water

MDPI

Article

Environmental Drivers of Macrozoobenthos Structure Along a Discontinuous Tributary of the Oder River (North-Western Poland)

Nadhira Benhadji [1], Jarosław Dąbrowski [1,*], Adam Brysiewicz [1], Przemysław Czerniejewski [2] and Łukasz Hałasa [1]

[1] Institute of Technology and Life Sciences-National Research Institute, Falenty, 3 Hrabska Avenue, 05-090 Raszyn, Poland; n.benhadji@itp.edu.pl (N.B.); a.brysiewicz@itp.edu.pl (A.B.); l.halasa@o2.pl (Ł.H.)
[2] Department of Commodity, Quality Assessment, Process Engineering and Human Nutrition West Pomeranian University of Technology in Szczecin, Kazimierza Królewicza 4 Street, 71-550 Szczecin, Poland; przemyslaw.czerniejewski@zut.edu.pl
* Correspondence: j.dabrowski@itp.edu.pl

Abstract

The Myśla River, a right-bank tributary of the Oder catchment, was the focus of our study on the impact of environmental parameters on macrozoobenthos diversity and composition. We surveyed 18 sites along the Myśla catchment, from upstream to the outlet, recording environmental features and sampling macrozoobenthos. The taxa composition (31 taxa) was dominated by insect larvae, particularly Diptera Chironomidae, with moderate contributions from mollusc families such as Sphaeriidae, Bithyniidae, and Planorbidae, which are primarily filter-feeders or grazers. Based on environmental affinities, the river was divided into three sections. Sites within lake areas and those with diverse sediment types exhibited the highest biodiversity. Conductivity, flow rate, nitrogen compound levels, dissolved oxygen, suspended particles, and current velocity most strongly influenced biodiversity, while substrate type shaped taxa composition. Lakes heavily disrupt the ecological continuity of the Myśla River, significantly altering natural ecological processes and causing deviations from the River Continuum Concept (RCC), whereas artificial structures exert only minor additional influence. We examined the applicability of the RCC by analyzing macrozoobenthos structure along the upstream-to-downstream gradient. This preliminary study contributes to ongoing regional research, highlighting the role of lakes in shaping the Myśla River ecosystem and assessing the relevance of RCC in unique river systems.

Keywords: macrozoobenthos; biodiversity; distribution; fluvial discontinuum; Myśla River

check for updates

Academic Editor: Haibo Wang

Received: 15 September 2025
Revised: 16 October 2025
Accepted: 17 October 2025
Published: 19 October 2025

Citation: Benhadji, N.; Dąbrowski, J.; Brysiewicz, A.; Czerniejewski, P.; Hałasa, Ł. Environmental Drivers of Macrozoobenthos Structure Along a Discontinuous Tributary of the Oder River (North-Western Poland). *Water* **2025**, *17*, 3005. https://doi.org/10.3390/w17203005

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Rivers and their basins represent some of the largest freshwater ecosystems on Earth [1]. River ecosystems are significant biodiversity hotspots [2] and provide numerous ecosystem services [3]. Ferreira et al. [4] identified 27 ecosystem services provided by small rivers, including the provision of drinking water, maintenance of primary production, fertilization of riparian zones, supply of renewable energy, and various recreational, cultural, and other services. However, the transformation of natural ecosystems to meet human needs has led to species loss and habitat disruption, ultimately reducing biodiversity, species richness, and the biomass of organisms in rivers [5,6].

According to Ding et al. [7], anthropogenic pressures particularly affect the richness and composition of macrozoobenthos communities, highlighting the importance of monitoring these organisms as indications of environmental changes and river health [8]. Therefore, macrozoobenthos are often considered as bioindicators of water quality [9]. This bioindication property stems from their specific environmental requirements, benthic lifestyle, and limited mobility, making them more susceptible to changes than other aquatic organisms. In Europe, macrozoobenthos is used by regulatory agencies to assess the ecological status of water bodies under the guidelines of the Water Framework Directive (WFD) [10]. Additionally, macrozoobenthos are an important link in the food chain, serving as a major dietary component for fish and other predators [11]. Some taxa, such as grazers, feed on plankton and bacteria at the base of the food chain, playing a key role in energy and nutrient flow [12]. Moreover, macrozoobenthos can regulate primary production and organic matter decomposition, affecting water clarity, thermal stratification (via e.g., bioturbation and respiration), and nutrient cycling within aquatic ecosystems [11].

The diversity and structure of macrozoobenthos respond to variations in physical and chemical water parameters (e.g., dissolved O_2 content, temperature, nutrient concentrations), hydrological conditions (e.g., flow rate and discharge), turbidity, and sediment content [13]. For instance, increased nutrient levels, mainly nitrogen (N) and phosphorus (P), create environmental stress for invertebrate communities, leading to declines in sensitive species [14]. Furthermore, suspended sediments and their deposition on the riverbed reduce habitat heterogeneity and negatively impact invertebrate respiration, primarily by clogging interstitial spaces that restrict water flow [15,16]. In contrast, a stable riverbed, heterogeneous substrate, and low compactness promote greater macroinvertebrate diversity [17].

In rivers free from anthropogenic pressures, the distribution and biodiversity of macrozoobenthos undergo only natural temporal and spatial changes [18]. These changes are associated with organism life cycles and seasonal variations in habitat conditions [19]. The gradient of physical conditions along watercourses, from upstream to downstream, triggers responses from biological communities [20]. Traditionally, the spatial and temporal dynamics of macrozoobenthos communities along a river are explained by the River Continuum Concept (RCC) [21]. This concept describes structural and functional changes in zoobenthos communities due to shifting environmental conditions from river's source to its outlet. The RCC predicts a continuous gradient of physical conditions, mainly associated with stream size (e.g., width, flow), which affect food resource availability and, in turn, the functional feeding groups of macroinvertebrate communities.

While longitudinal continuity is essential in river networks [22], discontinuity also plays a significant role [23]. This river 'discontinuum' can result from human activities, such as dam construction, or natural disturbances, including tributaries and lakes [24]. Such modifications, particularly dams, impact geomorphology, hydrology, and water quality [25], disrupting river connectivity, altering sediment transport, and changing habitat heterogeneity, ultimately affecting species composition and biodiversity [26]. Natural barriers along rivers can similarly disrupt the composition and structure of aquatic communities. Understanding how environmental variables influence biodiversity and community structure is therefore critical for developing accurate bioassessment tools, especially in rivers characterized by a discontinuum.

Several indices are used in Poland and the EU to assess the ecological status of rivers [27]; however, this study focused exclusively on community structure metrics of macrozoobenthos to investigate the River Continuum Concept.

The aim of this study is to describe the biodiversity and distribution of macrozoobenthos in diverse habitats within a discontinuous tributary of the Oder River, the Myśla River,

including an assessment of bottom sediment granulometry and its role in shaping the biodiversity of this environment.

2. Materials and Methods

2.1. Study Site

Environmental conditions of macrozoobenthos habitats were investigated over a 12-month period (March 2022 to March 2023) to ensure representative mean values. Macrozoobenthos specimens were collected in April 2022, considered the optimal sampling period before insect emergence (May–June) [28]. This timing is preferable to autumn (September–October), as insect larvae hatched in July are often too small to be retained by the sieve mesh [28].

The study area corresponds to the Myśla River, a right-bank tributary of the Oder River in northwestern Poland (GPS coordinates: river source 52°58′25.3″ N 15°06′07.2″ E; confluence with the Oder 52°39′37″ N 14°28′15″ E). The Myśla River is approximately 95.6 km long, with a catchment area of 1334 km^2. The study was conducted at 18 sites along the river (Figure 1), selected for their accessibility, position relative to the lakes, and habitat diversity. The river flows through several protected areas: the upper reaches traverse the lake-rich Myśliborsko-Barlineckie Lake District, the middle reaches pass through the Gorzowska Upland Protected Landscape Area, and the lower reaches lie within the Warta Mouth Landscape Park.

Site	Coordinates	Part
Mys_1	53°00'26.9"N 15°04'44.2"E	upper
Mys_2	53°00'26.9"N 15°04'44.2"E	upper
Mys_3	52°59'57.6"N 14°58'39.5"E	upper
Mys_4	52°59'43.0"N 14°58'14.2"E	middle
Mys_5	52°57'47.6"N 14°54'51.2"E	middle
Mys_6	52°57'43.3"N 14°53'05.1"E	middle
Mys_7	52°54'48.2"N 14°52'37.8"E	middle
Mys_8	52°53'59.4"N 14°53'02.4"E	middle
Mys_9	52°53'26.3"N 14°53'26.1"E	middle
Mys_10	52°48'06.1"N 14°50'38.7"E	middle
Mys_11	52°47'16.9"N 14°46'34.1"E	middle
Mys_12	52°44'39.6"N 14°46'06.1"E	lower
Mys_13	52°42'49.3"N 14°42'00.1"E	lower
Mys_14	52°42'26.0"N 14°39'34.2"E	lower
Mys_15	52°41'36.8"N 14°37'36.0"E	lower
Mys_16	52°40'52.4"N 14°35'11.5"E	lower
Mys_17	52°40'32.4"N 14°34'14.2"E	lower
Mys_18	52°39'43.3"N 14°28'25.0"E.	lower

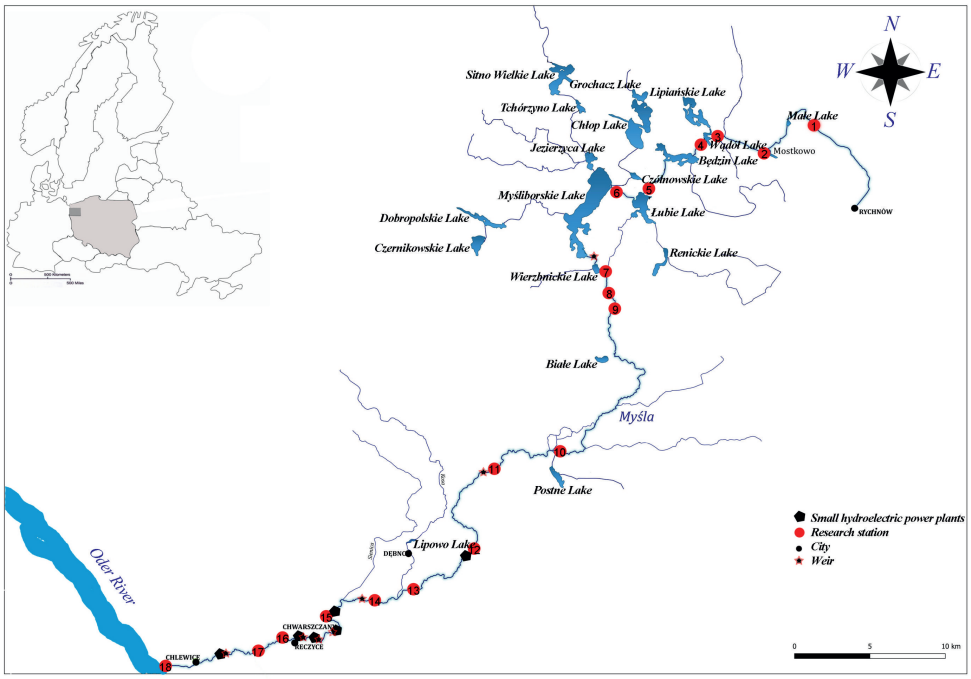

Figure 1. Map of the sampling sites.

2.2. Macroinvertebrates Sampling

Samples were collected using a standard kicknet with a 25 cm^2 frame and 0.5 × 0.5 mm mesh, pulled over 1 m (covering 1 m^2) for improved quantitative sampling. Four subsamples were taken per site, targeting characteristic substrates (gravel, sand, silt, underwater vegetation, branches) and varied flow velocities. The samples were then sieved through a 0.5 × 0.5 mm benthic sieve and preserved in 96% ethanol diluted with sample water [28]. In the laboratory, organisms were sorted and identified using Tachet et al. 2010 [29] and classified to the family level following Hewlett [30]. According to Cardoso et al. [31], higher

taxonomic resolution reduces analytical noise, improving reliability and accuracy. Based on Krepski et al. [32], the family level was deemed appropriate for our analyses. Trophic group assignment followed Tachet et al. [29] and Schmidt-Kloiber and Hering [33].

2.3. Granulation Analysis of the Substrate

Sediment samples were collected from the same locations and substrate types as the macrozoobenthos samples. Following Chiorino et al. [34], only substrates comprising $\geq$ 5% of the riverbed surface at a site were sampled. Subsamples from each site had the same substrate composition, each subsample was collected from different parts of the site (e.g., riverbanks, mid-channel areas). Subsamples were then combined into a single sample for the entire site [35]. In the laboratory, the samples were dried for 24 h at 105 °C (Goldbrunn 1450 dryer, Obersdorf, Germany) and sieved using an ANALYSETTE 3 SPARTAN vibratory shaker (Fritsch, Obersdorf, Germany) equipped with mesh sizes of 4, 2, 1, 0.5, 0.125, and 0.063 mm. Each fraction was weighed separately [36]. Sediment classification followed Elvira et al. and Fu et al. [37,38]: <0.1 mm—silt, 0.1–2.0 mm—sand, >2.0 mm—gravel.

2.4. Environmental Data

Field measurements of water temperature (°C), pH, conductivity (EC) (μS cm^{-1}), and dissolved O_2 content (mg dm^{-3}) were conducted every 30 days using an HQD30 multi-parameter meter (Hach, Düsseldorf, Germany). Water samples were also collected for nutrient analysis (mg dm^{-3}) of N-NO_3, N-NH_4, and P-PO_4, following current standards. Nitrogen forms and phosphate concentrations were determined colorimetrically using an automatic flow analyser (Skalar, Breda, The Netherlands). Chlorophyll-a was measured using the acetone extraction method [39]. Water flow velocity ($m \cdot s^{-1}$) was measured in the field using an electromagnetic SENSA RC2 m equipped with an RV2 probe (Quantum Dynamics Ltd. Aqua Data Services Division, Oxfordshire, UK). The average river depth was determined through three measurements at each site using a calibrated rod probe.

2.5. Statistical Analysis

All analyses were conducted in R–4.3.1 [40], with additional packages including FactoMineR (2.12), dunn.test (1.3.6), ggplot2 (4.0.0), and rcmdrplugin (2.9-5). Normality was assessed using the Shapiro–Wilk test, and variance homogeneity with Levene's test [41]. PCA (Principal Component Analysis) analysis was performed using FactoMineR [42] to explore environmental variable relationships. CCA (Canonical Correspondence Analysis) was conducted in PAST 4.16 [43] to assess bottom sediment type influence on macrozoobenthos families. Kruskal–Wallis and Dunn's tests were performed with dunn.test [44]. Similarity dendrograms were created in PAST 4.16 [43] using Ward's method and Euclidean distance to analyze site similarities in physicochemical and environmental features. In Table S2, sites are ordered according to the similarity dendrogram rather than a low-to-high scale.; solid lines indicate dendrogram branch boundaries, while dashed lines separate less similar sites within branches. The dominance index (D) was calculated according to the specified formula [45]. All community structure metrics (e.g., family diversity index) were calculated at the family level [46,47].

Pearson correlation analysis between macrozoobenthos family densities and water physicochemical variables is presented in Table S4 [48]. For clarity, only those taxa and water physicochemical variables with at least one statistically significant correlation were included. Table S5 summarizes the statistical methods used, the purpose of the analysis, and explanatory variables.

For trophic group analysis, only dominant groups were selected according to Cummins and Wilzbach [49] due to the river's lowland and slow flow characteristics. According to

Allan [50], in streams without continuity disruptions, the dominant guilds are shredders and gatherers, and gatherers and grazers. However, he noted that river discontinuities, such as lakes, alter guild composition, with filter feeders becoming particularly significant.

3. Results

3.1. Longitudinal Granulometric Zonation of the Myśla River and Its Physicochemical and Hydrological Variables

Based on the granulometric, physicochemical, hydrological characteristics, the Myśla River was divided into three sections, and site affinities within each section were analyzed (Figure 2). The cophenetic correlation coefficient was 0.786, indicating good agreement between the dendrogram and the actual distances among the objects. Thus, these analyses allowed us to divide the river into upper, middle, and lower sections. The upper section, upstream of the lakes, included sites 1–3; the middle section, within the lakes, consisted of sites 4–11; and the lower section, downstream of the lakes, included sites 12–18. Sites 4–7 are directly influenced by the lakes, as they are located near their outflows to the Myśla River (Figure 1). Sites 5 and 6 lie between the lakes, closer to the two entry points of Lake Łubie, whereas sites 4 and 7 are near the outlets of Lakes Lipiańskie and Wądoł. Site 4 corresponds with the outlet of Lake Wierzbnickie and site 7 with Lake Myśliborskie. Sites 8 and 9 are located in the main river flow downstream of the lakes. Collectively, these sites demonstrate the extended geographical influence of the lakes. However, sites 9 and 15 appear as exceptions in the dendrogram. This deviation is likely related to differences in flow rate compared with other sites within their respective clusters.

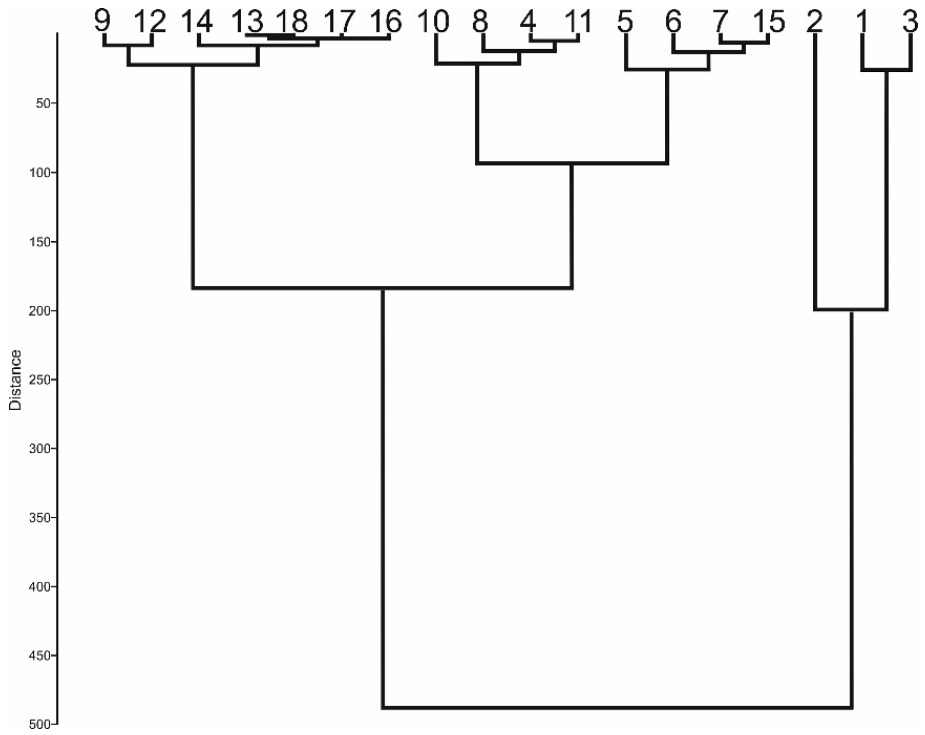

Figure 2. Dendrogram of similarities between the studied sites along the Myśla River.

Substrate granulometry (Table 1) indicates a clear division among the sites. Sites 1–3 and 5 are highly silty relative to stream conditions, whereas most other sites (except 4, 7, and 14) are dominated by sand with a small proportion of gravel. This division is also reflected in Figure 2, where silty sites (1–3) form one dendrogram branch, while the remaining sites form a second branch based on similarities.

Table 1. Granulometric fractions per site. Values expressed as percentages.

Site	Silt (<0.1 mm)	Sand (0.1–2.0 mm)	Gravel (>2 mm)
1	6.331	89.761	3.909
2	3.688	72.563	23.750
3	2.862	95.177	1.960
4	0.209	42.354	57.437
5	3.742	87.401	8.857
6	0.227	97.442	2.332
7	0.000	46.375	53.625
8	0.347	82.118	17.535
9	0.096	70.369	29.536
10	1.495	97.152	1.353
11	1.271	84.699	14.030
12	0.535	97.147	2.318
13	0.242	81.759	17.998
14	0.112	33.614	66.273
15	0.506	96.538	2.956
16	0.087	81.047	18.866
17	0.059	73.149	26.792
18	0.224	98.004	1.772

Environmental variables differed across the river sections (Table 2). The most significant differences were observed between the upper and lower sections, affecting conductivity, flow, NH_4^+, NO_3, dissolved O_2, suspension, and velocity. In contrast, variables such as BOD_5, chlorophyll a, gravel, sand, silt, and temperature showed no statistically significant differences. The Myśla is slow-moving, with velocities between 0.04–0.23 m s^{-1}, flowing through several lakes on a gravelly–sandy bed dominated by sand. Hence, silt is scarce, not exceeding 6% and recorded only at site 3, indicating that granulometric effects are primarily associated with gravel and sand.

Table 2. Results of the Kruskal–Wallis and Dunn's tests for environmental variables in the different river sections. * means that it is statistically important [$\alpha \leq 0.05$].

Feature	Differentiating Variable	K-W χ^2	*p*-Value	Dunn Test—*p*-Value for Parts of River		
				Lower-Medium	Medium-Upper	Upper-Lower
BOD_5 [mg dm^{-3}]	River parts	0.286	0.867	-	-	-
Chlorophyl A		3.654	0.161	-	-	-
EC [µS cm^{-1}]		11.262	0.004	0.063	0.116	0.002 *
Flow [cm^3 s^{-1}]		10.865	0.004	0.079	0.108	0.002 *
Gravel [%]		0.465	0.793	-	-	-
NH_4 [mg dm^{-3}]		6.229	0.044	0.247	0.224	0.021 *
NO_3 [mg dm^{-3}]		7.012	0.03	0.704	0.051	0.013 *
O_2 [mg dm^{-3}]		7.811	0.022	0.091	0.307	0.012 *
P-PO_4 [mg dm^{-3}]		5.051	0.08	0.928	0.039	0.106
pH		8.260	0.016	0.429	0.052	0.006 *
Sand [%]		0.128	0.938	-	-	-
Silt [%]		6.490	0.039	0.663	0.069	0.017 *
Suspension [mg dcm^{-3}]		6.243	0.044	0.082	0.044	0.728
Temperature [°C]		3.297	0.192	-	-	-
Velocity [cm s^{-1}]		6.167	0.046	0.188	0.301	0.024 *

3.2. Macrozoobenthos Communities' Structure Along the Myśla River

The taxonomic structure of the communities was assessed using the dominance coefficient (Table 3) and indices including the number of taxa, number of individuals, Simpson index, family diversity index, and Pielou Evenness index (Table S1). In total, 31 taxa were collected (Table S2). Insecta dominated (22 families), representing approximately 50% of total abundance and diversity. Within Insecta, Diptera were most abundant (7 families, 44% of total abundance), largely dominated by Chironomidae (98%). Molluscs accounted for 32% of total abundance across 17 families, with Sphaeriidae (46%, filter-feeders), Bithyniidae (23%) and Planorbidae (17%, scrapers-grazers), being the most abundant.

Table 3. Taxa dominance per site.

Site	Dominance_D	Taxa	A [%]	Ni
1	0.400	Chironomidae	62.9	127
2	0.263	Sphaeriidae	42.4	28
3	0.149	Sphaeriidae	35.7	20
4	0.411	Chironomidae	59.6	1070
5	0.665	Chironomidae **	81.5	369
6	0.780	Chironomidae **	88.1	275
7	0.248	Chironomidae	42.9	70
8	0.213	Caenidae	37.2	35
9	0.205	Planorbidae	30.9	129
10	0.322	Sphaeriidae	45.5	5
11	0.430	Gammaridae *	64.3	162
12	0.482	Chironomidae *	67.4	227
13	0.352	Sphaeriidae	60.0	9
14	0.353	Bithyniidae	55.0	204
15	0.248	Tubificidae	32.9	24
16	0.405	Gammaridae	58.4	180
17	0.433	Gammaridae *	63.3	209
18	0.413	Gammaridae *	61.4	27

Note(s): A—percentage of the assemblage dominated by the most numerous taxon. Ni—number of individuals. **—site strongly dominated by one taxon (>80%), *—site less strongly dominated by one taxon (60–70%).

Sites 1, 7, 9, 17 exhibited the highest taxa richness (15, 16, 17, and 15, respectively), whereas sites 10, 13, and 18 had the lowest number of individuals (11, 15, and 44, respectively) and taxa richness (4, 6, and 7, respectively). Most sites displayed high family diversity index, with sites 7–9 showing the greatest diversity (1.854, 1.895 and 1.963, respectively; Table S1, indicating good resilience to environmental stressors. Exceptions were sites 5 and 6, dominated by Chironomidae (81% and 88%), suggesting high fine particulate organic matter (FPOM) content. Chironomids, mainly detritivores or collectors/filterers, most likely thrived in these areas due to water containing significant amounts of fine organic particles or algae originating from such lakes as Będzin, Wądoł and Lipiańskie for site 5 and lakes Grochacz, Chłop, Czółnowskie, Sitno Wielkie, Tchórzyno and Jezierzyca for site 6 (Figure 2). The Pielou Evenness Index (Table S1) indicates that macroinvertebrate communities at sites 4 and 10 are relatively evenly distributed, whereas most other sites exhibit moderate evenness except for sites 5, 6, and 17, dominated by Chironomidae (5, 6) and Gammaridae (17). Thus, the distribution of species at these sites is skewed, leading to lower community evenness.

Despite the abundance of Chironomidae at sites Myśla 1 and 4, they did not dominate the communities (Dominance_D = 0.400 and 0.411, respectively). Both Chironomidae

and Sphaeriidae are filter-feeders [51], concentrated near outlets from Wądoł and Lipiańskie lakes. Additionally, site 7 exhibited high Chironomidae abundance (42%) alongside Acroloxidae (grazers). From sites 16 to 18, shredders, specifically Gammaridae, dominated, accounting for over 50% of total abundance at each site (Table 3).

3.3. Holistic Impact: Sediments and Other Environmental Factors

PCA analysis revealed sediment impacts and environmental gradients affecting macroinvertebrates (Figure 3 and Table S3). In the PCA plot, macroinvertebrates are distributed along a eutrophication gradient (axis 1). Cluster A contains high levels of epibenthic arthropods with shredding and/or predatory traits (Coleoptera, Odonata, Amphipoda), adapted to higher flow, well-oxygenated, and low-mineralized waters.

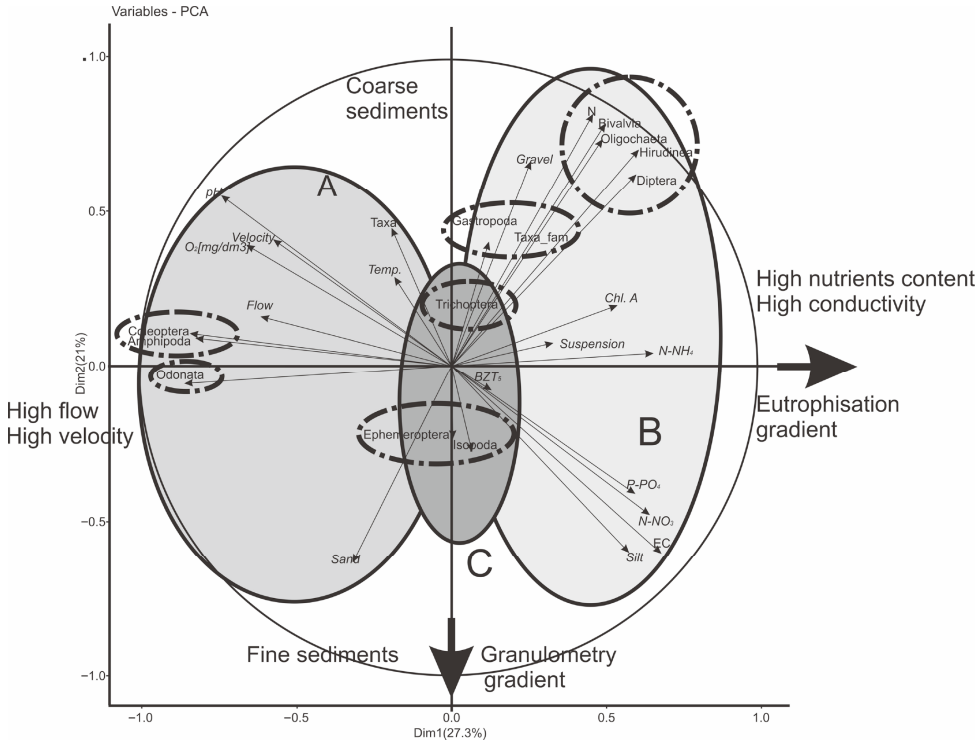

Figure 3. PCA analysis showing the relationship between environmental variables and Higher taxa. Along the y-axis, the gradient of distribution of the taxa runs from coarse sediments (top) to fine sediments (bottom), while along the x-axis, the gradient runs from lower (left) to (right) higher eutrophication. Explanation of cluster A, B and C are in title 3.3.

Cluster B includes Gastropoda and Bivalvia, positively correlated with nutrient content and conductivity. These taxa play an important role in nutrient cycling, with their abundance influenced by levels of nutrients, vegetation, and phytoplankton algae (primary production). These factors affect their feeding behaviour, which is mainly herbivorous or reliant on detritus. Cluster B also contains endobenthic taxa (filter-feeding and/or scavenger Diptera, sediment-eating Oligochaeta, and predatory Hirudinae), which thrive in well-mineralized waters rich in nutrients and fine organic matter and contribute to bioturbation, the physical translocation of sediments via their burrowing and feeding behaviour. This process enhances nutrient cycling by promoting the breakdown of organic matter and oxygenation of sediments. Cluster C comprises taxa preferring moderately mineralized waters, with diverse feeding strategies, including shredders (Trichoptera, Isopoda) that feed on coarse organic matter such as dead leaves, and scrapers and grazers (e.g., Ephemeroptera) that consume fine organic matter.

Axis 2 indicates macroinvertebrate distribution along an up-down granulometry gradient. Endobenthic taxa prefer coarser substrate such as gravel, typically found in sedimentation zones of the river. This offers greater stability, porosity, and aeration than sand, which is more compact, easily movable, and unstable. With its larger interstitial spaces, gravel also facilitates burrowing, dissolved O_2 exchange and water circulation. Bivalvia and, to a lesser extent, Gastropoda are endobenthic and/or burrowers, whereas epibenthic insects and crustaceans prefer finer sediments.

CCA analysis (Figure 4) shows a negative correlation between gravel and sand, with minor silt impact. In the CCA plot, Cluster A families occur on sand-dominated substrates, as they can forage among sand grains, hide in the sand (e.g., Sphaeriidae), or live near rooted vegetation. Cluster B families depend on gravel substrates, and Cluster C families associate with silt. Chironomidae, primarily use silt as food, while families such as Limnephilidae and Erpobdellidae are influenced by both sand and silt.

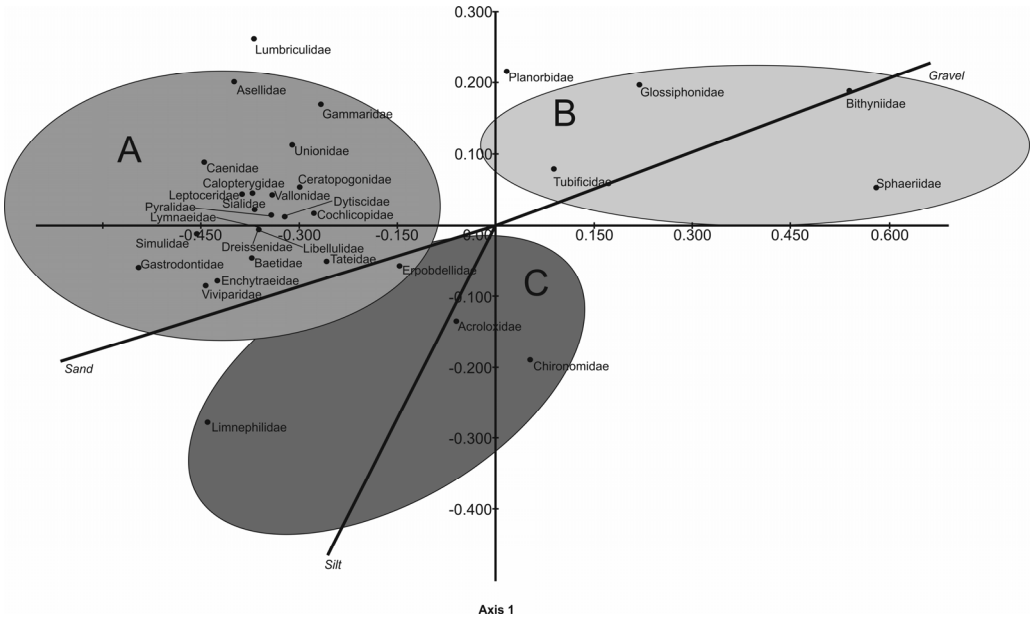

Figure 4. CCA plot showing the impact of substrate type on the distribution of families. Explanation of cluster A, B and C are in title 3.3.

Families dependent on sand in the substrate and thus located near the sand vector on the CCA diagram are mostly epibenthic insects with swimming or crawling locomotion. Gravel-associated families (Planorbidae, Tubificidae, Glossiphonidae, Bithyniidae, and Sphaeriidae), either burrow into the substrate (Sphaeriidae and Tubificidae) or feed on algae growing on hard surfaces (e.g., Planorbidae).

4. Discussion

Our study aimed to investigate the applicability of the River Continuum Concept (RCC) along the Myśla River, focusing on how lakes as natural disruptions influence macrozoobenthos communities and overall biodiversity. Our main findings are as follows:

(1) the river's continuity is strongly disrupted by lake interference, which primarily alters water temperature and nutrient concentrations, driving significant changes in macrozoobenthos composition and functional structure;
(2) the taxa family richness was significant (31 taxa) indicating favourable habitat conditions in this lowland river dominated by filter-feeding and grazing taxa; and
(3) granulometry, dominated by sandy substrate, also played an important role in shaping community structure and influencing taxa composition.

Collectively, these findings demonstrate that the Myśla River deviates from the predictions of the RCC, highlighting the importance of integrating the influence of natural discontinuities, such as lakes, when evaluating riverine ecological processes.

4.1. Myśla River Continuity Disruption and Lake Influence

The River Continuum Concept [21], one of the most important concepts in running water ecology, applies well to unimpeded streams systems but its applicability is limited in rivers disrupted by disturbances [52]. Our results indicate that the continuity of the Myśla River has been significantly disrupted, primarily by natural features (large lakes catchments) and, to a lesser extent, by artificial impacts (e.g., well-managed hydrotechnical infrastructure and human-made regulatory facilities). In the upper reaches (sites 1–3; 15% of the river catchment), where the river flows through two lakes, moderate agricultural influence has resulted in a high proportion of sediment accumulation at the bottom, supporting organism groups adapted to these habitats. The mid-reach sites (4–11), where the river flows through several lakes, show higher water temperatures than the upstream sites. This is particularly evident at sites 7–9, located downstream of the shallow, wind-exposed Lake Wierzbnickie, and at site 6, between Lakes Łubie and Myśliborskie. The increase in water temperature downstream of the lakes, due to the discharge of warmed lake waters, is consisted with the observations of Jones [53]. These sites also exhibit lower BOD_5 values than the upper reach sites, suggesting that the lakes act as small reservoirs that facilitate nutrient purification process. This observation is in line with Dąbrowski and Więcaszek 2018 [54], who discussed the impact of small reservoirs on water quality in lowland rivers claiming [55] that lakes act as dynamic filters that alter the concentrations of dissolved compounds in flowing water.

In the lower course (sites 12–18), the Myśla River has partially retained its natural character, featuring meanders, abundant channel vegetation, riparian cover, and diverse microhabitats. The surrounding catchment area is dominated by forests and cultivated fields. This near-outlet section continues the purifying function of the upstream lakes. Significant differences were observed between river sections both in abiotic (physicochemical parameters, hydrology, and bottom sediment types) and biotic features (macrozoobenthos composition, structure, and density). These differences highlight substantial deviations from the predictions of the RCC. The observed deviations are primarily caused by natural barriers in the form of lakes along the Myśla. This aligns with the Serial Discontinuity Concept [56,57], which predicts that natural or artificial disruptions in the river continuum, such as lakes or reservoirs, create a spatial reorganization of abiotic and biotic conditions downstream. Specifically, the SDC offers a framework for interpreting the changes in nutrient cycling, temperature regulation, and species composition observed in the Myśla River.

4.2. Macrozoobenthos Communities Composition and Structure

Across the 18 sampling stations, a total of 31 macrozoobenthos taxa were recorded. The most abundant were Sphaeriidae (771 individuals; filter feeders), Bithyniidae (384 individuals), and Planorbidae (288 individuals; scrapers-grazers). This diversity indicates relatively favourable habitat conditions, comparable to those reported for other lowland European rivers. For instance, Koszałka and Jabłońska-Barna [58] recorded between 19 and 55 families in rivers within the European Central Plains Ecoregion of northeastern Poland. Examples include the Drela River with 26 families, Drwęca (36), Guber (33), Łyna (42), Narew (36), Nidka (22), Pisa (19), Wel (55), and Wkra (21). Likewise, Krepski and al. [59] found 30 invertebrate families in the small Dzierżecinka River, and 57 in the Drawa River [32].

Site 4 was the most distinct, showing the highest number individuals, dominated by Chironomidae (Tables 3 and S2). The overlap between the Middle and Lower section sites in Table S2 suggest shared habitat conditions conducive to the taxa present, aligning with their ecological requirements [60].

4.3. Influence of Abiotic Factors on Macrozoobenthos Communities

Macrozoobenthos diversity was greatest in the upper and lower sections of the Myśla river. This variation appears driven by conductivity, flow, nitrogen compounds, dissolved oxygen, suspended matter, and velocity.

As Doretto et al. [52] observed, lakes and tributaries disrupt the longitudinal continuum at the catchment scale, altering water temperature, nutrient concentrations, substrate composition, sediment transport, and organic matter availability. In summer, lakes supply warmer, nutrient-rich water with lower dissolved O_2 levels [61], whereas in spring, lakes tend to lower the river temperature [52]. This effect gradually diminishes downstream as groundwater inflows and shading from riparian vegetation cool the water [62]. These temperature fluctuations significantly influence macrozoobenthos density, particularly in Decapoda, Ephemeroptera, Coleoptera, Diptera, and Plecoptera [63]. Furthermore, as noted by Pander et al. [64], elevated water temperatures may also favour invasive species such as *Dikerogammarus villosus*, although in the Myśla River, no significant temperature were observed between sections, possibly due to compensatory cooling from lakes acting as tributaries. However, other lake-influenced factors, such as dissolved O_2 content, nutrient composition, and hydrological characteristics, may have shaped specific macrozoobenthos taxa distribution.

In the case of the Myśla River, substrate heterogeneity complicates the identification of trends in changes in the substrate composition along the river. Following the Intermediate Disturbance Hypothesis [65], moderate levels of disturbance, such as fluctuating hydrological conditions or substrate heterogeneity, can maximize species diversity by preventing competitive exclusion. In the Myśla River, the diversity observed may result from the interplay between natural disturbances, such as seasonal variations and anthropogenic impacts, which create a mosaic of microhabitats supporting a range of taxa.

The taxa richness observed in the Myśla River compares favourably with other European rivers. For instance, in the Allier River, a tributary of the Loire in France, which is approximately 410 km long (four times the length of the Myśla) and experiences minimal anthropogenic impacts, Beauger et al. [66] recorded the presence of 63 invertebrate taxa (mostly identified to the genus level). Of these, 14 were abundant, based on 76 samples collected at about 40 sites. Golovatyuk et al. [67] recorded 156 macrozoobenthos species in minor saline watercourses of the Volga River basin (15 tributaries) and two Lake Elton tributaries in Russia. The species richness ranged from six in the Solyanka River (a tributary of Lake Elton) to 72 in the Solenaya Kuba River (within the Volga River basin). Only Oligochaeta and Chironomidae were consistently present in all the small rivers flowing into the Volga, while Diptera (excluding Chironomidae), Chironomidae, Coleoptera, and Heteroptera were present in the Lake Elton tributaries (the Solyanka and Chernavka Rivers). Leitner et al. [68] studied the influence of in-stream sediment on the taxonomic composition of macrozoobenthos at 12 sites in rivers of the Bohemian Massif in Austria. They found that sediment-impacted sites, compared to reference sites (unaffected by sediment), showed an increase in the number of taxa such as Gastropoda, Oligochaeta, Hirudinea, Ephemeroptera, Trichoptera, and a decrease in Turbellaria, Isopoda, Plecoptera, Coleoptera, and Diptera. For Turbellaria and Isopoda, this decline was total. In contrast, Jansen et al. [69] recorded 109 invertebrate taxa and 28 fish species at 21 sites in the Enz River in southwestern Germany. Additionally, Varadinova and others [70] recorded 110 species of benthic animal

taxa in the Martisa River and its tributaries (southern Bulgaria) at 15 sites (11 on the main river and 4 on tributaries) in 2021. This represents a notable decrease compared to 2020, when 165 taxa were recorded in the same system [71].

The Myśla River hosts a full spectrum of taxa adapted to a wide range of flow velocities, from slow- water species such as Tubificidae, Tabanidae, or Psychodidae, to fast-water species including snails (Bithynellidae), mayflies (Baetidae), and black flies (Simuliidae) [29]. Water velocity, combined with flow, depth, substrate type, and dissolved O_2, shapes the distribution mosaic and diversity of macrozoobenthos [72,73]. In the upper reaches, particularly in areas with increased biogenic compound concentrations, eurytopic species dominated the macrozoobenthos. These included taxa such as Diptera (Chironomidae) and Bivalvia (Sphaeriidae), which exhibit excellent tolerance to high water pollution and can survive over a wide range of temperatures as indicated by numerous authors [29,74] and biotic indices (e.g., Polish biotic indices BMWP and BMWP (PL) [75]. In contrast, in the lower reaches, less influenced by anthropogenic pressure, more sensitive taxa were observed, including mayflies (Baetidae). The hydrochemical and hydrological diversity of the Myśla River's macrozoobenthos habitats allowed assessment of how these factors affect taxon density and abundance. Among these physicochemical parameters, dissolved O_2 and nitrate nitrogen concentrations had the greatest impact, consistent with earlier findings [76–78].

Taxa sensitivity also explains the observed distributions: groups tolerant of polluted, polysaprobic or α-mesosaprobic waters (e.g., Psychodidae or Erpobdellidae leeches) thrive under high nutrient and low oxygen conditions, whereas taxa such as Gammaridae prefer oligosaprobic waters [29].

Additionally, higher abundance of taxa such as Bivalvia, Oligochaeta, Hirudinae, and Diptera was correlated with high conductivity. This finding aligns with Brysiewicz et al. [63], who noted similar trends in macroinvertebrates from small streams in the European Central Plains. These taxa were predominantly recorded in gravel substrates, which are more stable over time [79] for these slow-moving or sedentary organisms. In contrast, sandy or silt substrates were commonly inhabited by mobile organisms, such as insects. Adaptation to low dissolved O_2 levels in water was observed in Trichoptera, such as Limnephilidae. These organisms build cases and use wave-like movements of their abdomens to ventilate their gills [80].

4.4. The Influence of Substrate as a Habitat for Macrozoobenthos Communities

Substrate surface structure is one of the most critical determinants of species richness and density. It provides habitats that support greater macroinvertebrate diversity, thereby contributing significantly to river biodiversity [81], although its effects are challenging to assess due to its interactions with other environmental parameters [82]. In the Myśla River, sandy substrate dominated (83% of the sites), similar to many lowland rivers, where sand covers approximately 70% of the riverbed [50].

Moreover, the presence of more diverse substrates such as branches, tree limbs, or fallen trees in the riverbed, is crucial for macrozoobenthos biodiversity by providing CPOM, which is gradually degraded and processed by different macroinvertebrate trophic groups [83]. In the Myśla, Diptera, Coleoptera, Odonata, and Oligochaeta were found exclusively on sandy substrates, while Diptera and Trichoptera occurred on muddy substrates. Furthermore, studies have shown that an increase in sand content leads to a decline in the abundance of taxa such as Oligochaeta, Gastropoda, Bivalvia, Hirudinea, and Diptera within the macrozoobenthos community.

Conversely, sand quantity correlated positively with Ephemeroptera and Isopoda abundance. Ephemeroptera (Baetidae, Caenidae, and Ephemerellidae), and Isopoda (Asell-

idae *Asellus aquaticus*), favour sandy substrates. However, *A. aquaticus*, Baetis species prefer submerged vegetation, which notably increases macrozoobenthos abundance [84]. Similar substrate preferences were observed for two species of Ephemeroptera (Caenidae *Caenis macrura* and Potamanthidae *Potamanthus luteus*) the Timiș River [85], and for Ephemerellidae in Bulgaria, which favoured submerged vegetation, gravel, stones, and mud [86].

Substrate granulation, along with hydrological and hydrochemical parameters, plays an important role in shaping diversity and macrozoobenthos richness As Brysiewicz et al. (2022) [63] note, lowland rivers in the European Central Plains are typically dominated by eurytopic species that tolerate a wide range of hydrochemical and hydrological conditions.

4.5. Functional Feeding Group Distribution

Along the Myśla River, disruptions to ecological continuity likely prevented typical trophic guilds gradients [49]. In the upper reaches, filter feeders such as Sphaeriidae mussels and Chironomidae dominated, indicating high fine particulate organic matter (FPOM) content. For example, site 4 exhibited the highest abundance of Chironomidae, Sphaeriidae, Tubificidae, and Glossiphoniidae. Chironomids play a crucial role in FPOM dynamics [87] and in processing and recycling of organic matter, resulting in its mineralization and significantly impacting the substrate structure and composition [88]. Sphaeriidae and other Bivalvia species contribute to filtering processes; they primarily feed on fine particulate organic matter from the water column, along with phytoplankton and bacteria [89]. In contrast, the lower reaches were dominated by shredders, mainly Gammaridae [29], most likely due to the high CPOM content from riparian vegetation, such as dead leaves and branches [90], and also noted in Hungarian midland streams [91]. Moreover, Gerhardt et al. [92] referred to Gammarus taxa as shredders that break down leaves and other CPOM covered with biofilm into smaller particles (FPOM). Shredders play a vital ecological role by converting CPOM into FPOM, which then supports other macroinvertebrates feeding groups, such as collectors and filter-feeders [93].

Correlation analysis revealed further ecological relationships (Table S4): Erpobdellidae correlated with BOD_5 and P-PO_4, consistent with their well-documented tolerance of organic enrichment conditions [29]. Molluscs Acroloxidae and Gastrodontidae were strongly related to warmer, nutrient-rich waters, which corresponds to the affinities of molluscs to meso-/eutrophic waters, rich in nutrients (N, P) that promote macrophytes and algae, while Tateidae (namely *Potamopyrgus antipodarum* (Gray, 1843)) exhibited a negative correlation with oxygen, compatible with euryoecious organisms [94]. Asellidae correlated positively to BOD_5 showing tolerance to organic matter loading [29]. Among Diptera, Ceratopogonidae were associated with higher temperatures [95], reflecting their ubiquity in warmer and slow-moving waters [96], while Simuliidae were sensitive to nitrogenous pollution [97].

According to the RCC [21], upper reaches (stream orders 1–3) are dominated by shredders and collectors, mid-sections (mid-sized rivers, stream orders 4–6) by grazers and collectors dominate, and lower reaches (stream orders greater than 6) by collectors, with invertebrate predators throughout. However, as Minshall [84] observed, such textbook patterns often fail to appear in streams with diverse habitat conditions, such as the Myśla River.

Additionally, the large number of taxa found in the Myśla River represents a valuable macrozoobenthos resource for supporting the restoration of biodiversity in the Oder River through natural migration, especially in the aftermath of the 2022 ecological disaster [98]. This highlights the critical role of small tributaries in rebuilding invertebrate fauna resources for larger rivers [99].

Given the rich biodiversity observed in this major tributary, smaller rivers should be recognized as valuable habitats and shelters for many aquatic species of plants and animals. Their monitoring and protection must be prioritized within sustainable river management frameworks. Community-based citizen science initiatives, which engage non-specialists alongside experts [100,101], offer a cost-effective and educational means to extent monitoring coverage and encourage young people to engage in science in the future. This study serves as a preliminary step toward long-term surveys needed to capture temporal variability and strengthen understanding of biodiversity patterns and ecosystem dynamics, potentially with the support of community-based science initiatives.

5. Conclusions

In this study, 31 macrozoobenthos families were identified in the Myśla River catchment. The primary factors influencing their diversity were flow, velocity, nutrients, electrical conductivity (EC), and sediment size. Considerable variation in taxa and habitat conditions was observed along the river, which is typical for many rivers in Central Europe. This variability reflects both anthropogenic disturbances (e.g., river regulation) and natural factors such as the presence of lakes, which together partially challenge the assumptions of the River Continuum Concept (RCC). While the RCC effectively describes mountain river catchments, it is less applicable to lowland rivers often characterized by slower and more variable flow influenced by anthropogenic and natural factors (e.g., lakes).

This study serves as a pilot investigation, providing baseline data for future research on the Myśla River. Subsequent studies will examine the impact of lakes on the river's fluvial ecosystem and conduct parallel investigation into macrozoobenthos microhabitats.

Overall, the findings underscore the need for a more nuanced understanding of riverine ecosystems that accounts for both natural and human impacts. Such knowledge is crucial for effective river management and conservation efforts, especially in the context of environmental change and increasing anthropogenic pressures. Further research should also focus on the role of sediments in shaping macrozoobenthos communities.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w17203005/s1, Table S1. Biotic indexes for site; Table S2. Presence of taxa at sites; Table S3. Scores of PCA; Table S4. Correlations between families and physicochemical variables of water; Table S5. Summary of statistical methods used in the article.

Author Contributions: Conceptualization, N.B., J.D., A.B. and P.C.; methodology, N.B., J.D., A.B. and P.C.; software, J.D.; validation, N.B., J.D. and A.B.; formal analysis, J.D.; investigation, N.B. and J.D.; resources, J.D., A.B., P.C. and Ł.H.; data curation, J.D.; writing—original draft preparation, N.B., J.D., A.B. and P.C.; writing—review and editing, N.B., J.D., A.B. and P.C.; visualization, J.D. and N.B.; supervision, P.C.; project administration, A.B.; funding acquisition, A.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable. In Polish law, information on the act on the protection of animals used for scientific or educational purposes (from 15 January 2015), is available in the first chapter on which situations the above-mentioned act does not apply—in point 3: "activities performed for the purpose of identifying animals". Our activities aimed to identify animals at the research point.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors would like to thank M.A. Ewa Sitko from the Environmental Chemistry Research Laboratory in Falenty for performing hydrochemical analyses. We also thank M.A.

Agnieszka Kozioł and Martyna Sobczyk for their help in field work and performing measurements in the laboratory.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Thorp, J.H.; Dodds, W.K.; Robbins, C.J.; Maasri, A.; Arsenault, E.R.; Lutchen, J.A.; Tromboni, F.; Hayford, B.; Pyron, M.; Mathews, G.S.; et al. A Framework for Lotic Macrosystem Research. *Ecosphere* **2021**, *12*, e03342. [CrossRef]
2. Dudgeon, D.; Arthington, A.H.; Gessner, M.O.; Kawabata, Z.-I.; Knowler, D.J.; Lévêque, C.; Naiman, R.J.; Prieur-Richard, A.; Soto, D.; Stiassny, M.L.J.; et al. Freshwater Biodiversity: Importance, Threats, Status and Conservation Challenges. *Biol. Rev.* **2006**, *81*, 163–182. [CrossRef] [PubMed]
3. Pu, X.; Ding, W.; Ye, W.; Nan, X.; Lu, R. Ecosystem Service Research in Protected Areas: A Systematic Review of the Literature on Current Practices and Future Prospects. *Ecol. Indic.* **2023**, *154*, 110817. [CrossRef]
4. Ferreira, V.; Albariño, R.; Larrañaga, A.; LeRoy, C.J.; Masese, F.O.; Moretti, M.S. Ecosystem Services Provided by Small Streams: An Overview. *Hydrobiologia* **2023**, *850*, 2501–2535. [CrossRef]
5. Ahmedi, F.; Makolli, S. The Correlation of Water Quality Parameters over Wireless Sensors Generated Dataset in the Sitnica River in Kosovo. *J. Water Land Dev.* **2023**, *59*, 8–12. [CrossRef]
6. Moi, D.A.; Barrios, M.; Tesitore, G.; Burwood, M.; Romero, G.Q.; Mormul, R.P.; Kratina, P.; Juen, L.; Michelan, T.S.; Montag, L.F.A.; et al. Human Land—Uses Homogenize Stream Assemblages and Reduce Animal Biomass Production. *J. Anim. Ecol.* **2023**, *92*, 1176–1189. [CrossRef]
7. Ding, N.; Yang, W.; Zhou, Y.; González-Bergonzoni, I.; Zhang, J.; Chen, K.; Vidal, N.; Jeppesen, E.; Liu, Z.; Wang, B. Different Responses of Functional Traits and Diversity of Stream Macroinvertebrates to Environmental and Spatial Factors in the Xishuangbanna Watershed of the Upper Mekong River Basin, China. *Sci. Total Environ.* **2017**, *574*, 288–299. [CrossRef]
8. Elias, J.D.; Ijumba, J.N.; Mgaya, Y.D.; Mamboya, F.A. Study on Freshwater Macroinvertebrates of Some Tanzanian Rivers as a Basis for Developing Biomonitoring Index for Assessing Pollution in Tropical African Regions. *J. Ecosyst.* **2014**, *2014*, 985389. [CrossRef]
9. Deborde, D.; Hernandez, M.B.; Magbanua, F. Benthic Macroinvertebrate Community as an Indicator of Stream Health: The Effects of Land Use on Stream Benthic Macroinvertebrates. *Sci. Diliman* **2016**, *28*, 5–26.
10. European Commission. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 Establishing a Framework for Community Action in the Field of Water Policy. *Off. J. Eur. Community* **2000**, *L327*, 1–72.
11. Strayer, D.L. Challenges for Freshwater Invertebrate Conservation. *J. N. Am. Benthol. Soc.* **2006**, *25*, 271–287. [CrossRef]
12. Duan, X.; Wang, Z.; Xu, M.; Zhang, K. Effect of Streambed Sediment on Benthic Ecology. *Int. J. Sediment Res.* **2009**, *24*, 325–338. [CrossRef]
13. Horváth, Z.; Ptacnik, R.; Vad, C.F.; Chase, J.M. Habitat Loss over Six Decades Accelerates Regional and Local Biodiversity Loss via Changing Landscape Connectance. *Ecol. Lett.* **2019**, *22*, 1019–1027. [CrossRef]
14. Wagenhoff, A.; Townsend, C.R.; Matthaei, C.D. Macroinvertebrate Responses along Broad Stressor Gradients of Deposited Fine Sediment and Dissolved Nutrients: A Stream Mesocosm Experiment. *J. Appl. Ecol.* **2012**, *49*, 892–902. [CrossRef]
15. Meißner, T.; Sures, B.; Feld, C.K. Multiple Stressors and the Role of Hydrology on Benthic Invertebrates in Mountainous Streams. *Sci. Total Environ.* **2019**, *663*, 841–851. [CrossRef]
16. McKenzie, M.; Brooks, A.; Callisto, M.; Collins, A.L.; Durkota, J.M.; Death, R.G.; Jones, J.I.; Linares, M.S.; Matthaei, C.D.; Monk, W.A.; et al. Freshwater Invertebrate Responses to Fine Sediment Stress: A Multi-continent Perspective. *Glob. Change Biol.* **2024**, *30*, e17084. [CrossRef] [PubMed]
17. Beisel, J.-N.; Usseglio-Polatera, P.; Moreteau, J.-C. The Spatial Heterogeneity of a River Bottom: A Key Factor Determining Macroinvertebrate Communities. *Hydrobiologia* **2000**, *422*, 163–171. [CrossRef]
18. Leunda, P.M.; Oscoz, J.; Miranda, R.; Ariño, A.H. Longitudinal and Seasonal Variation of the Benthic Macroinvertebrate Community and Biotic Indices in an Undisturbed Pyrenean River. *Ecol. Indic.* **2009**, *9*, 52–63. [CrossRef]
19. Kanaya, G.; Suzuki, T.; Kikuchi, E. Spatio-Temporal Variations in Macrozoobenthic Assemblage Structures in a River-Affected Lagoon (Idoura Lagoon, Sendai Bay, Japan): Influences of Freshwater Inflow. *Estuar. Coast. Shelf Sci.* **2011**, *92*, 169–179. [CrossRef]
20. Lévêque, C. *Ecosystèmes Aquatiques. Volume 77 de Les Fondamentaux. La Bibliothèque de Base de l'Étudiant En Sciences*, 1st ed.; Hachette: New York, NY, USA, 1996; Volume 77.
21. Vannote, R.L.; Minshall, G.W.; Cummins, K.W.; Sedell, J.R.; Cushing, C.E. The River Continuum Concept. *Can. J. Fish. Aquat. Sci.* **1980**, *37*, 130–137. [CrossRef]
22. Cote, D.; Kehler, D.G.; Bourne, C.; Wiersma, Y.F. A New Measure of Longitudinal Connectivity for Stream Networks. *Landsc. Ecol.* **2009**, *24*, 101–113. [CrossRef]

23. Poole, G.C. Fluvial Landscape Ecology: Addressing Uniqueness within the River Discontinuum. *Freshw. Biol.* **2002**, *47*, 641–660. [CrossRef]
24. Scown, M.W.; Thoms, M.C. The Discontinuum of River Networks: The Importance of Geomorphic Boundaries. *Landsc. Ecol.* **2023**, *38*, 1307–1319. [CrossRef]
25. Calapez, A.R.; Serra, S.R.Q.; Rivaes, R.; Aguiar, F.C.; Feio, M.J. Influence of River Regulation and Instream Habitat on Invertebrate Assemblage' Structure and Function. *Sci. Total Environ.* **2021**, *794*, 148696. [CrossRef]
26. Wang, J.; Bao, S.; Zhang, K.; Heino, J.; Jiang, X.; Liu, Z.; Tao, J. Responses of Macroinvertebrate Functional Trait Structure to River Damming: From within-River to Basin-Scale Patterns. *Environ. Res.* **2023**, *220*, 115255. [CrossRef]
27. Cichocka, M. Assessment of the Ecological Status of Rivers Based on Macrozoobenthos. In *Biological Methods of Assessing the Status of the Environment*; Ciecierska, H., Dynowska, M., Eds.; Mantis Publishing House: Olsztyn, Poland, 2013; Volume 2, pp. 150–178.
28. Bis, B.; Mikulec, A.; Bielczyńska, A. Macrozoobenthos in Rivers. In *Manual for monitoring biological elements and classification of the ecological status of surface waters. In Update of Methods*; Kolada, A., Ed.; Environmental Monitoring Library: Warsaw, Poland, 2020; pp. 113–159. (In Polish)
29. Tachet, H.; Richoux, P.; Bournaud, M.; Usseglio-Polatera, P. *Invertébrés d'Eau Douce. Systematique, Biologie, Ecologie*; CNRS Editors: Paris, France, 2010.
30. Hewlett, R. Implications of Taxonomic Resolution and Sample Habitat for Stream Classification at a Broad Geographic Scale. *J. N. Am. Benthol. Soc.* **2000**, *19*, 352–361. [CrossRef]
31. Cardoso, M.; Shimano, Y.; Cruz, P.; Boldrini, R.; Mariano, R.; Nessimian, J.; Molineri, C.; Salles, F.; Andrade, A.; De Marco Júnior, P.; et al. Assessing the Distribution of Mayflies (Ephemeroptera: Insecta) in the Brazilian Amazon to Guide More Effective Conservation. *Aquat. Conserv.* **2023**, *33*, 337–348. [CrossRef]
32. Krepski, T.; Kuczyńska, K.; Czerniawski, R. Outflows from Lakes as Ecotones—Stable Conditions Maintain Macroinvertebrates Biodiversity. *Sci. Total Environ.* **2023**, *881*, 163264. [CrossRef]
33. Schmidt-Kloiber, A.; Hering, D. www.Freshwaterecology.Info—An Online Tool That Unifies, Standardises and Codifies More than 20,000 European Freshwater Organisms and Their Ecological Preferences. *Ecol. Indic.* **2015**, *53*, 271–282. [CrossRef]
34. Chiorino, M.; Spreafico, C.; Solazzo, D.; Doretto, A. Biodiversity, Ecological Status and Ecosystem Attributes of Agricultural Ditches Based on the Analysis of Macroinvertebrate Communities. *Diversity* **2024**, *16*, 558. [CrossRef]
35. Astorga Roine, A.; Reid, B.; Uribe, L.; Moreno-Meynard, P.; Fierro, P.; Madriz, I.; Death, R.G. Macroinvertebrate Community Composition and Richness along Extreme Gradients: The Role of Local, Catchment, and Climatic Variables in Patagonian Headwater Streams. *Freshw. Biol.* **2022**, *67*, 445–460. [CrossRef]
36. Tolkamp, H.H. Organism-Substrate Relationships in Lowland Streams. Ph.D. Thesis, Landbouwhogeschool Wageningen, Wageningen, The Netherlands, 1980.
37. Elvira, B.; Nicola, G.G.; Ayllón, D.; Almodóvar, A. Determinants of Large-scale Spatial Distribution and Seasonal Microhabitat Selection Patterns of the Endangered Freshwater Blenny Salaria Fluviatilis in the Ebro River Basin, Spain. *Aquat. Conserv.* **2021**, *31*, 3261–3275. [CrossRef]
38. Fu, L.; Jiang, Y.; Ding, J.; Liu, Q.; Peng, Q.-Z.; Kang, M.-Y. Impacts of Land Use and Environmental Factors on Macroinvertebrate Functional Feeding Groups in the Dongjiang River Basin, Southeast China. *J. Freshw. Ecol.* **2016**, *31*, 21–35. [CrossRef]
39. Johan, F.; Jafri, M.Z.; Lim, H.S.; Wan Maznah, W.O. Laboratory Measurement: Chlorophyll-a Concentration Measurement with Acetone Method Using Spectrophotometer. In Proceedings of the 2014 IEEE International Conference on Industrial Engineering and Engineering Management, Selangor Darul Ehsan, Malaysia, 9–12 December 2014; pp. 744–748.
40. R Core Team. A Language and Environment for Statistical Computing: R Foundation for Statistical Computing, Vienna. Available online: https://www.R-project.org/ (accessed on 3 April 2025).
41. Fox, J. *Using the R Commander: A Point-and-Click Interface for R*; CRC Press, Taylor & Francis Group: Boca Raton, FL, USA, 2017; ISBN 978-1-4987-4190-3.
42. Lê, S.; Josse, J.; Husson, F. FactoMineR: An RPackage for Multivariate Analysis. *J. Stat. Softw.* **2008**, *25*, 1–18. [CrossRef]
43. Hammer, Ø. *PAleontological Statistics, Version 4.10 Reference Manual*; University of Oslo: Oslo, Norway, 2024.
44. Dinno, A. *Dunn's Test of Multiple Comparisons Using Rank Sums*, Version 1.3.6. 2024. Available online: https://cran.r-project.org/web/packages/dunn.test/dunn.test.pdf (accessed on 14 September 2025).
45. Krebs, C.J. *Ecological Methodology*, 1st ed.; Harper & Row, Publishers: New York, NY, USA, 1989.
46. Zou, Y.; van der Werf, W.; Liu, Y.; Axmacher, J.C. Predictability of Species Diversity by Family Diversity across Global Terrestrial Animal Taxa. *Glob. Ecol. Biogeogr.* **2020**, *29*, 629–644. [CrossRef]
47. Pires, M.M.; Grech, M.G.; Stenert, C.; Maltchik, L.; Epele, L.B.; McLean, K.I.; Kneitel, J.M.; Bell, D.A.; Greig, H.S.; Gagne, C.R.; et al. Does Taxonomic and Numerical Resolution Affect the Assessment of Invertebrate Community Structure in New World Freshwater Wetlands? *Ecol. Indic.* **2021**, *125*, 107437. [CrossRef] [PubMed]
48. Lewis, N.D. *100 Statistical Tests in R. Easy R Series*, 1st ed.; Heather Hills: Bradenton, FL, USA, 2013.

49. Cummins, K.W.; Wilzbach, M.A. *Field Procedures of Analysis of Functional Feeding Groups of Stream Macroinvertebrates*; Appalachian Environmental Laboratory, University of Maryland: College Park, MD, USA, 1985.
50. Allan, J.D. *Stream Ecology. Structure and Function of Running Waters*, 1st ed.; Chapmann & Hall: New York, NY, USA, 1995; ISBN 978-0-412-35530-1.
51. Lamberti, G.A.; Moore, J.W. Aquatic Insects as Primary Consumers. In *The Ecology of Aquatic Insects*; Resh, V.H., Rosneberg, D.M., Eds.; Greenwood Press: New York, NY, USA, 1984; pp. 164–195.
52. Doretto, A.; Piano, E.; Larson, C.E. The River Continuum Concept: Lessons from the Past and Perspectives for the Future. *Can. J. Fish. Aquat. Sci.* **2020**, *77*, 1853–1864. [CrossRef]
53. Jones, N.E. Incorporating Lakes within the River Discontinuum: Longitudinal Changes in Ecological Characteristics in Stream–Lake Networks. *Can. J. Fish. Aquat. Sci.* **2010**, *67*, 1350–1362. [CrossRef]
54. Dąbrowski, J.; Więcaszek, B. Analysis of Fish Species Composition in Miazga—A Stream Blocked with a Small Dam Reservoir (Pilica River Basin, Central Poland). *Folia Pomeranae Univ. Technol. Stetin. Aliment. Piscaria Et Zootech.* **2018**, *345*, 27–44. [CrossRef]
55. Vilbaste, S.; Pall, P.; Haldna, M.; Nõges, P.; Piirsoo, K.; Nõges, T. How the Catchment-River-Lake Continuum Shapes the Downstream Water Quality. *J. Limnol.* **2024**, *83*, 2167. [CrossRef]
56. Stanford, J.A.; Ward, J.V. Revisiting the Serial Discontinuity Concept. *Regul. Rivers Res. Manag.* **2001**, *17*, 303–310. [CrossRef]
57. Hornbach, D.J.; Sietman, B.E.; William Bouchard, R., Jr. The Relationship between Stream Size and Life-History Traits in Freshwater Mussels: An Examination of the Host-Habitat Continuum Concept. *Hydrobiologia* **2024**, *851*, 4419–4437. [CrossRef]
58. Koszałka, J.; Jabłońska-Barna, I. Aquatic Macroinvertebrate Biodiversity in Freshwaters in Northeastern Poland. In *Polish River Basins and Lakes*; Korzeniewska, E., Harnisz, M., Eds.; Springer: Cham, Switzerland, 2020; Volume II, pp. 103–125.
59. Krepski, T.; Sługocki, Ł.; Goździk, I.; Humiczewski, M.; Popko, R.; Czerniawski, R. Spatial Distribution Patterns of Zooplankton and Macroinvertebrates in a Small River under Strong Anthropogenic Pressure. *Water* **2024**, *16*, 262. [CrossRef]
60. Kędzior, R.; Kłonowska-Olejnik, M.; Dumnicka, E.; Woś, A.; Wyrębek, M.; Książek, L.; Grela, J.; Madej, P.; Skalski, T. Macroinvertebrate Habitat Requirements in Rivers: Overestimation of Environmental Flow Calculations in Incised Rivers. *Hydrol. Earth Syst. Sci.* **2022**, *26*, 4109–4124. [CrossRef]
61. Dorava, J.M.; Milner, A.M. Role of Lake Regulation on Glacier-Fed Rivers in Enhancing Salmon Productivity: The Cook Inlet Watershed, South-Central Alaska, USA. *Hydrol. Process.* **2000**, *14*, 3149–3159. [CrossRef]
62. Luecke, C.; MacKinnon, P. Landscape Effects on Growth of Age-0 Arctic Grayling in Tundra Streams. *Trans. Am. Fish. Soc.* **2008**, *137*, 236–243. [CrossRef]
63. Brysiewicz, A.; Czerniejewski, P.; Dąbrowski, J.; Formicki, K. Characterisation of Benthic Macroinvertebrate Communities in Small Watercourses of the European Central Plains Ecoregion and the Effect of Different Environmental Factors. *Animals* **2022**, *12*, 606. [CrossRef]
64. Pander, J.; Habersetzer, L.; Casas-Mulet, R.; Geist, J. Effects of Stream Thermal Variability on Macroinvertebrate Community: Emphasis on Native Versus Non-Native Gammarid Species. *Front. Environ. Sci.* **2022**, *10*, 869396. [CrossRef]
65. Connell, J.H. Diversity in Tropical Rain Forests and Coral Reefs: High diversity of trees and corals is maintained only in a nonequilibrium state. *Science* **1978**, *199*, 1302–1310. [CrossRef]
66. Beauger, A.; Lair, N.; Reyes-Marchant, P.; Peiry, J.-L. The Distribution of Macroinvertebrate Assemblages in a Reach of the River Allier (France), in Relation to Riverbed Characteristics. *Hydrobiologia* **2006**, *571*, 63–76. [CrossRef]
67. Golovatyuk, L.V.; Nazarova, L.B.; Kalioujnaia, I.J.; Grekov, I.M. Taxonomic Composition and Salinity Tolerance of Macrozoobenthos in Small Rivers of the Southern Arid Zone of the East European Plain. *Biology* **2023**, *12*, 1271. [CrossRef]
68. Leitner, P.; Graf, W.; Hauer, C. Ecological Assessment of High Sediment Loads Based on Macroinvertebrate Communities in the Bohemian Massif in Austria—A Sensitivity Analysis. *Limnologica* **2023**, *98*, 125941. [CrossRef]
69. Jansen, W.; Böhmer, J.; Kappus, B.; Beiter, T.; Breitinger, B.; Hock, C. Benthic Invertebrate and Fish Communities as Indicators of Morphological Integrity in the Enz River (South-West Germany). *Hydrobiologia* **2000**, *422*, 331–342. [CrossRef]
70. Varadinova, E.; Sakelarieva, L.; Park, J.; Ivanov, M.; Tyufekchieva, V. Characterisation of Macroinvertebrate Communities in Maritsa River (South Bulgaria)—Relation to Different Environmental Factors and Ecological Status Assessment. *Diversity* **2022**, *14*, 833. [CrossRef]
71. Park, J.; Sakelarieva, L.; Varadinova, E.; Evtimova, V.; Vidinova, Y.; Tyufekchieva, V.; Georgieva, G.; Ihtimanska, M.; Todorov, M. Taxonomic Composition and Dominant Structure of the Macrozoobenthos in the Maritsa River and Some Tributaries, South Bulgaria. *Acta Zool. Bulg.* **2023**, *16*, 61–74.
72. Nautiyal, P.; Mishra, A.S. Role of Depth, Habitat and Current Velocity on Distribution of Benthic Macroinvertebrate Fauna in the Himalayan River, Ramganga. *Proc. Zool. Soc.* **2022**, *75*, 349–360. [CrossRef]
73. Cristiano, G.; Di Sabatino, A. How Does Water Current Velocity Affect Invertebrate Community and Leaf-litter Breakdown in a Physicochemically Stable Freshwater Ecosystem? An Experimental Study in Two Nearby Reaches (Erosional vs. Depositional) of the Vera Spring (Central Italy). *Ecohydrology* **2024**, *17*, e2532. [CrossRef]

74. Thakur, Y.; Grover, A.; Sinha, R. Differential Distribution of Macroinvertebrate Associated with Water Quality. *World Water Policy* **2023**, *9*, 84–112. [CrossRef]
75. Klimaszyk, P.; Joniak, T.; Trawiński, A. Assessment of Running Water Quality Based on Zoobenthos Communities—Biotic Index BMWP-PL for the Kłodawa River. *Ekol. I Tech.* **2011**, *19*, 132–138.
76. Croijmans, L.; De Jong, J.F.; Prins, H.H.T. Oxygen Is a Better Predictor of Macroinvertebrate Richness than Temperature—A Systematic Review. *Environ. Res. Lett.* **2021**, *16*, 023002. [CrossRef]
77. Pineda-Pineda, J.J.; Muñoz-Rojas, J.; Morales-García, Y.E.; Hernández-Gómez, J.C.; Sigarreta, J.M. Biomathematical Model for Water Quality Assessment: Macroinvertebrate Population Dynamics and Dissolved Oxygen. *Water* **2022**, *14*, 2902. [CrossRef]
78. Vagheei, H.; Laini, A.; Vezza, P.; Palau-Salvador, G.; Boano, F. Ecohydrologic Modelling Using Nitrate, Ammonium, Phosphorus, and Macroinvertebrates as Aquatic Ecosystem Health Indicators of Albaida Valley (Spain). *J. Hydrol. Reg. Stud.* **2022**, *42*, 101155. [CrossRef]
79. Mathers, K.L.; Armitage, P.D.; Hill, M.; McKenzie, M.; Pardo, I.; Wood, P.J. Seasonal Variability of Lotic Macroinvertebrate Communities at the Habitat Scale Demonstrates the Value of Discriminating Fine Sediment Fractions in Ecological Assessments. *Ecol. Evol.* **2023**, *13*, e10564. [CrossRef]
80. Wiggins, G.B. *Caddisflies: The Underwater Architects*, 1st ed.; University of Toronto Press: Toronto, ON, Canada, 2005.
81. Gao, Y.; Rong, L.; Zhao, X.; Wang, X.; Lin, C.; Cao, L.; Yang, H. Short-Term Effects of Substrate Surface Structure on Macroinvertebrates Community Structure and Functional Characteristics. *Ecol. Eng.* **2024**, *201*, 107215. [CrossRef]
82. Allan, J.D.; Castrillo, M.M.; Capps, K.A. *Stream Ecology: Structure and Function of Running Waters*, 3rd ed.; Springer Nature: Cham, Switzerland, 2020.
83. Lamberti, G.A.; Gregory, S.V. CPOM Transport, Retention, and Measurement. In *Methods in Stream Ecology*; Hauer, F.R., Lamberti, G.A., Eds.; Elsevier: Burlington, MA, USA, 2007; pp. 273–289.
84. Minshall, G.W. Aquatic Insects-Substratum Relationship. In *The Ecology of Aquatic insects*; Resh, V.H., Rosenberg, D.M., Eds.; Praeger Publisher: New York, NY, USA, 1984; pp. 358–400.
85. Curtean-Bănăduc, A.; Olosutean, H.; Bănăduc, D. Influence of Environmental Variables on the Structure and Diversity of Ephemeropteran Communities: A Case Study of the Timiş River, Romania. *Acta Zool. Bulg.* **2016**, *68*, 215–224.
86. Vidinova, Y.; Russev, B. Distribution and Ecology of the Representatives of Some Ephemeropteran Families in Bulgaria. In *Ephemeroptera & Plecoptera: Biology-Ecology-Systematics*; Landolt, P., Sartori, M., Eds.; MTL: Fribourg, Switzerland, 1997; pp. 139–146.
87. Romito, A.M.; Eggert, S.L.; Diez, J.M.; Wallace, J.B. Effects of Seasonality and Resource Limitation on Organic Matter Turnover by Chironomidae (Diptera) in Southern Appalachian Headwater Streams. *Limnol. Oceanogr.* **2010**, *55*, 1083–1092. [CrossRef]
88. Hirabayashi, K.; Wotton, R.S. Organic Matter Processing by Chironomid Larvae (Diptera: Chironomidae). *Hydrobiologia* **1998**, *382*, 151–159. [CrossRef]
89. Vaughn, C.C.; Hakenkamp, C.C. The Functional Role of Burrowing Bivalves in Freshwater Ecosystems. *Freshw. Biol.* **2001**, *46*, 1431–1446. [CrossRef]
90. Straka, M.; Syrovátka, V.; Helešic, J. Temporal and Spatial Macroinvertebrate Variance Compared: Crucial Role of CPOM in a Headwater Stream. *Hydrobiologia* **2012**, *686*, 119–134. [CrossRef]
91. Kovács, K.; Selmeczy, G.B.; Kucserka, T.; Abdel-Hameid, N.-A.H.; Padisák, J. The Effect of Stream Bed Morphology on Shredder Abundance and Leaf-Litter Decomposition in Hungarian Midland Streams. *Pol. J. Environ. Stud.* **2011**, *20*, 1547–1556.
92. Gerhardt, A.; Bloor, M.; Mills, C.L. Gammarus: Important Taxon in Freshwater and Marine Changing Environments. *Int. J. Zool.* **2011**, *2011*, 524276. [CrossRef]
93. Patrick, C.J. The Effect of Shredder Community Composition on the Production and Quality of Fine Particulate Organic Matter. *Front. Freshw. Sci.* **2013**, *32*, 1026–1035. [CrossRef]
94. Piechocki, A.; Wawrzyniak-Wydrowska, B. *Guide to Freshwater and Marine Mollusca of Poland*, 1st ed.; Bogucki Wydawnictwo Naukowe: Poznań, Poland, 2016; ISBN 978-83-7986-109-5.
95. Van den Eynde, C.; Sohier, C.; Matthijs, S.; De Regge, N. Temperature and Food Sources Influence Subadult Development and Blood-Feeding Response of *Culicoides obsoletus* (Sensu Lato) under Laboratory Conditions. *Parasites Vectors* **2021**, *14*, 300. [CrossRef]
96. Becquet, J.; Lamouroux, N.; Condom, T.; Gouttevin, I.; Forcellini, M.; Launay, B.; Rabatel, A.; Cauvy-Fraunié, S. Macroinvertebrate Distribution Associated with Environmental Variables in Alpine Streams. *Freshw. Biol.* **2022**, *67*, 1815–1831. [CrossRef]
97. Lock, K.; Adriaens, T.; Goethals, P. Effect of Water Quality on Blackflies (Diptera: Simuliidae) in Flanders (Belgium). *Limnologica* **2014**, *44*, 58–65. [CrossRef]
98. Sługocki, Ł.; Czerniawski, R. Water Quality of the Odra (Oder) River before and during the Ecological Disaster in 2022: A Warning to Water Management. *Sustainability* **2023**, *15*, 8594. [CrossRef]
99. Milner, V.S.; Yarnell, S.M.; Peek, R.A. The Ecological Importance of Unregulated Tributaries to Macroinvertebrate Diversity and Community Composition in a Regulated River. *Hydrobiologia* **2019**, *829*, 291–305. [CrossRef]

100. Hsu, C.; Kang, J.; Chang, Y.; Yeh, L.; Chen, C.; Hsieh, H.; Lin, H. Reliable Data From Community-Based Citizen Science for Coastal Biodiversity Research in the Taoyuan Algal Reef, Taiwan. *Aquat. Conserv.* **2025**, *35*, e70138. [CrossRef]
101. Hegarty, S.; Hayes, A.; Regan, F.; Bishop, I.; Clinton, R. Using Citizen Science to Understand River Water Quality While Filling Data Gaps to Meet United Nations Sustainable Development Goal 6 Objectives. *Sci. Total Environ.* **2021**, *783*, 146953. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.