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Diversity and spatio-temporal distribution of benthic macroinvertebrate communities in a transboundary river basin in the Caucasus region (Aras river, NE Türkiye)

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Abstract
This study evaluates the ecological status of the Aras River Basin (Türkiye) by analyzing benthic macroinvertebrate communities in relation to seasonal variations and anthropogenic pressures. During 2014–2015 sampling campaigns, we identified 126 taxa, of which 107 were identified at the species level and 19 at the genus level across 17 stations, with Insecta (87 taxa, 69%) showing the highest richness, followed by Clitellata (23 taxa, 18%). The dominant species *Tubifex tubifex* (15.87%), *Chironomus riparius* (15.60%), and *Gammarus balcanicus* (15.11%) served as key bioindicators, revealing significant organic pollution impacts, particularly in lentic habitats. Canonical Correspondence Analysis (CCA) for the summer period identified dissolved oxygen (DO) and pH as the primary environmental drivers, with pollution-tolerant taxa (e.g., *Chironomus riparius*) clustering in low-DO areas, while sensitive species (e.g., *Baetis rhodani*) were predominantly associated with well-oxygenated, alkaline conditions. Seasonal analyses demonstrated autumn as the most productive period (3,765 ind., 91 taxa), with Station 9 maintaining pristine conditions (BMWP score: 66, "Good") year-round. Conversely, spring showed the poorest water quality (BMWP < 25 at most stations), while summer exhibited intermediate conditions. Multivariate analyses (UPGMA, TWINSPAN) confirmed spatial clustering based on pollution gradients, with tolerant taxa (e.g., aquatic leeches, *Chironomus* spp.) dominating organically enriched sites and sensitive species (e.g., Plecoptera) restricted to high-quality habitats. Our findings highlight: (1) severe degradation at stations receiving agricultural/domestic waste (Stations 1–6), (2) the critical role of seasonal monitoring in detecting climate-driven stressors, and (3) the utility of macroinvertebrate-based indices (BMWP/ASPT) for basin-scale water quality assessment. The study provides a scientific basis for conserving transboundary freshwater ecosystems through targeted pollution control and habitat protection measures.

Keywords Bioindicators, Water quality assessment, Organic pollution, Seasonal dynamics, Pollution-tolerant taxa

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Introduction

Freshwater is one of Earth's most vital natural resources, essential for sustaining life and supporting human civilizations throughout history. As the foundation of diverse ecosystems, freshwater habitats reflect the ecological integrity of their watersheds, yet they face escalating threats from anthropogenic activities. Population growth, agricultural irrigation demands, and untreated domestic and industrial wastewater discharge have degraded freshwater quality and diminished usable supplies, disrupting the balance between utilization and conservation [1]. This imbalance challenges the principle of sustainable resource management.

In response to these pressures, the European Union adopted the Water Framework Directive (WFD) in 2000, a landmark policy mandating the restoration and protection of all surface waters, coastal waters, transitional waters, and groundwater to "good ecological and chemical status" [2]. Aligning with these standards, Türkiye has implemented integrated river basin management strategies, incorporating WFD principles into national legislation and developing targeted protection plans for critical watersheds [3].

Benthic macroinvertebrates play a crucial role in the assessment and monitoring of water quality due to their cosmopolitan distribution, high abundance, sedentary nature, short life cycles, ease of sampling, and the widespread availability of taxonomic identification keys [4]. Moreover, the presence of indicator species that are sensitive to specific environmental stressors makes these organisms highly effective tools for evaluating ecological conditions. Their community structure provides insights into water quality, ecological functioning, and the cumulative effects of watershed disturbances. Therefore, determining the composition of benthic macroinvertebrate fauna, understanding the ecological requirements of its constituent species, and identifying the factors influencing their communities are essential for accurate evaluations of the ecological status and water quality of the studied habitat [5, 6].

Numerous studies have examined water pollution, biodiversity, water quality, and management in the Aras River systems. While the majority of these investigations focus on lotic ecosystems, others have explored invertebrate fauna and lake environments using biomonitoring indices [7–13].

This study investigates the macrobenthic invertebrate fauna of the Aras River Basin, a transboundary basin in Türkiye. The objectives are threefold: (1) to characterize the biodiversity and spatial distribution of benthic macroinvertebrates in the Turkish section of the Aras River Basin, (2) to evaluate the ecological quality of sampled localities using macroinvertebrate-based indicators, and (3) to contribute to the broader understanding of Türkiye's freshwater biodiversity.

Materials and methods

Study area

The Aras River Basin is located within the Kura-South Caspian Drainages ecoregion, one of the 26 freshwater ecoregions in Türkiye, and is the main water source of the region together with the Kura River. The river, which is 1072 km long and has a basin area of 102,000 km^2, is one of the largest rivers in the Caucasus. 548 km of the river is within the borders of Türkiye. River waters are used for energy production, agricultural irrigation, and drinking water supply. While 16.5 km^3 of the total water budget is used for drinking water supply, 70% of the remaining water is used for agricultural irrigation and 25% for industrial purposes.

Sampling procedures

Sampling was conducted at 17 localities (6 lentic + 11 lotic habitats) in the Aras River Basin during 2014 (summer and autumn) and 2015 (spring) (Fig. 1; Table 1). In the winter period, field studies could not be done due to inappropriate conditions (road closures and transportation restrictions due to heavy snowfall).

Of the 17 stations selected in the summer of 2014, sampling couldn't be conducted at one station (St. 4) in the autumn of 2014 and at three stations (St. 1, 4, and 11) in the spring of 2015 due to the absence of water at the selected localities.

Five physicochemical parameters were measured in situ at each sampling location: water temperature (°C), dissolved oxygen (DO, mg/L), pH, electrical conductivity (EC, µS/cm), and salinity (‰) in the summer period (no data are available for autumn and spring). Measurements were conducted using calibrated portable instruments: a WTW pH-meter (Model 330) for pH, a WTW oxygenmeter (Model 330) for DO, and a YSI 30 SCT-meter for EC and salinity.

In this study, benthic macroinvertebrate communities in stream habitats were sampled using a standard kick-net with a mesh size of 500 µm and dimensions of 30 × 30 cm. At each sampling station, a total sampling duration of 3 min was applied as a standard procedure, incorporating subsamples from different microhabitats within the reach. During this period, the subsampling effort was adjusted to cover an area of approximately 1 m^2 per station. This approach provided a standardized basis for estimating the density of individuals per square meter. Organisms attached to stone surfaces or other substrates were collected manually using forceps. Sampling was done in lakes with the help of an Ekman-Birge Grab, and triplicate grab samples were taken from each locality. The abundance data have been standardized

Fig. 1 Map of the Aras river basin and the sampling localities

to individuals per m². Then the collected samples were fixed in a 4% formalin solution and sent to the laboratory for sorting and taxonomic studies. The samples were washed under tap water and then separated with the help of a binocular stereomicroscope (Olympus SZ61) in the laboratory. The sorted samples were examined under a microscope (Olympus CKX41) for taxonomic identification. The identification and taxonomic classification of the species recorded in this study were carried out using a wide range of regional and global taxonomic keys, species descriptions, and monographs. Sources numbered 14 to 46 include classical and recent taxonomic works that are widely accepted in marine and freshwater invertebrate taxonomy. These references provided essential morphological criteria, updated synonymies, and ecological notes to ensure accurate species determination [14–46].

Data analyses

The biological data obtained were analyzed using ASTERICS 3.3.1 (AQEM/STAR Ecological River Classification System; AQEM Consortium 2002) software. The indices used to determine the ecological status of the sampled habitats, to analyze the feeding types of the determined taxa, and the dominance and frequency values of the organisms are listed below;

a. Saprobic Index (SI) [47].
b. BMWP score (Biological Monitoring Working Group) [48].
c. ASPT (Average Score per Taxon) [49].

Table 1 Sampling stations, habitat types and geographic locations

Stat. No	Locality	Latitude longitude	City/District	Habitat type
1	Lake Çıldır	41° 00′01.30″N 43° 17′56.33″E	Ardahan	Littoral zone (muddy bottom) with rich macrophytes
2	Lake Balık	39° 49′40.69″N 43° 33′08.57″E	Ağrı	Littoral zone (stony, gravelly bottom) without macrophyte
3	Lake Aktaş	41° 11′22.06″N 43° 10′04.91″E	Ardahan	Littoral zone (stony, muddy bottom) with weak macrophytes
4	Lake Kuyucuk	40° 44′29.18″N 43° 26′57.52″E	Kars	Very shallow water, muddy bottom with rich macrophytes
5	Lake Aygır	40° 46′16.72″N 43° 01′21.54″E	Kars	Littoral zone (stony, gravelly bottom) with weak macrophytes
6	Lake Deniz	40° 06′23.65″N 42° 53′19.97″E	Kars	Littoral zone (stony, muddy bottom) with some macrophytes
7	Çot Stream	41° 11′50.86″N 42° 50′40.88″E	Ardahan	Rocky, stony bottom. Fast-flowing stream, without macrophyte
8	Aras River	40° 06′22.10″N 43° 29′09.28″E	Iğdır	Stony, muddy bottom. Slow-flowing turbid river, without macrophyte
9	Eğritaş Stream	39° 54′51.91″N 43° 36′24.88″E	Iğdır	Stony, sandy bottom, moderately flowing stream, with macrophytes
10	Karakoyunlu Stream	39° 58′48.29″N 44° 12′32.80″E	Iğdır	Sandy, muddy bottom. Slow-flowing stream, with rich macrophytes
11	Sarısu Stream	39° 26′52.08″N 44° 23′26.02″E	Ağrı	Sandy, muddy bottom. Slow-flowing turbid stream, with rich macrophytes
12	Aras River	40° 10′12.43″N 43° 10′16.86″E	Kars	Silty, gravelly bottom. Slow-flowing turbid stream, with weak macrophytes
13	Karasu Stream	39° 42′25.60″N 41° 51′25.74″E	Erzurum	Stony bottom. Slow-flowing stream, with no macrophyte
14	Ilıgöze Stream	39° 36′28.30″N 41° 35′10.32″E	Erzurum	Stony, sandy bottom. Moderately flowing stream, with rich macrophytes
15	Aras River	39° 50′21.23″N 41° 50′23.32″E	Erzurum	Stony, gravelly bottom. Fast-flowing stream, without macrophytes
16	Handere Stream	40° 07′37.42″N 42° 14′54.13″E	Kars	Stony, muddy bottom. Slow-flowing turbid stream, without macrophyte
17	Bozkuş Stream	40° 37′09.30″N 42° 47′07.76″E	Kars	Stony, gravelly bottom. Moderately flowing stream, without macrophytes

d. Diversity indices (Simpson, Shannon-Wiener, and Margalef) [50–52].
e. Dominance index [15] ($Di = Ni/Nt \times 100$ where Ni = number of individuals of species i; and Nt = total number of benthic macroinvertebrate specimens) [53].
f. Frequency index [17] ($F = m/M \times 100$ where m = number of stations where the species is found and M = total number of stations × total number of seasons) [54].

Before conducting inter-seasonal comparisons, the normality of data distribution was assessed separately for each seasonal group using the Shapiro-Wilk test. The results indicated that the data did not conform to a normal distribution ($p < 0.05$), thus necessitating the use of non-parametric statistical methods [55].

To evaluate whether there were statistically significant differences among the seasonal groups, a Kruskal-Wallis H test was performed. Upon identifying significant overall differences, Dunn's post-hoc test was subsequently applied to determine specific pairwise differences between seasons, using PAST software [56, 57].

Based on the taxa identified in the study, the Multivariate Statistical Package (MVSP) Program version 3.1 [58] was used to determine the percentage similarity of the sampled localities (UPGMA, Unweighted Pair Group Average).

TWINSPAN analysis was performed using the WinTWINS program (version 2.3). Cut-off levels were set as 0, 2, 5, 10, 20. The maximum number of division levels was 6; the minimum group size for the section was 5, and the maximum number of indicators per section was 7. The TWINSPAN dendrogram was drawn manually and the program analysis outputs were followed in the drawing [59].

Statistical analysis

A Detrended Correspondence Analysis (DCA) was performed to assess the gradient structure of the species data. The analysis revealed a maximum gradient length of 42.67, which far exceeded the 4.0 standard deviation threshold, confirming the unimodal response of species distributions and justifying the use of Canonical Correspondence Analysis (CCA) over linear methods such as Redundancy Analysis (RDA) [60]. To preserve the natural ecological gradients, raw species abundance and environmental data were analyzed without transformation. The CCA was carried out using only the physicochemical data obtained during the summer season, as data from other seasons were excluded due to data limitations. Forward selection was employed to identify the most influential environmental variables, and their statistical significance was tested using Monte Carlo permutation procedures (499 permutations under a reduced model). For clarity, a 20% species fit threshold was applied in the CCA biplot visualization. All analyses were conducted using CANOCO 5.0 software.

Results

A total of 7134 benthic macroinvertebrate individuals were sorted and examined. A total of 126 taxa were recorded, of which 107 were identified at the species level and 19 at the genus level. The taxonomic list, frequency, and dominancy values of the identified taxa are presented in Table 2.

Insecta was the most abundant class in terms of both individual density (2,577 ind./m²; 36%) and taxonomic richness (87 taxa; 69%), followed by Clitellata (2,293 ind./m²; 32%; 23 taxa; 18%) and Malacostraca (1,838 ind./m²; 26%). Mollusca accounted for 6% of the total taxa (8 taxa), while Turbellaria represented the least diverse class, with only a single species recorded (62 specimens) (Fig. 2).

Among insect groups, Diptera was the most diverse and abundant order, with 1,643 individuals/m² and 43 taxa, followed by Trichoptera (365 ind./m²; 19 taxa) and Ephemeroptera (337 ind./m²; 15 taxa) (Fig. 2). In contrast, Plecoptera was the least represented order within Insecta, with only a single specimen (*P. caucasica*) recorded (Table 2).

Regarding species dominance, *T. tubifex* exhibited the highest dominance value (15.87%) across the entire sampling period, followed by *C. riparius* (15.60%) and *G. balcanicus* (15.11%).

As shown in Fig. 3a, Station 9 recorded the highest taxon richness (21 taxa) and individual abundance (748 individuals), followed by Station 14 with 585 individuals. In contrast, as indicated in Fig. 3a, Stations 16 (1 taxon, 1 individual) and 8 (3 taxa, 4 individuals) displayed the lowest diversity and density values.

The data presented in Fig. 3b reveal that the highest biological diversity across all seasons occurred during this period. Station 9 (26 taxa) and Station 7 (19 taxa) had the greatest taxon richness, while Station 3 (689 individuals) and Station 9 (536 individuals) exhibited the highest individual densities. Some stations, such as Station 6 (3 taxa, 14 individuals) and Station 8 (5 taxa, 6 individuals), showed relatively low values during this season as well.

Findings presented in Fig. 3c indicate that the lowest biological activity was observed in this season. Station 9 maintained the highest taxon richness (11 taxa), while Stations 14 (426 individuals) and 10 (359 individuals) had the highest individual densities. Stations such as Station 12 (1 taxon, 2 individuals) and Station 7 (3 taxa, 4 individuals) exhibited very low values.

Sampling data on the seasonal distribution of benthic macroinvertebrate communities are visualized in Fig. 3, with statistical analyses confirming significant seasonal differences (Kruskal-Wallis test, $p < 0.05$). Pairwise Dunn's post-hoc tests reinforced the observed trends, revealing a distinct hierarchy: Autumn exhibited the highest taxon richness (91 taxa) and individual density (3,765 individuals), clearly surpassing other seasons, significantly surpassing summer ($Z = -3.42$, $p = 0.001$). Spring showed lower values (55 taxa, 1,173 individuals) than summer, though less pronounced ($Z = -2.11$, $p = 0.035$), with moderate densities at Station 14 (426 individuals). No autumn-spring difference emerged ($Z = 1.31$, $p = 0.189$), potentially due to sustained activity at stations like Station 9.

During the summer period (Fig. 4a), the dominance index (D) reached relatively high values across multiple stations, particularly at Stations 4, 15, and 16, indicating the prevalence of a few tolerant species within the macroinvertebrate communities. Shannon-Wiener diversity (H′) values remained moderate, with peaks observed at Stations 7, 9, and 13. Evenness (J′) values were mostly low to moderate, reflecting an uneven distribution of individuals among taxa. These findings suggest a community structure dominated by opportunistic and pollution-tolerant species, likely shaped by environmental stressors such as elevated water temperature and low dissolved oxygen levels.

Autumn (Fig. 4b) displayed the most balanced ecological conditions among the three seasons. Dominance values were generally lower, indicating reduced competitive exclusion and a more equitable community structure. Diversity (H′) reached its highest levels at Stations 7 and 9, where values exceeded 2.5, while evenness (J′) showed a relatively uniform distribution across stations, with most values between 0.6 and 1.0. This season also corresponded with increased taxon richness and abundance, reinforcing the notion of post-summer ecological recovery and optimal conditions for species coexistence.

Table 2 List of the identified benthic macroinvertebrate taxa with their frequency (F%) and dominancy (D%) values.

Class	Order	Taxa	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	F%	D%
Turbellaria	Tricladida	*Schmidtea polychroa* (Schmidt, 1861)	0	62	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.87
Clitellata	Tubificida	*Aulodrilus pluriseta* (Piguet,1906)	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	5.9	0.06
		Ilyodrilus templetoni (Southern, 1909)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.01
		Limnodrilus hoffmeisteri Claparède, 1862	33	0	0	0	21	5	1	0	41	85	0	2	20	7	25	90	1	70.6	4.64
		Limnodrilus udekemianus Claparède, 1862	0	4	2	0	0	14	0	0	0	6	0	0	0	0	8	0	1	35.3	0.49
		Limnodrilus claparedeianus Ratzel, 1868	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	5.9	0.01
		Ophidonais serpentina (Müller, 1774)	4	0	0	0	0	0	34	0	0	0	0	1	0	0	0	0	0	17.6	0.55
		Paranais frici Hrabě, 1941	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.06
		Potamothrix hammoniensis (Michaelsen, 1901)	0	2	71	0	39	0	0	0	0	0	0	0	0	0	0	0	0	17.6	1.57
		Potamothrix bedoti (Piguet,1913)	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.11
		Psammoryctides deserticola (Grimm, 1876)	0	0	0	0	0	0	0	0	149	0	0	0	0	0	0	0	0	5.9	2.09
		Rhyacodrilus coccineus (Vejdovský, 1875)	0	0	0	0	0	0	0	0	1	0	0	0	0	4	0	0	0	11.8	0.07
		Spirosperma ferox Eisen, 1879	0	3	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	11.8	0.13
		Stylaria lacustris (Linnaeus, 1767)	25	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	11.8	0.42
		Tubifex tubifex (Müller, 1774)	25	17	807	0	38	6	1	0	28	22	2	0	3	6	17	160	0	76.5	15.87
		Tubifex blanchardi Vejdovský, 1891	0	2	2	0	0	4	0	0	1	65	0	1	0	4	0	45	0	47.1	1.74
		Uncinais uncinata (Oersted, 1842)	12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.17
	Haplotaxida	*Haplotaxis gordioides* (Hartmann,1821)	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	5.9	0.01
	Lumbriculida	*Lumbriculus variegatus* (Müller, 1774)	0	0	0	0	0	0	0	0	27	0	0	0	0	0	0	0	0	5.9	0.38
	Arhynchobdellida	*Erpobdella octoculata* (Linnaeus, 1758)	56	5	0	0	14	0	57	0	18	4	0	0	0	17	0	7	1	52.9	2.51
		Dina lineata (O.F. Müller, 1774)	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	5.9	0.06
		Erpobdella vilnensis Lieskiewicz, 1925	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	5.9	0.11
		Helobdella stagnalis (Linnaeus, 1758)	16	2	0	0	5	0	52	0	2	0	0	0	0	0	0	0	0	29.4	1.08
	Rhynchobdellida	*Placobdella costata* (Fr. Muller, 1846)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.01
Insecta	Ephemeroptera	*Baetis muticus* (Linnaeus, 1758)	0	0	0	0	0	0	17	0	0	0	0	0	0	0	0	0	0	5.9	0.24
		Baetis fuscatus (Linnaeus, 1761)	0	0	0	0	0	0	4	0	0	0	0	7	0	0	0	0	0	11.8	0.15
		Baetis pavidus Grandi, 1951	0	0	0	0	0	0	8	0	0	0	0	0	15	0	0	0	15	17.6	0.53
		Baetis vardarensis Ikonomov, 1962	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	10	0	11.8	0.24
		Baetis vernus Leach, 1815	0	0	0	0	0	0	0	0	25	0	15	0	23	1	0	16	25	35.3	1.47
		Baetis rhodani Leach, 1815	0	0	0	0	0	0	0	0	23	0	0	0	0	4	0	0	0	11.8	0.38
		Baetis buceratus Eaton, 1870	0	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	5.9	0.20
		Caenis macrura Stephens, 1835	1	0	0	0	0	0	0	2	0	0	4	0	0	5	0	0	0	23.5	0.17
		Serratella ignita (Poda, 1761)	0	0	0	0	0	0	0	0	55	0	0	0	5	0	0	0	0	11.8	0.84
		Ecdyonurus lateralis Curtis, 1834	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5.9	0.01
		Electrogena sp. Curtis, 1834	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	5.9	0.06
		Rhithrogena iridina (Kolenati, 1839)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	5.9	0.03
		Isonychia ignota Walker,1853	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	5.9	0.06
		Oligoneuriella orontensis Koch, 1980	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	7	5.9	0.10
		Potamanthus luteus (Linnaeus, 1767)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	5.9	0.25

Table 2 (continued)

Class	Order	Taxa	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	F%	D%
	Trichoptera	*Agapetus delicatulus* McLachlan, 1884	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	5.9	0.04
		Agapetus sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	40	0	0	0	5.9	0.56
		Cheumatopsyche lepida (Pictet, 1834)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	5.9	0.07
		Diplectrona felix McLachlan, 1878	0	0	0	0	0	0	0	2	3	0	0	0	0	0	0	0	0	11.8	0.07
		Hydropsyche angustipennis (Curtis, 1834)	0	0	0	0	0	0	23	0	46	0	0	0	9	0	8	35	5	35.3	1.77
		Hydropsyche pellucidula (Curtis, 1834)	0	0	0	0	0	0	51	0	8	0	0	0	16	0	8	0	8	29.4	1.28
		Hydropsyche saxonica McLachlan, 1884	0	0	0	0	0	0	27	1	0	0	0	0	0	2	0	0	9	23.5	0.55
		Hydropsyche sp.	0	0	0	0	0	0	6	0	9	0	0	0	8	0	8	4	0	29.4	0.49
		Hydropsyche fulvipes (Curtis, 1834)	0	0	0	0	0	0	0	1	2	0	0	0	0	3	0	0	0	17.6	0.08
		Hydropsyche contubernalis McLachlan, 1865	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	11.8	0.03
		Hydropsyche instabilis (Curtis, 1834)	0	0	0	0	0	0	0	0	1	0	0	0	5	0	0	0	1	17.6	0.10
		Hydropsyche exocellata Dufour, 1841	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5.9	0.01
		Cyrnus trimaculatus (Curtis, 1834)	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.01
		Psychomyia pusilla (FABRICIUS, 1781)	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5.9	0.01
		Rhyacophila dorsalis (Curtis, 1834)	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	5.9	0.03
		Rhyacophila fasciata Hagen, 1859	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5.9	0.01
	Plecoptera	*Perla caucasica* Guérin-Méneville, 1838	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	5.9	0.01
	Odonata	*Calopteryx splendens* (Harris, 1780)	0	0	0	0	0	0	0	0	4	0	0	22	0	0	0	0	0	11.8	0.36
		Enallagma cyathigerum (Charpentier, 1840)	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	5.9	0.04
		Enallagma sp.	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	5.9	0.08
		Gomphus schneiderii Selys, 1850	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	11.8	0.04
		Libellula depressa Linnaeus, 1758	0	0	0	0	0	0	0	0	3	0	0	0	2	0	2	0	0	17.6	0.10
	Hemiptera	*Aphelocheirus aestivalis* (Fabricius, 1794)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	5.9	0.03
		Corixa dentipes Thomson 1869	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5.9	0.01
		Callicorixa raddei (Kiritshenko & Jaczewski, 1960)	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	5.9	0.03
		Sigara lateralis (Leach, 1817)	0	0	0	0	0	0	0	0	0	143	0	0	0	0	0	0	0	5.9	2.00
		Nepa cinerea L., 1758	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5.9	0.03
	Coleoptera	*Laccophilus hyalinus* (De Geer, 1774)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	5.9	0.03
		Stenelmis consobrina Dufour, 1835	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	5.9	0.01
		Enochrus bicolor (Fabricius, 1792)	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	5.9	0.03
		Noterus clavicornis (De Geer, 1774)	0	0	0	0	0	0	0	0	0	40	0	0	0	0	0	0	0	5.9	0.56
	Diptera	*Atherix* sp.	0	0	0	0	0	0	2	1	0	0	0	0	0	0	3	0	0	17.6	0.08
		Blephericera sp.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	11.8	0.03
		Chironomus riparius (Meigen, 1804)	0	36	0	300	0	8	2	0	0	499	0	0	2	0	0	265	1	47.1	15.60
		Chironomus plumosus (Linnaeus, 1758)	2	0	30	0	8	0	0	0	0	0	0	0	0	0	0	0	0	17.6	0.56
		Chironomus anthracinus Zettersted, 1860	0	0	0	0	7	8	0	0	0	12	0	2	0	0	0	0	0	23.5	0.41
		Chironomus tentans Fabricius, 1805	0	0	0	0	0	0	0	0	0	90	0	0	0	0	0	0	0	5.9	1.26
		Chironomus viridicollis van der Wulp, 1858	0	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	5.9	0.35
		Conchapelopia sp.	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	5.9	0.06

Table 2 (continued)

Class	Order	Taxa	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	F%	D%
		Cricotopus albiforceps (Kieffer, 1916)	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0	0	5.9	0.08
		Cricotopus tremulus (Linneaus, 1758)	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	5.9	0.10
		Cricotopus trifascia Edwards, 1929	0	0	0	0	0	0	10	0	0	0	0	2	0	0	0	0	0	11.8	0.17
		Cricotopus bicinctus (Meigen, 1818)	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	5.9	0.06
		Cricotopus triannulatus (Macquart, 1826)	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	5.9	0.21
		Cryptochironomus defectus (Kieffer, 1913)	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	11.8	0.06
		Cryptotendipes holsatus Lenz, 1959	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	5.9	0.01
		Eukiefferiella gracei (Edvards, 1929)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	5.9	0.03
		Eukiefferiella sp.	0	0	0	0	0	0	0	0	1	0	0	0	7	0	0	0	0	11.8	0.11
		Eukiefferiella ilkleyensis (Edwards, 1929)	0	0	0	0	0	0	0	0	0	0	0	0	0	31	0	0	0	5.9	0.43
		Eukiefferiella gracei (Edvards, 1929)	0	0	0	0	0	0	7	0	0	0	0	0	0	19	4	0	0	17.6	0.42
		Heleniella ornaticollis (Edwards, 1929)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	5.9	0.01
		Paracladopelma laminata (Kieffer, 1921)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	5.9	0.01
		Paratanytarsus lauterborni (Kieffer, 1909)	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	11.8	0.03
		Paratendipes albimanus (Meigen, 1818)	0	0	0	0	0	0	4	0	2	0	0	0	0	0	0	0	0	11.8	0.08
		Polypedilum scalaenum (Schrank, 1803)	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	1	11.8	0.11
		Polypedilum laetum (Meigen, 1818)	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	17.6	0.04
		Polypedilum albicorne (Meigen, 1838)	0	0	0	0	0	0	0	0	3	0	0	4	0	0	0	0	0	11.8	0.10
		Potthastia gaedii (Meigen, 1838)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	5.9	0.13
		Procladius sp.	9	0	0	0	1	12	0	1	0	0	0	0	2	0	0	0	0	29.4	0.35
		Psectrocladius sordidellus (Zetterstedt, 1838)	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.03
		Psectrocladius stratiotis Kieffer, 1908	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	5.9	0.01
		Rheopelopia sp.	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	11.8	0.06
		Stictochironomus yalvaci Şahin, 1991	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	29	0	5.9	0.41
		Tanytarsus gregarius Kieffer, 1909	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.9	0.01
		Dolichopus sp.	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	5.9	0.01
		Hemerodromia sp.	0	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0	11.8	0.06
		Scatella sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	5.9	0.06
		Eloeophila sp.	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	5.9	0.01
		Antocha sp.	0	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	5.9	0.10
		Eristalis sp.	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	5.9	0.21
		Tabanus sp.	0	0	0	0	0	0	0	0	23	0	2	0	7	20	12	6	0	35.3	0.98
		Tipula sp.	0	0	0	0	0	0	0	2	1	0	0	0	1	0	0	0	0	17.6	0.06
Malacostraca	Amphipoda	*Gammarus balcanicus* (Schäferna, 1922)	0	73	0	0	1	0	0	0	582	0	32	0	16	374	0	0	0	35.3	15.11
		Gammarus sp.	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	17.6	0.04
		Gammarus lacustris Sars, 1863	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	5.9	0.17
		Gammarus komareki Schäferna, 1922	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	5.9	0.11
		Gammarus kischineffensis Schellenberg, 1937	0	0	0	0	0	0	0	0	0	0	0	0	0	548	0	23	0	11.8	8.00
	Isopoda	*Asellus aquaticus* (Linnaeus, 1758)	0	16	0	0	2	0	0	0	5	0	0	0	0	142	0	0	0	23.5	2.31

Table 2 (continued)

Class	Order	Taxa	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	F%	D%
	Decapoda	*Potamon ibericum* (Bieberstein, 1809)	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	5.9	0.01
Gastropoda	Basommatophora	*Ancylus fluviatilis* Müller, 1774	0	1	0	0	0	0	15	0	9	0	0	0	0	0	0	0	0	17.6	0.35
		Radix labiata (Rossmässler, 1835)	6	0	0	21	0	0	0	0	3	0	0	0	1	0	13	2	0	35.3	0.64
		Galba truncatula (Müller, 1774)	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	11.8	0.04
		Physella acuta (Draparnaud, 1805)	0	0	0	0	0	0	0	0	0	24	0	0	0	0	0	0	0	5.9	0.34
		Gyraulus albus (Muller, 1774)	1	0	0	2	0	0	0	0	0	5	0	0	0	0	1	1	0	29.4	0.14
		Planorbis planorbis (Linnaeus, 1758)	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	5.9	0.35
	Stylommatophora	*Succinea elegans* Risso, 1826	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	11.8	0.03
Bivalvia	Veneroida	*Pisidium casertanum* (Poli, 1791)	0	36	0	0	0	0	0	0	165	0	0	0	0	28	0	0	0	17.6	3.21

In contrast, the spring period (Fig. 4c) exhibited the greatest variability in community structure. Dominance (D) was high at certain stations such as 4, 14, and 15, indicating the overrepresentation of a few taxa. Although some stations (e.g., 8, 9, 13) recorded elevated diversity (H′), overall values were lower than in autumn. Evenness (J′) peaked at Stations 7 to 9, suggesting localized habitat conditions that supported a more equitable distribution of individuals. These patterns reflect a transitional phase in community dynamics, potentially influenced by recruitment events or unstable environmental parameters following winter conditions.

Table 3 provides an overview of the benthic macroinvertebrate community structure at the 17 sampling stations, evaluated through several descriptive indices. These indices [dominance (D), Shannon-Wiener diversity (H′), Pielou's evenness (J′), and Margalef's species richness (R)] offer critical insights into the ecological condition and biodiversity status of each habitat.

Seasonal BMWP and ASPT scores of the sampling locations are presented in Fig. 5. The highest BMWP value (66) was observed at the 9th station in the autumn period. The highest ASPT value (6.125) was at the 13th station in the summer period.

The UPGMA dendrogram (Fig. 6) illustrates the taxonomic similarity among sampling stations based on benthic macroinvertebrate composition. The horizontal axis represents percent similarity, where closer linkages indicate greater resemblance in community structure among stations.

The highest degree of similarity (~ 50%) was observed between stations 4 and 16, indicating a strong overlap in their benthic macroinvertebrate assemblages. This close relationship may be attributed to shared habitat features, such as slow-flowing or lentic conditions, rich aquatic macrophyte cover, and high organic matter content. These sites were dominated by pollution-tolerant oligochaete species, particularly *T. tubifex* and *L. hoffmeisteri*, which are indicators of organic enrichment.

Station 10 clustered closely with stations 4 and 16, suggesting similar environmental conditions despite being sampled from a lotic habitat near a lake shore. Its grouping with lentic stations implies comparable ecological characteristics, such as low flow velocity and soft sediment substrate, which support similar macroinvertebrate communities.

Station 3, although somewhat more distinct, also falls within this cluster and was similarly dominated by *T. tubifex*. This pattern reinforces the role of organic pollution-tolerant taxa in shaping the community structure at these sites.

In contrast, stations 8 and 12 exhibited the lowest similarity to all other stations. The absence of oligochaetes at these sites significantly differentiates their community

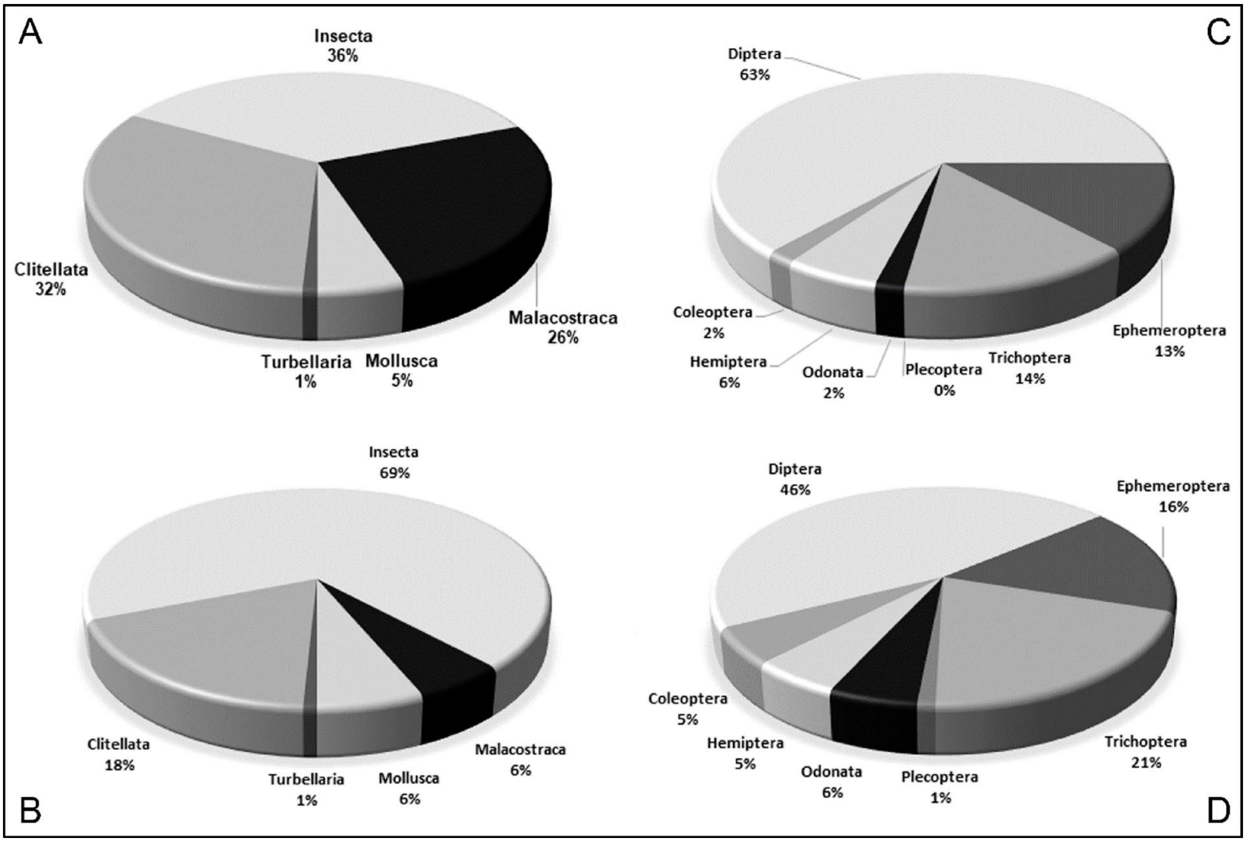

Fig. 2 Identified benthic macroinvertebrate classes and their rational distributions (**A**: number of taxa; **B**: number of individuals) and rational distribution of the class Insecta (**C**: number of taxa; **D**: number of individuals)

composition, likely reflecting better water quality, different habitat structure (e.g., rocky substrate, faster flow), or other limiting factors for oligochaete colonization.

The TWINSPAN (Two-Way Indicator Species Analysis) dendrogram presented in Fig. 7 classifies the studied localities based on similarities in species composition. At the top level, the dendrogram divides the dataset into two major groups (marked as 0* and 1*), each characterized by different assemblages of aquatic insect species.

Group 0. Dominated by *B. vernus*, *H. angustipennis*, *H. pellucidula*, and *H. saxonica.* This group represents a cluster of localities characterized by the presence of several species indicative of a particular ecological condition. It is further subdivided into subgroups.

Group 1 is notably defined by the presence of *C. anthracinus*, which is marked as an indicator species, reflecting its diagnostic importance for this assemblage. The dendrogram indicates a significant separation from Group 0 (Eigenvalue = 0.483), suggesting distinct environmental or ecological conditions.

In the summer dataset, the CCA revealed four constrained axes, collectively explaining 33.6% of the total species variance (cumulative percentage variance of species data) and 93.4% of the species-environment relationship. Marginal effects analysis identified dissolved oxygen (D.O.; λ_1= 0.89) and pH (λ_1 = 0.85) as the most influential variables, jointly explaining ~ 17.4% of species variance. Conditional effects confirmed their independent significance (D.O.: λ_a= 0.89, $p = 0.004$; pH: λ_a = 0.81, $p = 0.018$), while temperature, salinity, and conductivity showed no significant conditional effects ($p > 0.05$).

D.O. and pH vectors aligned closely with Axis 1, indicating their dominant role in structuring benthic invertebrate communities. Species such as *Noteclav* and *Enallagm* clustered near these vectors, suggesting preferences for high-oxygen, neutral-pH habitats. Secondary variables (e.g., temperature, salinity) exhibited shorter vectors, reflecting weaker or indirect effects, likely mediated by correlations with primary drivers.

The biplot reveals that *Baetrhod*, located in the lower-right quadrant, is positively associated with high dissolved oxygen levels. Conversely, eight species (*Chirripa*, *Limnudek*, *Limnhoff*, *Gyraalbu*, *Tubiblan*, *Physacut*, *Enallagm*, and *Noteclav*) clustered in the upper-left quadrant prefer habitats with elevated water temperatures and lower dissolved oxygen concentrations.

In the upper-right quadrant, salinity and electrical conductivity positively correlate with the distribution of species in this region. Meanwhile, four species (*Gammarus*, *Paraalbi*, *Hydropsy*, and *Hydrangu*) in the lower-left

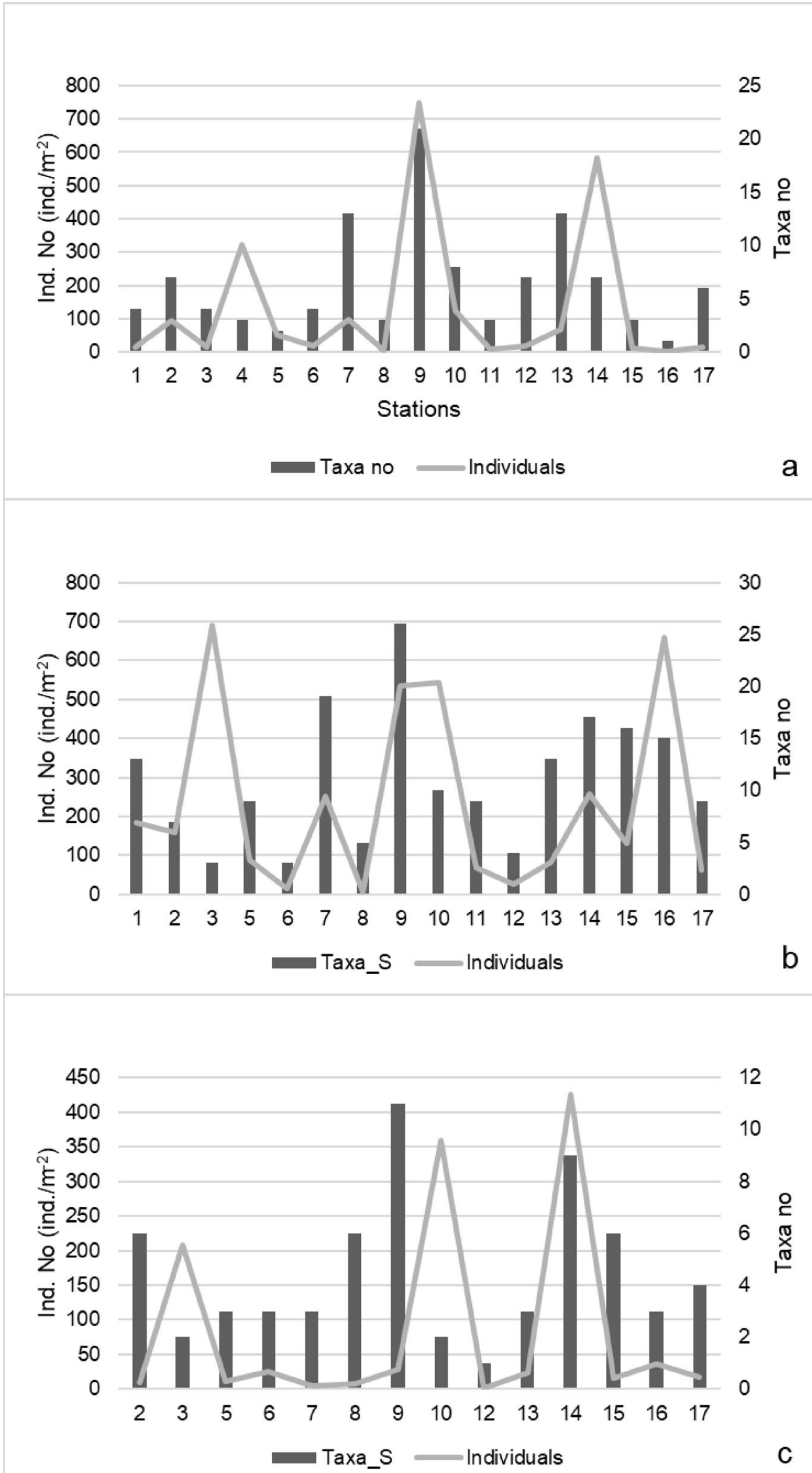

Fig. 3 Seasonal distribution of the taxa and individual numbers of the benthic macroinvertebrates (**a**: Summer; **b**: Autumn; **c**: Spring)

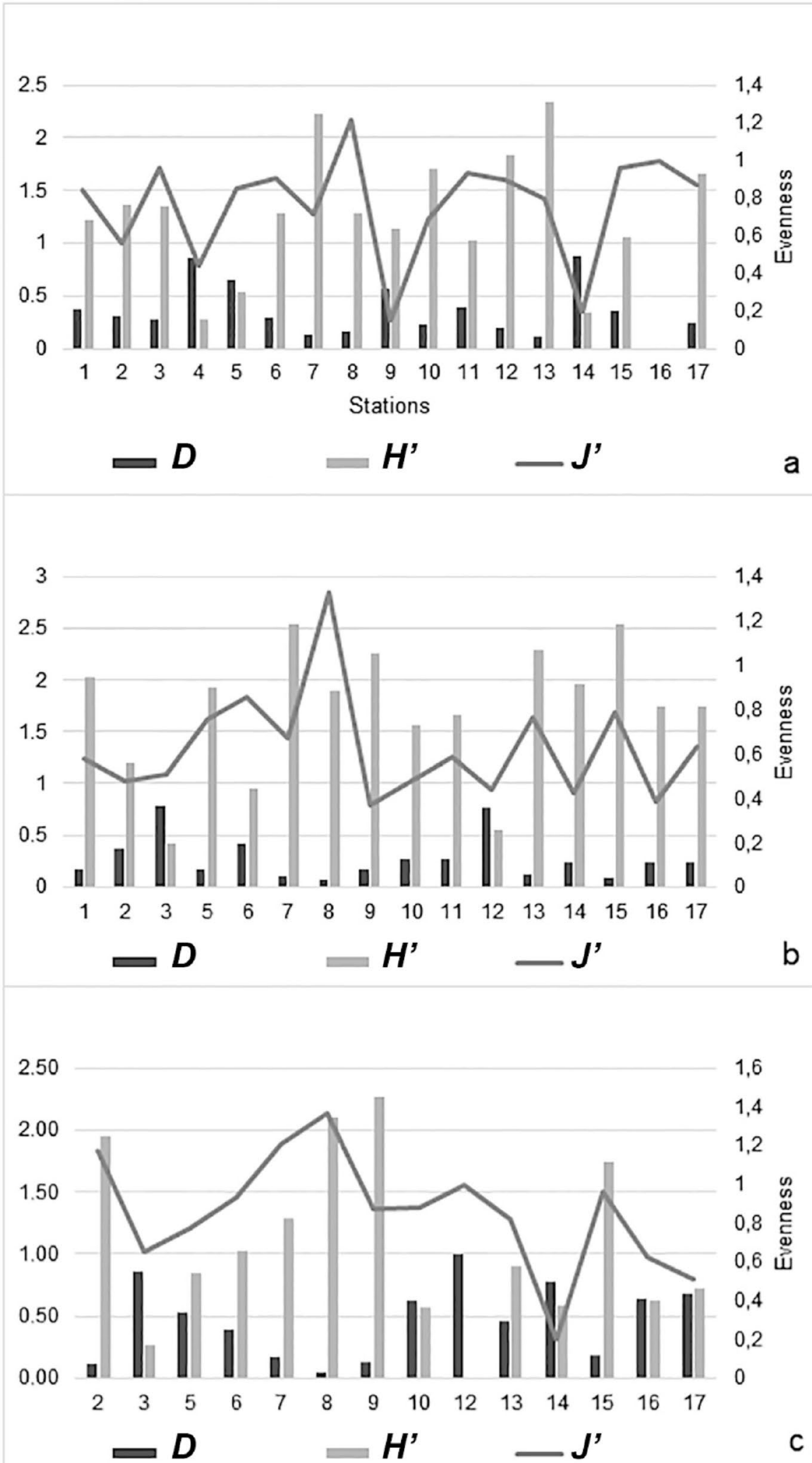

Fig. 4 Seasonal values of dominancy (D), Shannon-Wiener diversity (*H'*), and Pielou's Evenness (*J'*) of the stations (**a**: Summer; **b**: Autumn; **c**: Spring)

Table 3 Descriptive data and diversity values of the stations (D: dominancy; *H'*: Shannon-Wiener diversity; *J'*: pielou's evenness; R: margalef's species richness) (highest values indicated in bold character)

	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
Taxa	17	18	5	3	12	8	27	14	**42**	14	10	11	24	24	23	17	18
Individuals	200	264	912	323	149	58	354	17	**1312**	1026	78	45	174	1269	160	697	96
D	0.147	0.175	0.790	**0.867**	0.167	0.148	0.090	0.022	0.232	0.277	0.236	0.265	0.070	0.288	0.072	0.223	0.129
H'	2.230	2.045	0.448	0.281	2.045	1.976	2.742	**2.971**	2.201	1.773	1.785	1.857	2.859	1.675	2.850	1.879	2.394
J'	0.547	0.429	0.313	0.441	0.644	0.902	0.575	**1.394**	0.215	0.421	0.596	0.583	0.727	0.222	0.752	0.385	0.609
R	3.020	3.049	0.587	0.346	2.198	1.724	4.430	4.588	**5.711**	1.875	2.066	2.627	4.458	3.219	4.335	2.444	3.725

quadrant are associated with higher pH levels, indicating a preference for alkaline waters.

The study area comprised nine lentic systems (Stations 1–6, 8, 12, 16) and eight lotic systems (Stations 7, 9–11, 13–15, 17), each characterized by distinct substrate compositions (see Table 1). Key findings obtained from the study are summarized below:

- Macrophyte-rich lentic stations (1, 3–6) showed 38% higher oligochaete abundance ($p < 0.05$),
- Fast-flowing streams with stony substrates (7, 9, 15, 17) supported 22 Ephemeroptera-Plecoptera-Trichoptera (EPT) taxa,
- Turbid, slow-flowing rivers (8, 12, 16) exhibited 62% lower diversity than clear-water counterparts.
- Pollution-tolerant Tubificidae dominated macrophyte-rich lentic stations (1, 3, 5, 6) with densities reaching 1,842 ind./m^2.
- *G. balcanicus* showed exclusive preference for fast-flowing, well-oxygenated streams (Stations 9, 15; $\rho = 0.81$).
- Sensitive Plecoptera species were restricted to high-altitude streams (Stations 7, 17; >1,800 m elevation).
- Station 9 maintained stable BMWP scores across seasons (64–66), while agricultural-impacted stations (4, 6) showed 55% seasonal fluctuations.

Discussion

The primary impact of organic pollution in lotic and lentic ecosystems is reflected in the alteration of community structure. Changes in environmental conditions, particularly the accumulation of organic matter on substrates due to waste input, promote the proliferation of pollution-tolerant taxa. This results in a decline in overall species diversity, as dominant species outcompete and suppress others [61].

Within the Naididae family, the subfamily Tubificinae, which was found to be dominant in this study, originates from the northern temperate zone despite its current cosmopolitan distribution [62]. The most prevalent species, *T. tubifex*, is known to occur in habitats of marginal water quality, such as pristine alpine and subalpine lakes, oligotrophic lake beds, and severely polluted, organically enriched waters with low oxygen levels [63, 64]. *T. tubifex* was recorded in nearly all surveyed habitats (6 lentic and 11 lotic). Notably, in highly polluted sites, *T. tubifex* frequently co-occurs with *L. hoffmeisteri*. These species often dominate the oligochaete community and may represent the sole or primary benthic invertebrates present [64]. Arslan and Mercan [12] similarly reported co-occurrence of these species in Lake Çıldır, suggesting a shift from oligotrophic to mesotrophic conditions. Their increased dominance in lentic habitats (stations 1, 3, 5, and 6) supports these findings. Indeed, oligochaetes and

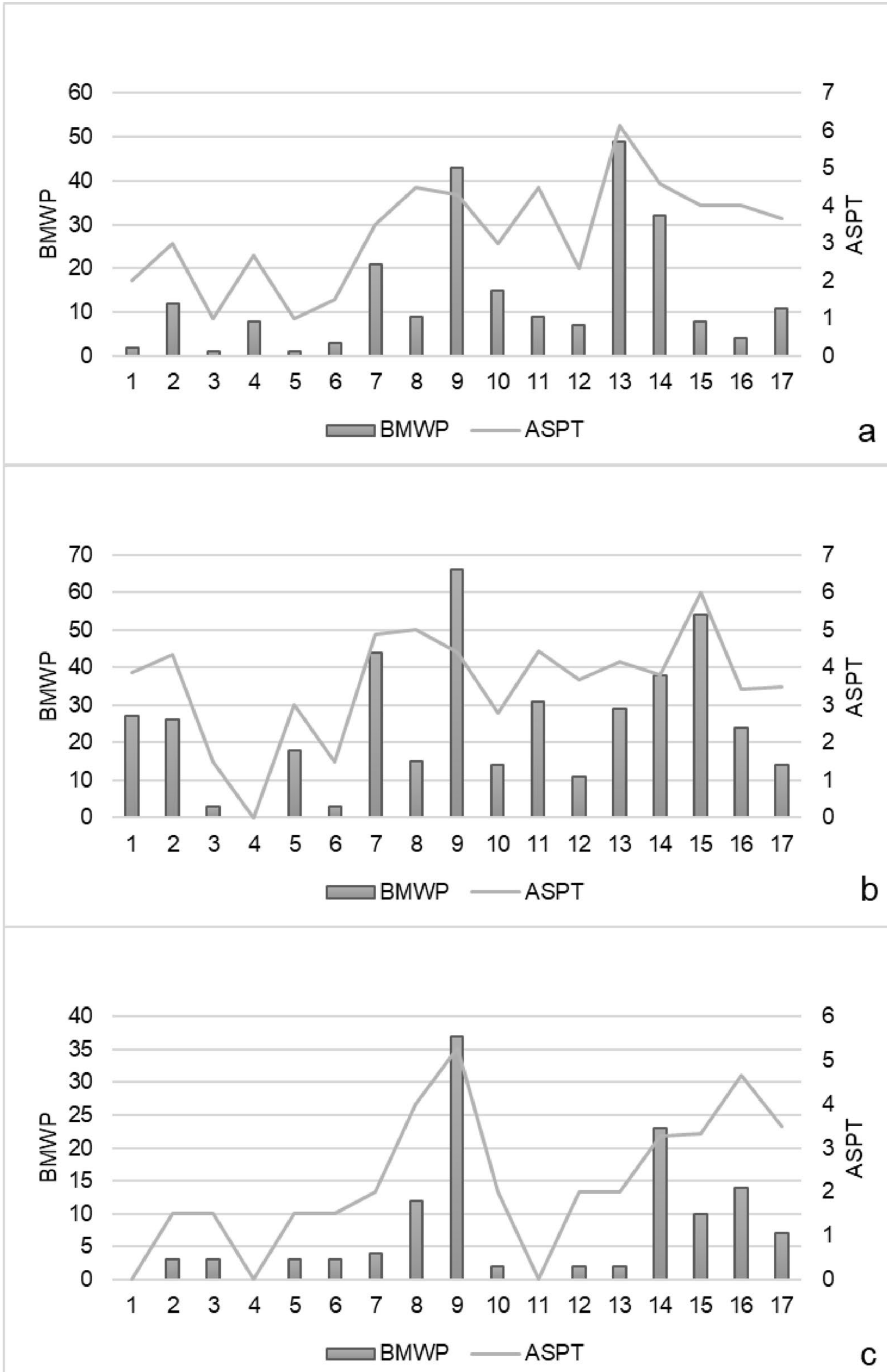

Fig. 5 Seasonal BMWP and ASPT scores of the stations (**a**: Summer; **b**: Autumn; **c**: Spring) [(BMWP Score: 0–25: Very Bad/Bad; 26–50: Moderate; 51–100: Good; >100: Very Good) (ASPT Score: <4: Moderate/Bad; 4–5: Good; >5: Very Good)]

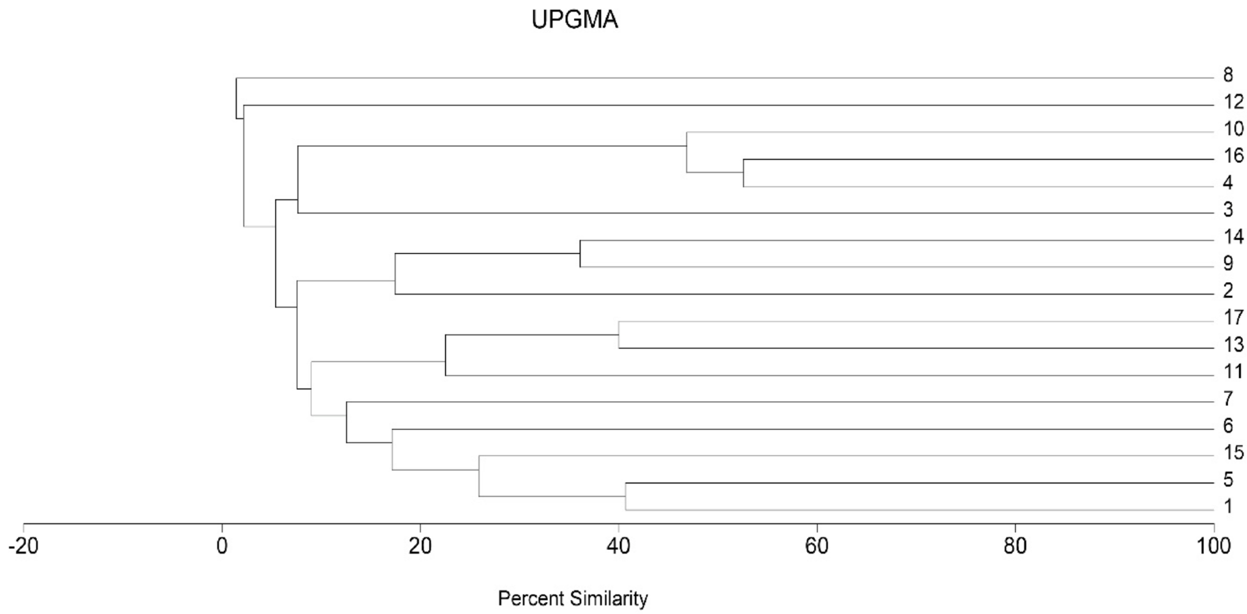

Fig. 6 The similarity diagram, based on the benthic macroinvertebrate data, of the stations

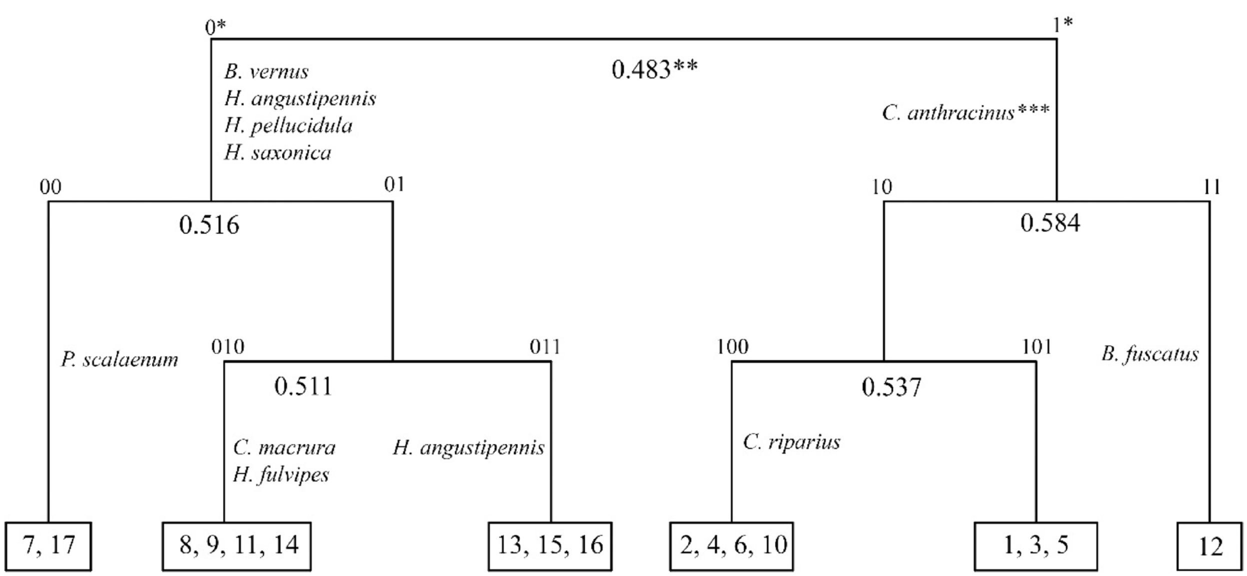

Fig. 7 TWINSPAN dendrogram of the studied localities (*: TWINSPAN groups; **: eigenvalue; ***: indicator species)

chironomid larvae composed the majority of macrozoobenthos in these lakes, consistent with prior observations [12].

Species of the genus *Chironomus* are commonly utilized in bioindication studies due to their pollution tolerance [61, 65]. In this study, 30 chironomid taxa were identified, spanning four subfamilies: Chironominae, Tanypodinae, Diamesinae, and Orthocladiinae. A significant proportion (15 taxa) were found in stagnant waters. Tolerant species such as *C. riparius*, *C. anthracinus*, *C. plumosus*, and *C. viridicollis* are frequently associated with eutrophic lakes [66, 67]. *C. plumosus*, in particular, is known to inhabit mesotrophic and eutrophic littoral zones and is capable of enduring prolonged anoxic conditions [68, 69].

The presence of pollution-tolerant chironomids and procladiid species in Lakes Çıldır, Aktaş, and Aygır indicates the influence of both organic and inorganic pollution. These findings corroborate earlier reports of a trophic shift toward mesotrophy in Çıldır and Aygır Lakes, likely driven by nearby agricultural practices and domestic waste discharge [13].

Among the identified Trichoptera, *D. felix*, *R. dorsalis*, and *H. instabilis* were categorized as highly sensitive to

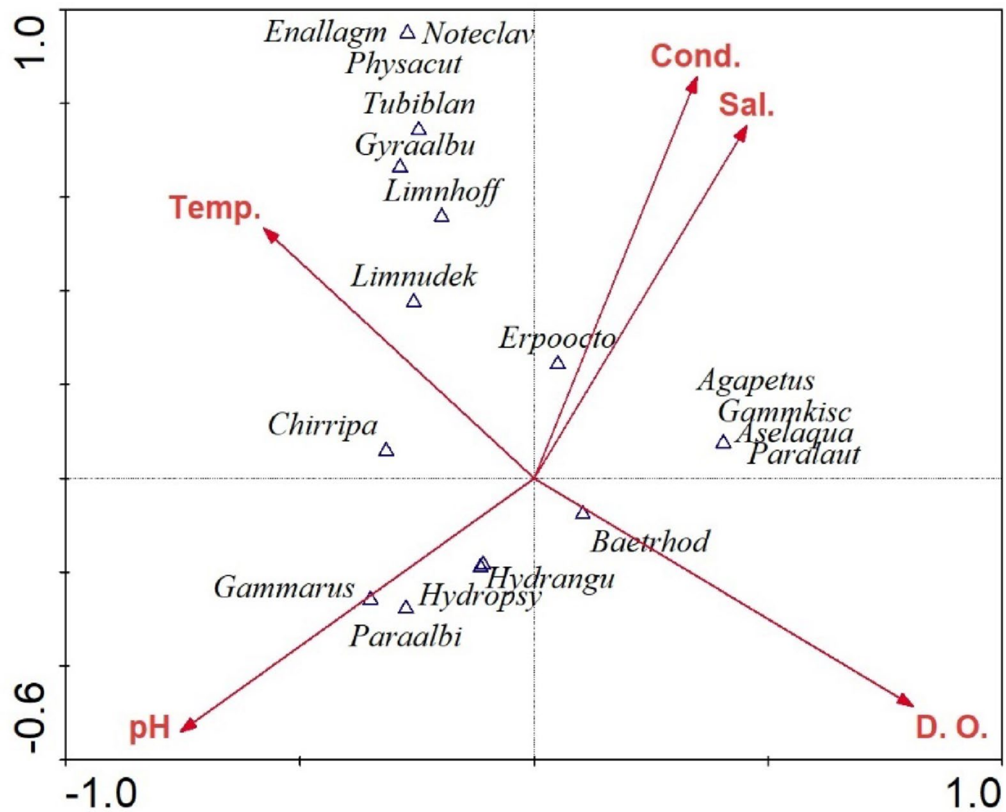

Fig. 8 The CCA Biplot showing the relationship between species and environmental variables (see Table 1 for the codes of the species) in the summer period

organic pollution. Moderately sensitive taxa included *H. pellucidula*, *H. saxonica*, and *C. lepida*, while tolerant species comprised *H. contubernalis*, *H. fulvipes*, and *H. angustipennis*. *H. exocellata* was classified as highly tolerant [68]. *H. angustipennis* exhibits a broad ecological distribution and tolerates temperatures up to 20 °C [70, 71]. It was dominant at station 16 in spring 2015. Notably, *R. dorsalis*, absent in earlier samplings, became dominant in spring 2015, suggesting seasonal variability.

The low number of Plecoptera taxa was expected, as this order includes species that are highly sensitive to pollution and generally serve as indicators of clean and well-oxygenated aquatic environments. As pollution increases, their numbers, and species diversity decrease [72–74].

Leeches were common in stagnant or slow-flowing macrophyte-rich waters, consistent with their preference for organically enriched environments [75, 76]. *E. octoculata* and *H. stagnalis* were detected in both lotic and lentic habitats. These species are typically found in alpha- to polysaprobic waters, indicating a tolerance to varying degrees of organic pollution [77].

Malacostraca were represented by a decapod (*P. ibericum*), an isopod (*A. aquaticus*), and five amphipod taxa. Among these, *G. balcanicus* exhibited the highest dominance value (15.1), suggesting a preference for clean, fast-flowing mountain streams [22]. Other amphipods, including *G. lacustris* and *G. komareki*, favored moderate pollution conditions, whereas *A. aquaticus* was primarily found in highly polluted waters [78].

A. aestivalis, a benthic hemipteran identified in this study, prefers oligotrophic waters with stony or sandy substrates [79].

Among gastropods, *A. fluviatilis* served as a clean water indicator [80], while *P. acuta*, a pollution-tolerant species, was widespread. *R. labiata* and *G. albus* were the most frequently encountered species. The only bivalve recorded, *P. casertanum*, has a cosmopolitan distribution and was found in various freshwater habitats across three stations [81].

The observed patterns in the distribution of the taxa and individual numbers (Fig. 3) underscore the seasonal dynamism of benthic macroinvertebrate communities, which are sensitive to abiotic and biotic fluctuations. The prominence of spring assemblages highlights its role as a critical period for ecosystem productivity and recruitment. Conversely, the summer decline may signal vulnerability to climate-driven stressors, emphasizing the need for targeted habitat protection during thermally stressful periods.

Descriptive ecological metrics revealed generally lower values in lentic compared to lotic habitats. An exception was station 4, a shallow wetland with abundant vegetation, which recorded the highest dominance index. Station 8 exhibited the highest Shannon-Wiener diversity and evenness, while station 9 had the greatest taxonomic richness, abundance, and Margalef's index. Station 9 also had high BMWP and ASPT scores across all seasons (Fig. 5), and field observations confirmed its pristine conditions, minimal anthropogenic disturbance, rich vegetation, and a suitable substrate and flow regime for benthic fauna.

The UPGMA diagram (Fig. 6), clearly reveals patterns of ecological similarity among sampling sites, shaped largely by environmental conditions and anthropogenic impacts. Stations clustered together shared dominant taxa and similar habitat characteristics, particularly in relation to organic enrichment. Conversely, sites with unique environmental parameters or minimal anthropogenic influence exhibited distinct macroinvertebrate assemblages.

The seasonal assessment of water quality across the 17 sampling stations revealed significant variations in BMWP (Biological Monitoring Working Party) and ASPT (Average Score Per Taxon) scores, reflecting the influence of seasonal and site-specific factors on benthic macroinvertebrate communities. Seasonal Trends in Water Quality: Autumn 2014 exhibited the highest overall water quality, with Station 9 achieving the highest BMWP score (66, "Good"), indicating a diverse and pollution-sensitive macroinvertebrate community. This aligns with the higher ASPT values (e.g., Station 15: 6.0, "Excellent"), which suggest favorable ecological conditions. Summer 2014 showed intermediate conditions, with Station 13 recording the highest ASPT (6.125, "Excellent"), though BMWP scores (e.g., Station 13: 49, "Moderate") indicated limited taxonomic richness. This discrepancy may stem from the dominance of a few high-scoring taxa. Spring 2015 demonstrated the poorest water quality, with most stations classified as "Poor" (BMWP < 25). Station 9, despite a moderate BMWP (37), had the highest ASPT (5.286, "Excellent"), suggesting localized resilience or sampling artifacts. Spatial Variability: Station 9 consistently outperformed others across seasons (BMWP: 37–66; ASPT: 4.3–5.286), likely due to habitat stability or lower anthropogenic pressure. Stations 1, 3, 4, and 6 repeatedly scored "Poor" in all seasons (BMWP ≤ 12), implicating chronic pollution or degraded habitats.

The TWINSPAN dendrogram reveals clear ecological differentiation among the sampled localities (Fig. 7). Key indicator species such as *C. anthracinus*, *P. scalaenum*, and *B. fuscatus* serve to define the boundaries between major ecological groups. The presence of high eigenvalues at several nodes supports the validity of these divisions and underscores significant variation in community composition. These findings provide valuable insights into species-habitat relationships and may guide future ecological assessments or conservation strategies.

The Canonical Correspondence Analysis (CCA) conducted in this study identified dissolved oxygen (DO) and pH as the primary environmental determinants shaping benthic macroinvertebrate community structure during the summer period. The findings emphasize the dominant role of DO in driving species distribution, particularly supporting the strong association between indicator species such as *B. rhodani* (*Baetrhod*) and well-oxygenated habitats [82]. Similarly, the significant influence of pH aligns with the observed preference of species like *Gammarus* and *Hydropsy* for alkaline environments. In contrast, the clustering of *Enallagma* sp. (*Enallagm*) and *C. riparius* (*Chirripa*) in low-DO, high-temperature zones suggests that these taxa are adapted to eutrophic or organically enriched conditions [83]. These outcomes highlight the necessity of incorporating DO and pH as critical parameters in freshwater bioassessment programs across Turkish aquatic ecosystems. Moreover, the non-significant statistical contributions of salinity and conductivity suggest that their ecological influence may vary depending on regional hydrological or geological context. Finally, the presence of pollution-tolerant taxa is proposed as an effective early-warning indicator of water quality degradation.

Conclusion

This study highlights the significant impact of organic and inorganic pollution on benthic macroinvertebrate communities in the Aras River Basin, as reflected by shifts in taxonomic composition, dominance of pollution-tolerant species, and declining ecological quality. The prevalence of Tubificinae oligochaetes (*T. tubifex*, *L. hoffmeisteri*) and chironomids (*C. riparius*, *C. plumosus*) in lentic habitats underscores their utility as bioindicators of eutrophication and organic enrichment, consistent with documented trophic shifts in Lakes Çıldır and Aygır. Conversely, the scarcity of sensitive taxa (e.g., Plecoptera) and the dominance of pollution-adapted species (e.g., *A. aquaticus*, *P. acuta*) in degraded sites emphasize the vulnerability of these ecosystems to anthropogenic pressures.

Seasonal dynamics further revealed autumn as the most ecologically productive period, with the highest diversity and BMWP scores, while spring exhibited the poorest water quality, likely due to cumulative stressors. Spatial variability was pronounced, with Station 9 emerging as a reference site due to its pristine conditions, high biodiversity, and resilience across seasons. In contrast, chronically polluted stations (e.g., 1, 3, 4, 6) consistently scored poorly, reflecting habitat degradation.

Multivariate analyses (UPGMA, TWINSPAN) corroborated these patterns, clustering sites by shared environmental conditions and highlighting the role of organic pollution in structuring communities. The ecological gradients identified—ranging from clean, high-flow habitats (e.g., Station 9) to organically enriched lentic systems—underscore the need for targeted conservation measures, particularly in areas affected by agriculture and wastewater discharge.

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Author contributions
M. Özbek: Field studies, identification of organisms, biological index and analysis, writing and editing of the article, drawing the map. A. Tasdemir: Field studies, identification of organisms, writing the manuscript. S. Yildiz: Field studies, identification of organisms, writing the manuscript. E. T. Topkara: Field studies, identification of organisms, writing the manuscript. E. Aydemir Cil: Identification of the organisms, writing the manuscript.

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Data availability
Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

Declarations

Ethical approval and consent to participate
Necessary and appropriate permissions or licenses were obtained.

Consent for publication
Not Applicable.

Competing interests
The authors declare no competing interests.

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