, chemical, and biological parameters (12–14). The Chili River sub-basin currently faces significant environmental challenges due to increasing anthropogenic pressures associated with internal migration and population growth. These processes have promoted urbanization of areas adjacent to the river, directly affecting both water and soil quality (15).

Springs provide valuable insights into the ecology of their ecosystems and thus contribute to defining priorities for sustainable water management, particularly under conditions of anthropogenic pressure and climate variability (16). In the Arequipa Region, several studies on aquatic macroinvertebrate communities have been conducted, although all of them focused exclusively on rivers (17–21). Therefore, the aim of this study was to characterize the structure of aquatic macroinvertebrate communities and assess water quality in three springs—one of them thermal—within the Chili River sub-basin in Arequipa, Peru, in order to establish a baseline that contributes to the conservation of these important water sources.

MATERIALS AND METHODS

Study Area

Located within the Chili River sub-basin in southwestern Peru, the study area belongs politically to the Arequipa Region (**Figure 1**) and includes the districts of Characato, Sabandía, and Yura, all within the Province of Arequipa. Sporadic snow precipitation occurs during winter, while continuous rainfall takes place between January and March, representing the only recharge mechanism for the aquifers. The average annual temperature in the study area is 15.8 °C, with a relative humidity of 40%.

The geomorphology of the area is the result of volcanic and tectonic processes, with a lithological composition dominated by highly fractured andesitic lavas, low-sloping, permeable surfaces that favor infiltration (22). Within the districts of the study area, there are zones with agricultural, environmental, touristic, landscape, and cultural value (23). The native vegetation consists of species adapted to the altitude and the semi-arid climate of the region (24- 25).

For this work, three main springs were selected, all of which maintain a relatively stable discharge flow throughout the hydrological cycle: Ojo del Milagro (OM**)** (−16.471389, −71.461944; 2546 m a.s.l.; 1.51 km in length), Yumina (YM) (−16.448611, −71.473333; 2564 m a.s.l.; 1.25 km in length), and Yura (YU) (−16.241389, −71.701389; 2478 m a.s.l.; 2.79 km in length), referenced to WGS84; the latter is hydrothermal in origin. These springs are classified as rheocrenes. The water from Ojo del Milagro is of calcium–sulfate composition (SO_4–Ca), while the Yura spring has calcium–bicarbonate water (HCO_3–Ca); both flow through natural channels. In contrast, Yumina spring, characterized by sodium–chloride water (Cl–Na), flows through a man-made channel constructed for agricultural irrigation (22).

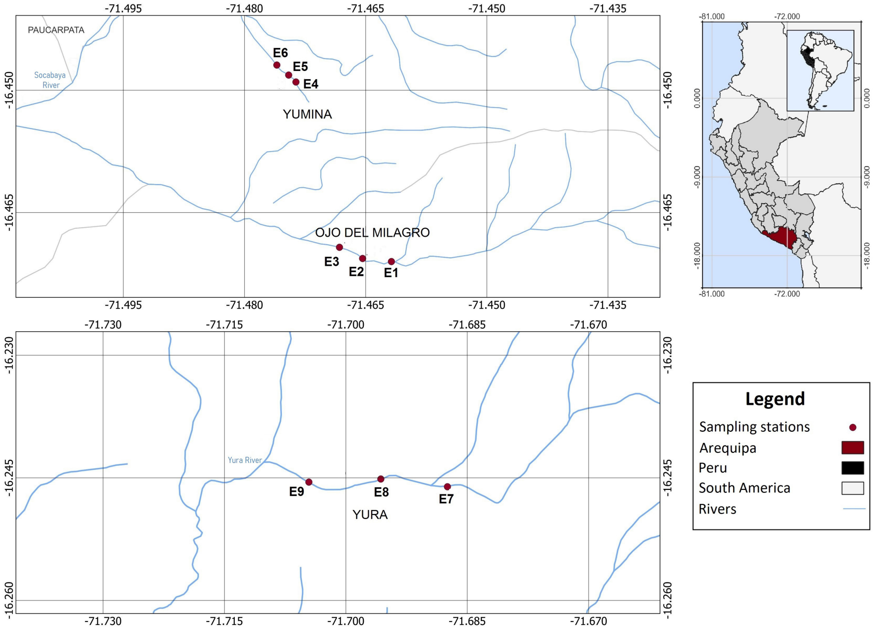

Figure 1. Sampling stations of the springs in the Chili River sub-basin, Arequipa, Peru.

Physicochemical parameters

Sampling was carried out during the dry season (June–December 2023). Three sampling stations were established in each spring (**Figure 1**). The first station was located at the water outlet (E1, E4, E7), the second at the middle section (E2, E5, E8), and the third at the downstream point before water abstraction for domestic and agricultural use (E3, E6, E9), covering the entire length of each spring. Physicochemical parameters were measured following the *National Protocol for Monitoring the Quality of Surface Water Resources* (26). Water temperature (°C), pH, dissolved oxygen (DO, mg/L), electrical conductivity (EC, µS/cm), total dissolved solids (TDS, mg/L), and discharge (L/s) were measured in situ using a portable multiparameter device (Aquared AP2000) and a current meter (Global Water FP111).

Collection and identification of aquatic macroinvertebrates

At each sampling station, three replicate samples of aquatic macroinvertebrates were collected using a Surber net (500 µm mesh size; 0.09 m^2 sampling area). Samples were transferred into 500 mL containers and preserved in 4% formalin. In the Laboratory of Aquatic Biology and Oceanography, Faculty of Biological Sciences, Universidad Nacional San Agustín de Arequipa, samples were washed and sieved through a 500 µm mesh and subsequently preserved in 70% ethanol for identification (27-28). Taxonomic identification was performed to the family level using the keys by Merritt et al. (29), Domínguez and Fernández (28), Prat and Rieradevall (30), and Thorp and Lovell (31).

Data analysis

Community structure was evaluated using family richness (S), abundance (number of individuals per family), Shannon–Wiener diversity index (H), Simpson's dominance index (D), and Pielou's evenness (J') (32). A one-way ANOVA was applied to compare community indices among springs. A non-metric multidimensional scaling (nMDS) based on Bray–Curtis similarities was performed to explore variations in macroinvertebrate composition. Differences in community composition among springs were tested using an Analysis of Similarities (ANOSIM; 9,999 permutations; $\alpha = 0.05$). A Similarity Percentage Analysis (SIMPER) was applied to identify families contributing most to dissimilarity among springs. Canonical Correspondence Analysis (CCA) was conducted to evaluate relationships between aquatic macroinvertebrates and physicochemical variables. Analyses were conducted using EXCEL® and PAST version 4.13 (33).

Ecological water quality

The ecological quality of the springs was assessed using the Andean Biotic Index (ABI), which classifies aquatic macroinvertebrate families into ten tolerance groups (10). Scores range from 10 (most sensitive families) to 1 (most tolerant), and the total ABI score is obtained by summing the values assigned to all families present. ABI builds on the BMWP approach adapted for Andean systems (27).

RESULTS

Physicochemical parameters

Water temperature in the springs ranged from 16.31 °C (E4, YM) to 21.28 °C (E8, YU). pH values varied between 7.52 (E9, YU) and 8.71 (E4, YM). Dissolved oxygen (DO) concentrations ranged from 3.15 mg/L (E9, YU) to 7.89 mg/L (E1, OM). Electrical conductivity (EC) fluctuated between 631 µS/cm (E1, OM) and 1405 µS/cm (E9, YU). Total dissolved solids (TDS) ranged from 410.33 mg/L (E1, OM) to 713 mg/L (E7, YU). Finally, discharge values varied between 7.6 L/s (E7, YU) and 129.5 L/s (E5, YM) (**Table 1**).

Table 1. Mean values of physicochemical parameters in the springs of the Chili River sub-basin, Arequipa, Peru.

Spring	Station	Temp. (°C)	pH	DO (mg/L)	EC (uS/cm)	TDS (mg/L)	Discharge (L/s)
OM	E1	17.93 ± 0.58	8.62 ± 0.03	7.89 ± 0.06	w631.00 ± 29.55	410.33 ± 19.86	69.80
OM	E2	18.97 ± 1.42	8.56 ± 0.11	7.78 ± 0.33	677.33 ± 5.13	440.33 ± 1.53	65.60
OM	E3	18.36 ± 0.20	8.61 ± 0.01	7.83 ± 0.07	710.33 ± 2.52	461.67 ± 1.15	73.20
YM	E4	16.31 ± 0.12	8.71 ± 0.03	5.08 ± 0.12	712.33 ± 0.58	462.00 ± 0.00	82.30
YM	E5	16.70 ± 0.69	8.69 ± 0.06	6.10 ± 0.04	690.67 ± 25.81	451.67 ± 18.93	129.50
YM	E6	17.23 ± 1.08	8.67 ± 0.07	6.53 ± 0.06	841.33 ± 10.26	548.00 ± 5.00	121.50
YU	E7	17.70 ± 0.01	7.62 ± 0.02	6.50 ± 0.30	1262.00 ± 97.00	713.00 ± 146.00	7.60
YU	E8	21.28 ± 0.01	7.55 ± 0.04	4.47 ± 0.30	1355.00 ± 164.00	655.00 ± 14.00	20.40
YU	E9	21.76 ± 0.01	7.52 ± 0.01	3.15 ± 0.30	1405.00 ± 15.00	707.00 ± 14.00	32.80

OM = Ojo del Milagro; **YM** = Yumina; **YU** = Yura.

Community structure

A total of 42 families and one unidentified nematode were recorded across the three springs (**Table 2**). By site, 23, 16, and 37 families were registered in Ojo del Milagro, Yumina, and Yura, respectively. The total number of aquatic macroinvertebrates was highest in Yura (5,396 individuals), followed by Ojo del Milagro (5,083 individuals) and Yumina (1,325 individuals).

The families Dugesiidae, Lumbriculidae, Physidae, Hyalellidae, Hydroptilidae, Chironomidae, Empididae, Muscidae, Libellulidae, Aeshnidae, and Elmidae were present in all three springs, although their abundances varied. In Ojo del Milagro, Chironomidae and Hydroptilidae dominated, representing 79.3% of total abundance; in Yumina, Hyalellidae and Glossosomatidae accounted for 89.1%; and in Yura, Hydroptilidae and Naididae together represented 49.3% of total abundance.

Richness (S) was highest in Yura (27 taxa) and lowest in Yumina (10 taxa), with significant differences among springs ($p < 0.05$). The mean Shannon–Wiener index in Yura was 1.96, higher than in Ojo del Milagro (1.36) and Yumina (0.85). A significant difference was found between Yumina and Yura ($p = 0.01544$). Mean Simpson dominance (D) was lowest in Yura (0.23) compared with Ojo del Milagro (0.35) and Yumina (0.64), with a significant difference between Yumina and Yura ($p = 0.03398$). Pielou's evenness (J') was lowest in Yumina (0.37), compared with Ojo del Milagro (0.47) and Yura (0.60), although these differences were not significant ($p > 0.05$) (**Figure 2**).

Table 2. Average abundance of aquatic macroinvertebrates in the springs of the Chili River sub-basin, Arequipa, Peru.

Taxa	Ojo del Milagro			Yumina			Yura		
	E1	E2	E3	E4	E5	E6	E7	E8	E9
Platyhelminthes									
Dugesiidae	1	9	1	12	1	3	135	99	87
Nematoda	–	–	–	–	–	–	5	1	1
Annelida									
Glossiphoniidae	1	–	–	–	–	–	–	–	1
Lumbriculidae	1	1	2	–	1	–	4	9	4
Naididae	42	26	124	–	–	–	374	279	43
Mollusca									
Physidae	2	16	34	1	1	–	19	81	107
Planorbidae	–	1	1	–	–	–	22	2	76
Lymnaeidae	–	1	1	–	–	–	1	0	1
Hydrobiidae	–	–	–	–	–	–	176	5	290
Sphaeriidae	–	–	–	–	–	–	12	–	–
Arthropoda Malacostraca									
Hyalellidae	6	134	170	116	18	883	119	124	1
Arthropoda Copepoda									
Cyclopidae	–	–	–	–	–	–	–	1	–
Arthropoda Ostracoda									
Cyprididae	–	–	–	–	–	–	–	–	1
Candonidae	–	–	–	–	–	–	1	1	51
Arthropoda Acari									
Limnesiidae	7	89	114	–	–	–	2	11	1
Limnozetidae	–	–	–	–	–	–	1	42	5
Arthropoda Hexapoda									
Glossosomatidae	0	0	0	11	134	19	–	–	–
Hydroptilidae	561	827	587	14	0	20	1	1901	61
Chironomidae	358	774	923	33	5	34	184	263	11
Empididae	23	66	84	1	0	7	26	13	1
Simuliidae	24	36	12	–	–	–	57	97	16
Muscidae	1	0	1	–	1	1	1	1	4
Ephydridae	1	1	1	–	–	–	1	–	–
Psychodidae	–	–	–	–	–	–	–	–	1
Tipulidae	–	1	1	–	–	–	–	–	–
Dolichopodidae	–	–	–	–	–	–	–	1	–
Sarcophagidae	–	–	–	–	–	–	–	1	–
Stratiomyidae	–	–	–	–	–	–	1	–	–
Sciomyzidae	–	–	–	–	–	–	0	1	–
Ceratopogonidae	–	–	–	–	–	–	34	1	–
Scathophagidae	–	–	–	–	–	1	–	–	–
Veliidae	–	–	–	–	–	–	–	18	1
Libellulidae	1	1	1	–	1	–	4	1	2
Gomphidae	–	4	2	–	–	–	1	–	–
Aeshnidae	–	–	1	1		–	3	6	9
Coenagrionidae	–	–	–	–	–	–	–	–	1
Dytiscidae	–	–	–	–	1	–	–	–	–
Elmidae	–	1	1	1	1	1	33	253	186
Hydrophilidae	1	1	1	–	–	–	–	1	1
Staphylinidae	–	1	–	–	1	–	–	–	–
Baetidae	–	–	1	–	–	–	–	–	1
Leptohyphidae	–	–	–	–	–	–	–	–	1
Crambidae	–	–	–	–	1	–	–	–	1

A dash (–) indicates that no individuals of the taxon were recorded at the corresponding station.

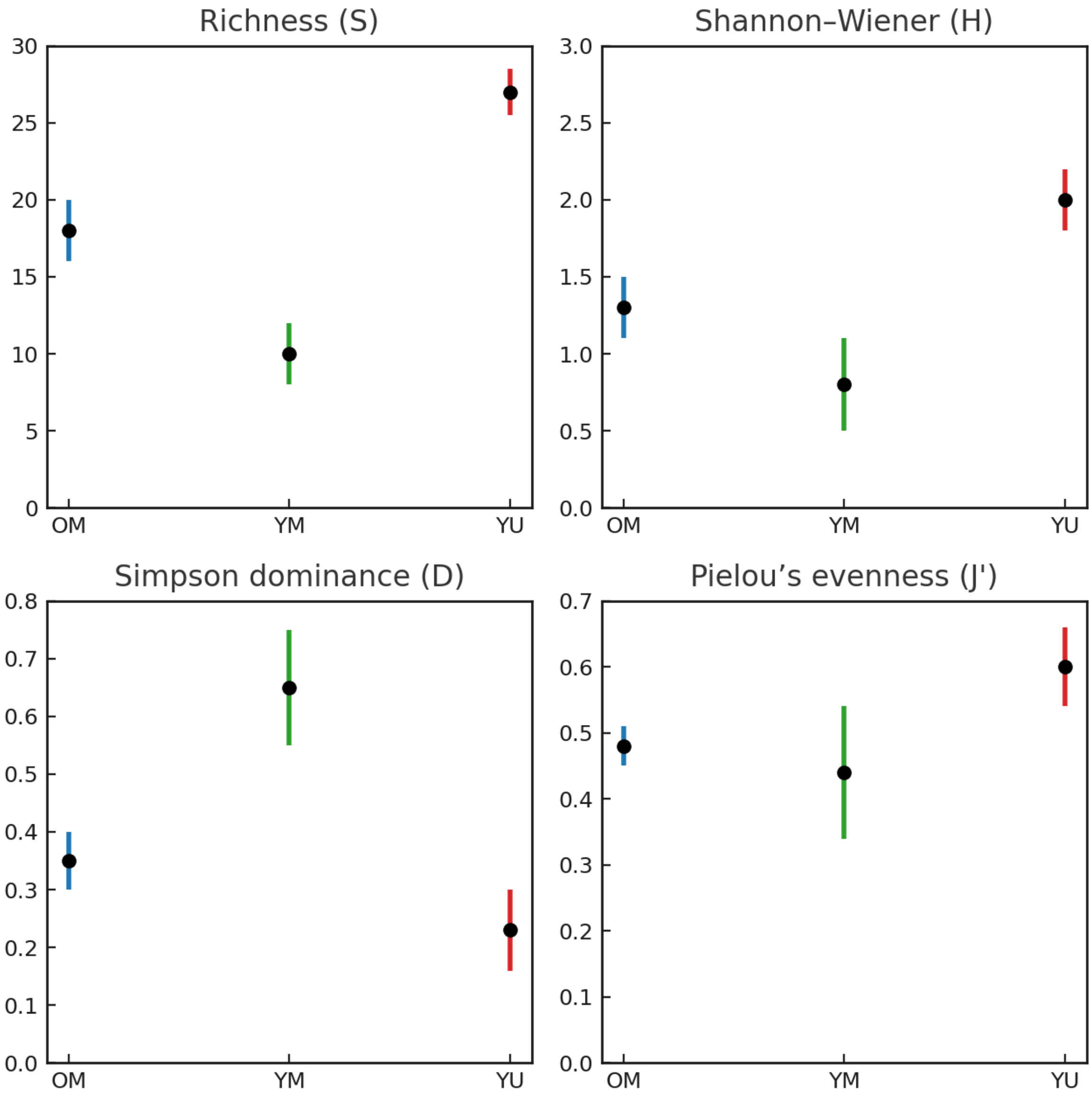

Figure 2. Community indices of aquatic macroinvertebrates by springs in the Chili River sub-basin. **YU** = Yura; **OM** = Ojo del Milagro; **YM** = Yumina.

nMDS analysis revealed a clear separation in macroinvertebrate community composition among springs (**Figure 3**). ANOSIM confirmed significant separation among the three springs (global R = 0.8848; p = 0.0038). SIMPER analysis showed an overall dissimilarity of 59.04%, with 18 families contributing most to differences (**Table 3**). Hydroptilidae and Naididae individually contributed more than 10% to the dissimilarity between Ojo del Milagro and Yumina, while other families contributed less than 10% (**Table 3**).

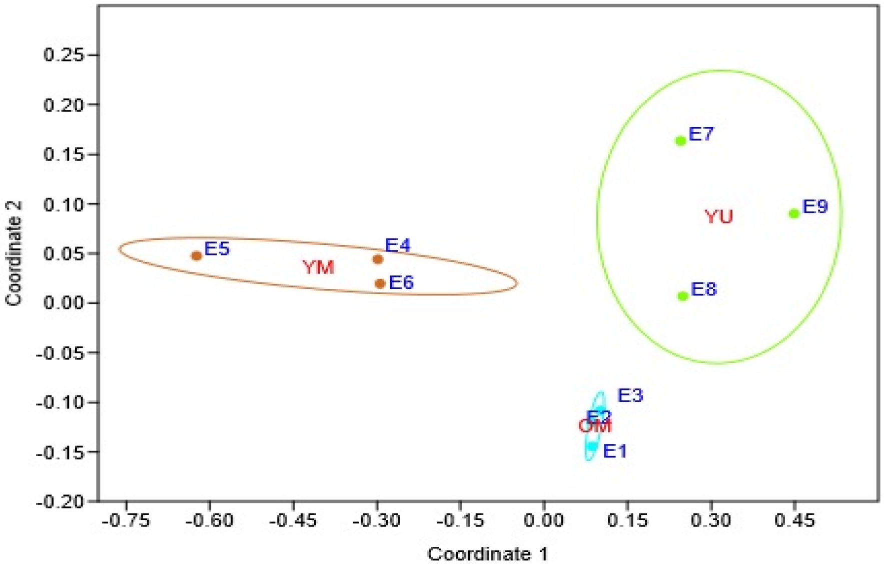

Figure 3. Non-metric multidimensional scaling (nMDS) analysis of aquatic macroinvertebrates in the Chili River sub-basin. **YU** = Yura (green), **OM** = Ojo del Milagro (blue), **YM** = Yumina (red). Stress value = 0.044.

Canonical Correspondence Analysis (CCA) explained 89.9% of the variance in the first two axes. The first axis (68.4%) was mainly associated with water temperature, EC, and TDS, whereas the second axis (21.5%) was associated with discharge and pH. The CCA showed that Yura spring was related to higher temperature, conductivity, and TDS, while Yumina and Ojo del Milagro were associated with higher pH, discharge, and DO.

Table 3. SIMPER analysis between springs in the Chili River sub-basin. **YU** = Yura; **OM** = Ojo del Milagro; **YM** = Yumina.

Family	**Contribution %**		
	OM–YM	**OM–YU**	**YM–YU**
Hydroptilidae	12.49	6.58	5.33
Naididae	10.70	–	8.64
Limnesiidae	9.83	5.06	–
Glossosomatidae	9.49	–	5.94
Chironomidae	9.44	4.33	–
Simuliidae	8.54	–	6.48
Empididae	8.10	–	–
Hyalellidae	5.26	3.99	–
Physidae	5.14	–	6.06
Elmidae	–	9.16	6.92
Hydrobiidae	–	9.07	7.32
Dugesiidae	–	7.34	5.33
Planorbidae	–	5.24	4.98
Limnozetidae	–	4.34	–
Total	**78.99**	**55.11**	**57.00**

Families Hydrobiidae and Elmidae correlated with high EC and TDS; Naididae and Hydroptilidae with higher temperatures and lower pH; Hyalellidae with higher discharge, pH, and lower temperatures; and Chironomidae with high DO levels (**Figure 4**).

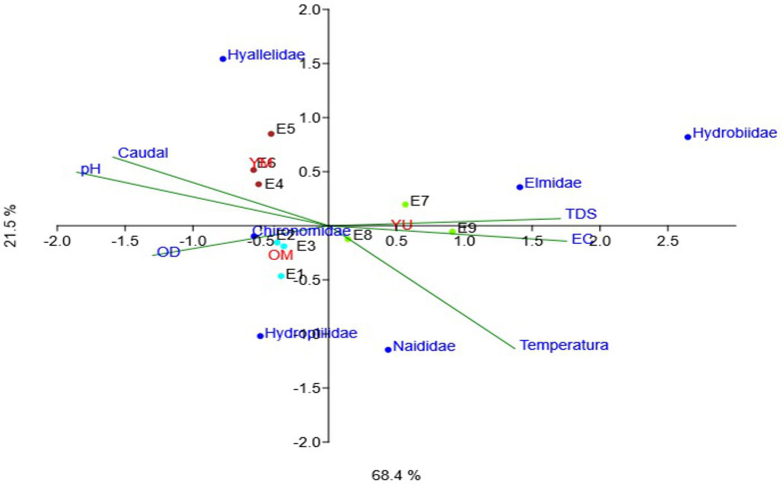

Figure 4. Canonical Correspondence Analysis (CCA) of aquatic macroinvertebrates and physicochemical parameters in the Chili River sub-basin. **YM** = Yumina (red); **OM** = Ojo del Milagro (blue); **YU** = Yura (green). **EC** = electrical conductivity; **TDS** = total dissolved solids; **DO** = dissolved oxygen.

Water quality

Overall, the mean ABI scores indicated water quality ranging from good to very good across the three springs (**Table 4**). The lowest scores were recorded in Yumina, indicating moderate water quality. The highest scores were observed in Yura, ranging from good to very good depending on the sampling station. In Ojo del Milagro, ABI values indicated good quality at the spring outlet (E1) and very good quality at downstream stations.

Table 4. ABI scores for ecological water quality in three springs of the Chili River sub-basin. **YU** = Yura; **OM** = Ojo del Milagro; **YM** = Yumina.

Station	ABI Index	Quality	Spring	ABI Score	Quality
E1	47	Good	OM	84	Very good
E2	69	Good			
E3	78	Very good			
E4	39	Moderate	YM	54	Good
E5	38	Moderate			
E6	32	Moderate			
E7	84	Good	YU	119	Very good
E8	76	Good			
E9	94	Very good			

DISCUSSION

Overall, the physicochemical parameters of the three springs were within the water quality standards (34) for Category 1 (waters suitable for drinking after conventional treatment) and Category 3 (irrigation and livestock use), as well as within the World Health Organization guidelines (35) for DO, pH, and TDS. However, water temperature, EC, and TDS were higher in Yura, most likely because this spring is hydrothermal and naturally rich in ions (36), which strongly influences the composition of aquatic macroinvertebrate communities (37-38). The strong influence of temperature and water chemistry on community structure in the hydrothermal spring (YU) mirrors patterns reported for rheocrene and geothermal springs in Europe and Oceania, where thermal regime and ionic content consistently shape assemblages (38-40). In contrast, Ojo del Milagro and Yumina exhibited similar physicochemical values, with only slight variations, probably due to their geographical proximity, lithological characteristics (39), and the natural origin of their waters. The discharge values recorded correspond to the dry season (May–December), and may be influenced by rainfall and climatic variability in the region. Flow regimes can alter community structure and lead to biodiversity loss (41). In Yumina, water is diverted through a man-made channel for irrigation and drinking water supply. Such channelization can cause habitat loss and environmental stress, influencing community structure and biodiversity decline (42-43). Our inference that channelization reduces habitat heterogeneity and macroinvertebrate density aligns with results from regulated and channelized rivers across temperate and mountain regions, highlighting community simplification under homogenized flow and habitat conditions (41-45) (**Table 1**).

In ecosystems that maintain good ecological conditions, aquatic macroinvertebrates usually occur in high abundance and diversity (46). This pattern explains the high number of individuals recorded in Yura and Ojo del Milagro. Among the 42 families registered (**Table 2**), several are indicators of good water quality and habitat conditions (47). In Ojo del Milagro, Diptera were the most abundant order, many species of which are tolerant to habitat changes and indicate organic pollution (46, 48). The high abundance of Chironomidae in Ojo del Milagro, and to a lesser extent in Yura, is likely related to their ability to colonize habitats rich in decomposing organic matter (46), conditions favored by agricultural and recreational activities near Ojo del Milagro. In Yura, Coleoptera and Diptera also occurred in high numbers, consistent with reports from thermal waters in Colombia (49). Families such as Hyalellidae (Amphipoda)—potentially representing new species for Peru—and ostracods have also been reported in extreme environments (50). Conversely, Trichoptera were absent from Yura, probably due to the hydrothermal origin of this spring, which could negatively affect their sensitivity and development (40,51). The scarcity of Trichoptera in YU is consistent with evidence from geothermal systems indicating thermal filtering of sensitive taxa and temperature-driven trait sorting (40, 51).

Ecological indices were generally low across the springs (**Figure 2**), which may be associated with the agro-urban context in which they are located. For example, Ojo del Milagro is surrounded by agricultural areas and public-use pools, while Yura is located in a touristic area with thermal baths. The geothermal characteristics of Yura may favor tolerant groups such as Chironomidae and certain annelids, as previously observed in the Caracha River, Ayacucho (52), and at other latitudes (53). Nevertheless, in both springs the natural channels are preserved, and riparian vegetation enhances habitat heterogeneity, likely explaining the higher diversity and family richness recorded. Studies by Meza et al. (54) and Bravo-Chaves & Restrepo-Franco (55) have shown that greater vegetation cover and lower human disturbance are associated with higher richness and abundance of macroinvertebrates. By contrast, Yumina is heavily channelized for irrigation, resulting in a less heterogeneous environment (46). This condition explains its lowest diversity, high dominance, and simplified community structure (46), consistent with hydrological fluctuations and anthropogenic pressure (56).

CCA revealed that Hydrobiidae and Elmidae were related to high EC and TDS. Vizcardo & Gil (56) reported that EC strongly influences the distribution and abundance of Hydrobiidae, while González et al. (57) emphasized the role of EC and suspended solids in the occurrence of Elmidae. The CCA associations of Elmidae with higher conductivity and suspended solids agree with sensitivity patterns documented for this family in Andean streams (57), while the link between Hydrobiidae and conductivity echoes reports of conductivity-driven distributions in spring-fed systems (39, 56). Hydroptilidae were associated with high temperature and low pH, as reported for Trichoptera species (58), which are strongly correlated with pH. In Yumina, where pH reached 8.71, Trichoptera were less abundant compared with the other springs. Hyalellidae were associated with higher discharge, pH, and lower temperature, in agreement with Hankel et al. (59), who indicated that their abundance can be affected by low temperatures, suggesting that this group is sensitive to thermal variability. Diptera, known for their tolerance to environmental changes (48), were abundant across the three springs. Chironomidae, in particular, showed an association with DO in the CCA analysis. Although they are tolerant to low oxygen levels, Villamarín et al. (61) found that chironomid communities are strongly associated with DO, EC, and pH, consistent with our results. This may reflect the ecological plasticity of different genera within the family (**Figure 4**).

According to ABI results, the studied springs generally showed good to very good water quality (**Table 4**), which likely allowed the establishment of diverse macroinvertebrate communities similar to those found in natural riverine systems (62). In Yumina, however, water quality was rated moderate, probably due to channelization for irrigation purposes. While its physicochemical conditions were favorable, structural modifications of the channel likely reduced habitat heterogeneity and macroinvertebrate density, consistent with previous studies showing that river channelization alters macroinvertebrate communities (42). Habitat homogenization caused by channelization is widely recognized as a factor reducing invertebrate densities (44-45). This likely explains the low abundance and simplified community observed in Yumina, although moderately sensitive families such as Hyalellidae (score 6 in the ABI index) were still present.

In summary, this work provides the first characterization of aquatic macroinvertebrate communities in springs of the Arequipa Region, offering valuable insights into ecosystems subject to marked climatic variability and human pressures. The baseline information on community structure and ecological quality indices reflects the current status of these systems and establishes a foundation for their long-term monitoring and management. Temperature-related responses observed here are consistent with patterns reported in other high-Andean geothermal streams, where thermal gradients shape community composition and tolerance spectra (37). At the same time, some limitations should be noted: sampling was restricted to the dry season, taxonomic resolution was limited to the family level, and key abiotic variables such as nutrients were not measured. Addressing these constraints in future studies—by broadening temporal coverage, integrating species-level or molecular identification, and including additional environmental parameters—will refine our understanding and support more robust ecological assessments of Andean springs.

CONCLUSIONS

The springs of the Chili River sub-basin host diverse aquatic macroinvertebrate communities whose structure is closely linked to local physicochemical conditions and the degree of anthropogenic intervention. Application of the Andean Biotic Index (ABI) revealed water quality ranging from moderate to very good, with more favorable conditions in springs that preserved natural channels and riparian vegetation.

These findings highlight the ecological and strategic value of springs as sources of freshwater and biodiversity refuges, while also confirming the effectiveness of macroinvertebrates as indicators for ecological monitoring. The results provide a fundamental baseline for the sustainable management and conservation of springs in high-Andean regions subjected to increasing urban and agricultural pressures, as well as for springs with hydrothermal characteristics.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ETHICAL CONSIDERATIONS

The research was conducted in accordance with Resolution No. 303-2016 of the Universidad Nacional de San Agustín de Arequipa. Sampling of aquatic macroinvertebrates was carried out under the provisions of Jefatural Resolution No. 10-2016-ANA.

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