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MACROINVERTEBRATE DIVERSITY IN POST-EXPLOITATION LIMESTONE PONDS OVER A 10-YEAR PERIOD

Abstract: The study aimed to investigate the structure and diversity of macroinvertebrate assemblages in five small permanent water bodies within a limestone quarry area. Benthic samples were collected monthly from April to November in 2009 and 2019, and basic physicochemical water parameters were measured. The results showed that the assemblages were dominated by mayflies (Baetidae and Caenidae), damselflies (Coenagrionidae), and dipterans (Chironomidae), with a total of 42 taxa recorded. Over the ten years, taxon richness and diversity increased, especially in spring, and became more diverse among the ponds. The abundance and frequency of occurrence of hololimic organisms, such as snails (Lymnaeidae and Planorbidae), oligochaetes, and water mites, also increased. However, macroinvertebrate densities, although they doubled overall, remained low due to the nature of the sediments. The RDA analysis indicated that temperature, seasonality, pond margin shading, and morphometry were the main environmental factors influencing macroinvertebrates, which explained 38.6 % of the total variance in macroinvertebrate abundance. Further research, including analysis at lower taxonomic levels, will help us better understand the factors driving the observed patterns in macroinvertebrate assemblages in small anthropogenic water bodies.

Keywords: limestone quarry, antropogenic ponds, zoobenthos, assemblage structure, long-term changes

Introduction

The literature provides extensive data on the negative impact of human activity on the quality of aquatic ecosystems, particularly rivers [1, 2]. There is, however, a growing recognition of the importance of both natural and anthropogenic ponds and their contribution to aquatic biodiversity [3]. The heterogeneity of individual ponds creates diverse habitats for wildlife at the landscape level, which combine physicochemical environment, resource availability, and biotic interactions, along with the potential impact of the surrounding landscape [4, 5]. However, despite many studies, long-term research data are still lacking, especially for ponds of anthropogenic origin. A long-term approach is crucial for assessing environmental changes in the habitat and biocenosis of these ecosystems, as well as emphasising their functioning and relevance.

Several studies have highlighted that ponds have a higher capacity to support more species, including rare and endangered ones, compared to other freshwater ecosystems [6, 7]. Despite their high conservation value, ponds face constant threats from human activities such as urbanisation, agricultural intensification, hydrological alterations, and

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climate change [8, 9]. However, new ponds have been created in response to new uses and are now permanent components of the industrial landscape, particularly associated with mining activity, both opencast, and underground exploitation of raw materials. According to the mining activity dataset, more than 44,900 areas worldwide are affected by active surface mining alone, covering 101,583 km² of land [10]. Thus, the potential for the development of pit lakes and other small water bodies in the post-mining landscape will still be enormous. This also applies to Poland, especially its southern part with a long history of mining [11]. The presence of ponds in these areas can enhance regional diversity by creating refuges and improving connectivity between aquatic ecosystems [12, 13]. On the other hand, some non-native species can use ponds as a dispersal corridor [14] which, consequently, may alter local macroinvertebrate assemblages either directly or through changes in the composition of stagnant water habitats [15].

Researchers have conducted studies on the traits of benthic macroinvertebrates in ponds at both local and regional scales [16]. Numerous environmental factors have been investigated to determine their impact on the distribution rates of organisms and macroinvertebrate assemblage structure, such as hydroperiod [17], surface area [18], water parameters [19], the presence of fish [20], vegetation cover [21], the dispersal ability of individuals [22], as well as tree canopy openness [23]. Although ponds of anthropogenic origin usually offer harsh and variable living conditions, many macroinvertebrates, especially those of high dispersal capacities such as Diptera, Coleoptera, Ephemeroptera, and Odonata, as well as less affected by water pollution, can recognise them as substitute habitats for natural ones [7, 13]. Non-insect macroinvertebrates commonly associated with these waterbodies include molluscs, crustaceans, and oligochaetes [6, 24].

In the Opole region of southwestern Poland, the origin of many ponds and reservoirs can be attributed to carbonate raw material exploitation (limestone and marl), resulting in severe impacts and degradation of the topography, soil profiles, water resources, and vegetation [25]. While various reclamation and revitalisation works have been undertaken to address these issues, the research has mainly focused on land surface management and vegetation cover or terrestrial fauna [26, 27].

The main objective of this study was to elucidate the development of macroinvertebrate assemblages in limestone quarry ponds, with a focus on seasonality, pond morphology, and habitat features created by plants. Additionally, the study aimed to evaluate changes in the distribution of invertebrates, as well as the composition and structure of benthic assemblages, over a relatively long period.

Materials and methods

Study area

The research was conducted within the Gorazdze Limestone Mine, located in the central part of the Opole Voivodeship (southwestern Poland), in the restored limestone quarry area of approximately 250 hectares. The survey for this study was conducted on five small permanent water bodies (P1-P5) located in close proximity to each other, as shown in Figure 1. The greatest distance between the ponds was 850 meters. At the start of the study, the ponds' ages ranged from six (P1) to 18 (P4) years. Table 1 provides a brief overview of the pond morphometry and other selected habitat characteristics, with name abbreviations used in the text.

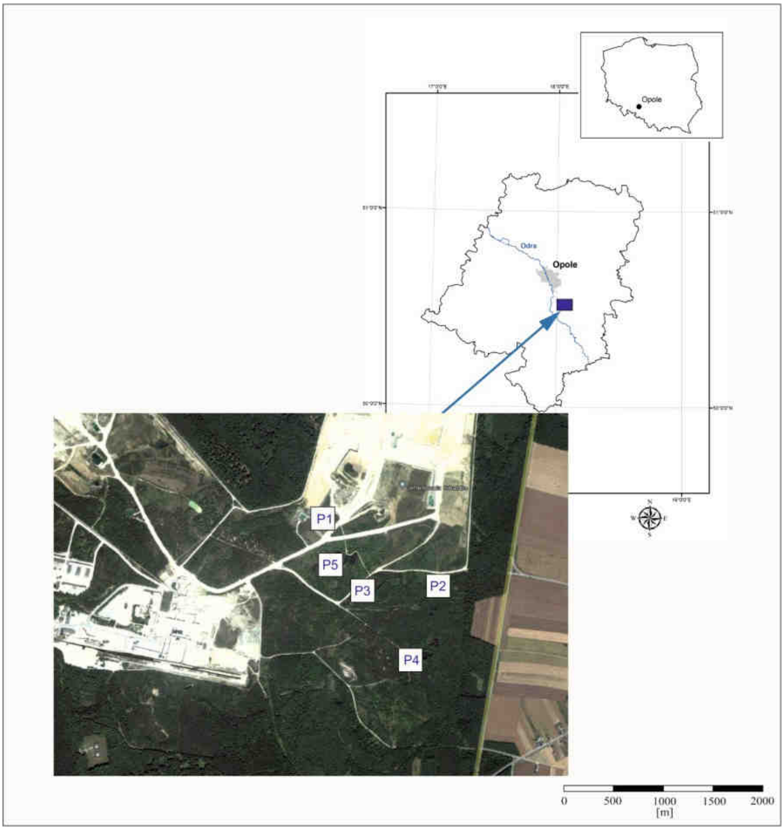

Fig. 1. Location of ponds (P1-P5) in the limestone quarry of the Gorazdze Mine

Table 1

Description of environmental variables characterising the surveyed ponds (P1-P5)

Characteristics		**Water body**				
		P1	**P2***	**P3**	**P4**	**P5**
Pond area** [m²]		2078	3064	5681	4134	6936
Pond depth [cm]		20-50	20-40	30-80	40-130	40-150
Rocky elements at the shoreline		-	+	+	-	-
Submerged macrophytes		-	-	charophyte meadows	charophyte meadows	charophyte meadows
Dominant halophytes in the rush strip		*Typha laxmannii*	*Scirpus* sp.	*Phragmites communis*	*Phragmites communis*	*Phragmites communis*
Large predators		newts (in 2019)	-	fish	fish	-
Shoreline shading [%]	2009	0	80	50	60	10
	2019	40	80	50	60	50

* A water body formed by the flooding of a previously herbaceous small area, overgrown by tufts of grasses and bulrushes *Scirpus* sp., as well as shrubs of white willow *Salix alba*, ** Measured according to the outer pond margin (maximum winter water level)

During the summer season, Pond P3 has been utilised as a water source for watering the internal roads in the exploitation part of the quarry to minimise dusting.

Macroinvertebrate sampling and water analysis

Between April and November of 2009 and 2019, the ponds were sampled every month for macroinvertebrates using a standard D-frame pond net with a mesh size of 500 µm. The time-limited and habitat-dependent sampling technique was used, involving a 1-minute kick and sweep sampling with equal sampling time split among the main microhabitats identified along a transect. Submerged and emergent macrophytes, soft sediments without vegetation (up to 15 cm thick), and pond shores with rocky material were among the typical microhabitats represented, and organisms on rocky elements and woody debris were collected manually if present. The three samples obtained were combined before analysis, and macroinvertebrates were identified at the family level, except for Oligochaeta and Hydrachnidia.

Additionally, basic physical and chemical water parameters such as temperature, pH, conductivity (*EC*), and dissolved oxygen (DO) were measured in the field using a portable meter. In July of each year, water was collected and stored in a cooler for laboratory analysis of total phosphorus (TP) and calcium content. The TP content was determined using a colorimetric method with molybdenum blue, while atomic emission spectrophotometry (AES) was employed to measure the calcium content using the BWB XP Flame Photometer.

Data analysis

The study calculated several parameters and indices based on taxon composition or percentage of individuals, including frequency of occurrence (F) [%], taxa dominance (D) [%], taxa richness (S), the Shannon-Wiener diversity index (H'), and the Pielou evenness index (J'). Non-parametric tests, such as the Kruskal-Wallis (KW), Friedman (F), and Wilcoxon (W+) tests, were used to examine differences in water parameters and macroinvertebrate assemblage metrics between groups spatially or temporally. Before statistical comparisons, data were tested for normality. Redundancy Analysis (RDA) with forward selection was conducted to explore the relationships between macroinvertebrate assemblages and environmental variables, including season, pond morphometry (area and depth), margin shading, elodeides occurrence, and water parameters (temperature, pH, DO, and *EC*). Taxa with a relative abundance of less than 2 % (recendents) and those that were sporadically distributed (< 10 %) were excluded from the analysis to avoid bias caused by rare and uncommon ones. The statistical significance was evaluated using the Monte Carlo permutation test (499 permutations). RDA was run using CANOCO version 5.0.

Results

Water physicochemical characteristics

Combined values of basic physicochemical water parameters (temperature, pH, dissolved oxygen, and conductivity) are presented in Table 2. In each year of the study, the dissolved oxygen content (DO) and conductivity (*EC*) differed significantly (KW test, $p < 0.05$) between the ponds. According to a posteriori comparison, in both years of research, the DO content in the P2 pond was significantly lower than in P1 and P5 (water bodies with varying margin shading), and the EC was lower in the P1 pond than in P3-P5 (water bodies of different age and depth). Furthermore, there was a noteworthy rise in the mean water temperature over the ten years, despite seasonal variations, with the increase primarily occurring in spring and autumn (W+test, $p < 0.05$). Ponds with a high content of calcium carbonate in their geology are likely to be eutrophic. Total phosphorus concentrations during the summer season ranged from 0.060 mg dm^{-3} (P4) to 0.129 mg dm^{-3} (P1), while calcium concentrations ranged from 63.8 mg dm^{-3} (P5) to 91.7 mg dm^{-3} (P2).

Table 2

Physicochemical characteristics of the ponds surveyed (means are given ±*SD*, range in parentheses)

Research year	Water body	Temp.* [°C]	pH [-]	DO** [$mgO_2\,dm^{-3}$]	*EC*** [$\mu S\,cm^{-1}$]
2009 (*n* = 35)	P1	16.0 ±6.5 (8.2 - 25.1)	8.0 ±0.3 (7.6 - 8.4)	8.0 ±0.7 (7.0 - 8.9)	357 ±54 (273 - 430)
	P2	13.6 ±5.0 (7.8 - 21.1)	6.9 ±1.7 (4.2 - 8.2)	6.2 ±1.3 (4.2 - 7.2)	458 ±86 (372 - 591)
	P3	14.8 ±5.0 (8.6 - 21.7)	7.2 ±0.5 (6.5 - 7.9)	7.6 ±0.7 (6.5 - 8.1)	551 ±58 (481 - 653)
	P4	14.8 ±5.2 (8.4 - 21.4)	7.3 ±0.8 (6.0 - 8.0)	7.0 ±0.7 (6.0 - 7.8)	521 ±61 (435 - 634)
	P5	15.3 ±5.2 (9.0 - 22.7)	7.7 ±0.6 (6.8 - 8.4)	8.0 ±0.8 (7.0 - 9.2)	547 ±48 (495 - 633)
2019 (*n* = 35)	P1	18.4 ±4.8 (9.9 - 24.6)	7.6 ±0.7 (6.7 - 8.8)	7.8 ±0.3 (7.5 - 8.2)	387 ±53 (325 - 480)
	P2	16.0 ±4.4 (7.9 - 20.9)	7.2 ±0.5 (6.5 - 7.9)	6.2 ±1.3 (4.3 - 7.4)	470 ±71 (382 - 605)
	P3	18.0 ±4.7 (9.3 - 23.6)	7.3 ±0.5 (6.8 - 8.1)	7.5 ±0.6 (6.5 - 8.0)	578 ±34 (506 - 601)
	P4	18.9 ±5.6 (8.1 - 24.1)	7.4 ±0.5 (6.8 - 8.1)	7.3 ±0.7 (6.2 - 8.0)	553 ±39 (494 - 590)
	P5	18.6 ±4.9 (9.2 - 24.7)	7.5 ±0.4 (7.1 - 8.0)	8.2 ±0.6 (7.6 - 9.4)	555 ±34 (505 - 593)

* Statistically important differences between the study years (Wilcoxon test, $p < 0.05$), ** statistically important differences between ponds (Kruskal-Wallis test, $p < 0.05$), *SD* - Standard deviation

Benthic macroinvertebrates

Throughout the course of this research, a total of 42 different taxa were identified, with 35 and 38 taxa observed in 2009 and 2019, respectively. A considerable proportion of the taxa (around one-third) were only present on less than 10 % of the sampling dates. Insects were the most abundant group, accounting for 37 of the identified taxa. The most commonly observed insects were the mayflies Baetidae and Canidae, the dipterans Chironomidae, and the damselflies Coenagrionidae. Interestingly, no crustaceans were found during the study period, although microcrustaceans such as Copepoda or Ostracoda were not included in the study.

In the first survey in 2009, the taxon richness of individual ponds ranged between five (P4) and 16 (P5). On the other hand, between four (P3) and 22 (P2) in the second survey in 2019 (Fig. 2).

Notwithstanding that the occurrence of macroinvertebrates is seasonally variable, there were no significant differences in taxon richness in the first year of the study, both between the ponds and seasons. In contrast, in the second survey, taxon richness was markedly higher in spring (median 14) compared to autumn (median 8.5) (F test: $\chi_{2\,(2,\,N=10)} = 8.36$, *p* = 0.0153), and macroinvertebrate richness significantly differed between the two ponds (P2 vs P5) (KW test: $H_{(4, N=35)} = 10.2$, $p = 0.0373$).

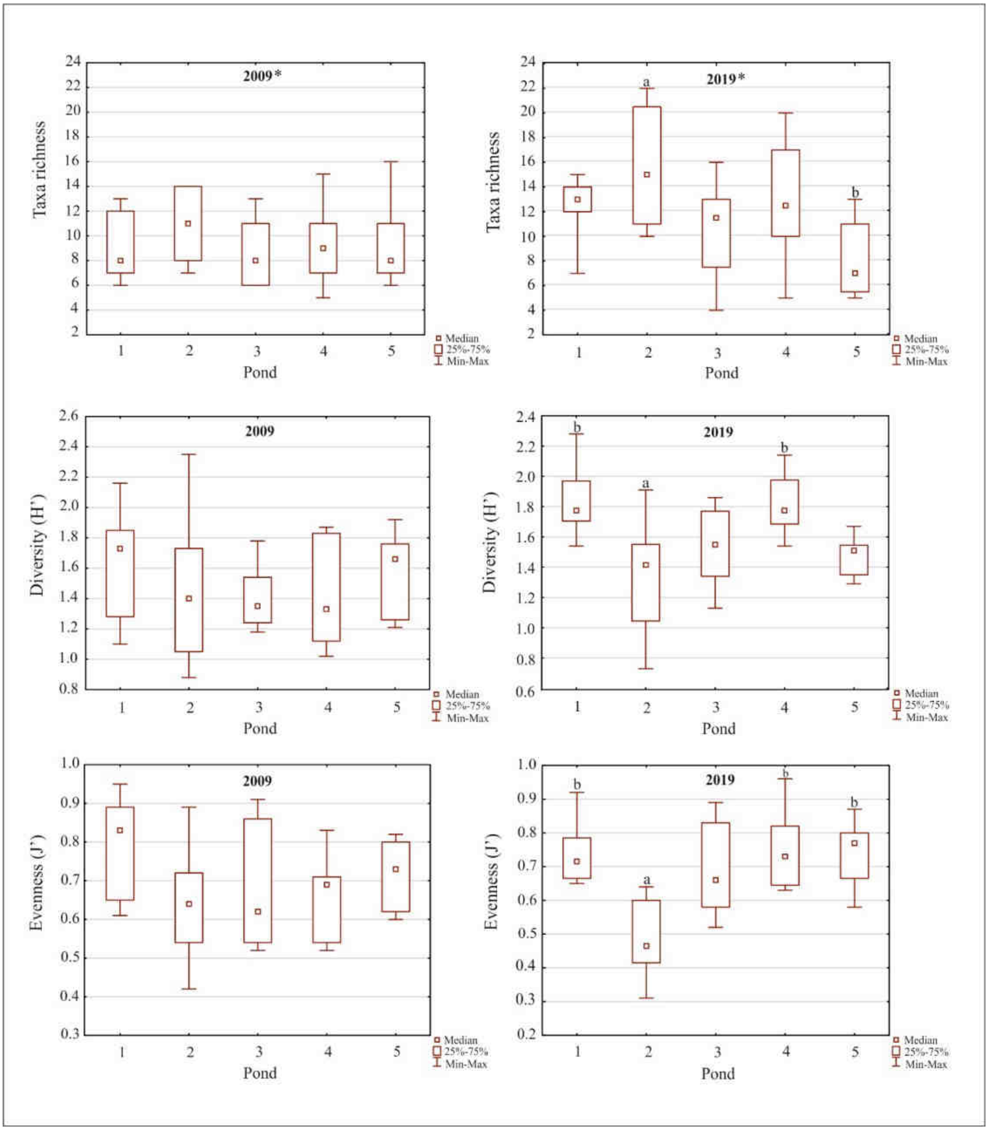

Fig. 2. Comparison of macroinvertebrate richness, diversity, and evenness in the surveyed ponds and years (lowercase letters denote significant differences between ponds in the Kruskal-Wallis test and the asterisk between study years in the Wilcoxon test, $p < 0.05$)

The study revealed a general increase in taxonomic richness, with an average of 9.2 + 2.9 (2009) and 11.8 + 4.8 (2019). There were no significant differences between the seasons in both years for the Shannon-Wiener diversity index (H') and Pielou evenness index (J'). The combined annual values did not show any significant differences between 2009 and 2019 (Fig. 2). However, when analysing the data on a seasonal basis, the H' index values were found to differ in spring (W+test: z = 2.24, p = 0.02), with a median of 1.29 (2009) and 1.71 (2019). For both indices, there were also no differences among ponds in 2009, as opposed to 2019, when their values varied considerably (KW test, $p < 0.05$).

Table 3

Mean densities (ind. m^{-2}) of invertebrate taxa found in the surveyed ponds (means are given ±*SD*, range in parentheses)

Taxa	Total in 2009 (*n* = 35)	Total in 2019 (*n* = 35)
Diptera	43 ±71 (0 - 343) $^{A>C}$	51 ±46 (2.0 - 180) $^{A>C}$
Ephemeroptera*	39 ±51 (0 - 188)	102 ±128** (0 - 491)
Odonata (P3-P4) *	13 ±13** (0 - 46)	17 ±18** (1.0 - 96)
Trichoptera	3.3 ±6.0 (0 - 34)	5.5 ±8.2** (0 - 35) $^{A>BC}$
Heteroptera (P5) *	3.4 ±5.0 (0 - 17)	3.8 ±5.2 (0 - 24)
Coleoptera	1.7 ±2.6 (0 - 11)	2.0 ±3.0 (0 - 9) $^{A>C}$
Megaloptera*	0.5 ±1.0 (0 - 4)	1.9 ±4.0 (0 - 23) $^{C>A}$
Gastropoda*	1.0 ±2.0 (0 - 11)	11 ±16** (0 - 77)
Bivalvia	0.09 ±0.30 (0 - 1)	1.1 ±3.5** (0 - 16)
Oligochaeta*	1.8 ±6.6 (0 - 29)	11 ±31 (0 - 210) $^{A>C}$
Hirudinea	0.5 ±1.2 (0 - 6)	0.9 ±1.4 (0 - 5)
Hydrachnida*	2.5 ±6.0** (0 - 32)	9 ±19** (0 - 98)
Total*	109 ±90 (14 - 375)	202 ±191 (12 - 766)

* statistically important (Wilcoxon test, $p < 0.05$), ** significant differences between ponds in the study year (Kruskal-Wallis test, $p < 0.05$), *SD* - Standard deviation, ^{ABC} letters denote significant differences between seasons: (A) spring, (B) summer, (C) autumn (Friedman test, $p < 0.05$)

Table 3 shows the mean densities for each taxon from all ponds and sampling dates combined for the years 2009 and 2019. Although the ponds had a high density of mayflies, their numbers increased significantly over the decade, more than two-fold on average (W+test: z = 2.7, p = 0.007). Statistically significant differences in density (W+test, $p < 0.05$) were also observed for Megaloptera, Gastropoda, Oligochaeta, and Hydrachnidia. When comparing individual ponds, significant differences were noted for Odonata (ponds P3 - a 30 % decline and P4 - a two-fold increase) and Heteroptera (P5 - a 60 % decline). In general, many taxa showed increasing abundance during the 2009-2019 period, but their densities varied among the ponds, especially for Odonata and Hydrachnidia. In 2019, Ephemeroptera, Trichoptera, Gastropoda, and Bivalvia also showed significant differences in density (KW test, $p < 0.05$). Additionally, greater seasonal variation in macroinvertebrate abundance was noted in 2019, especially in Diptera, Trichoptera, Coleoptera, Megaloptera, and Oligochaeta. The spring surveys provided a higher number of these invertebrates, except for Megaloptera larvae which were more numerous in autumn.

There is an increase in the frequency of occurrence of hololimnic organisms over the decade (Fig. 3). This group includes gastropods Lymnaeidae and Planorbidae, bivalves Sphaeridae, oligochaetes, and water mites, with their occurrence rate increasing by 12.5 % - 39 %. Among the merolimnic organisms, which are aquatic insects, only alderfly Sialidae larvae had an equally high increase in the frequency of occurrence. The true bugs Corixidae were the only taxa that showed a decrease in occurrence rate, by more than 10 %.

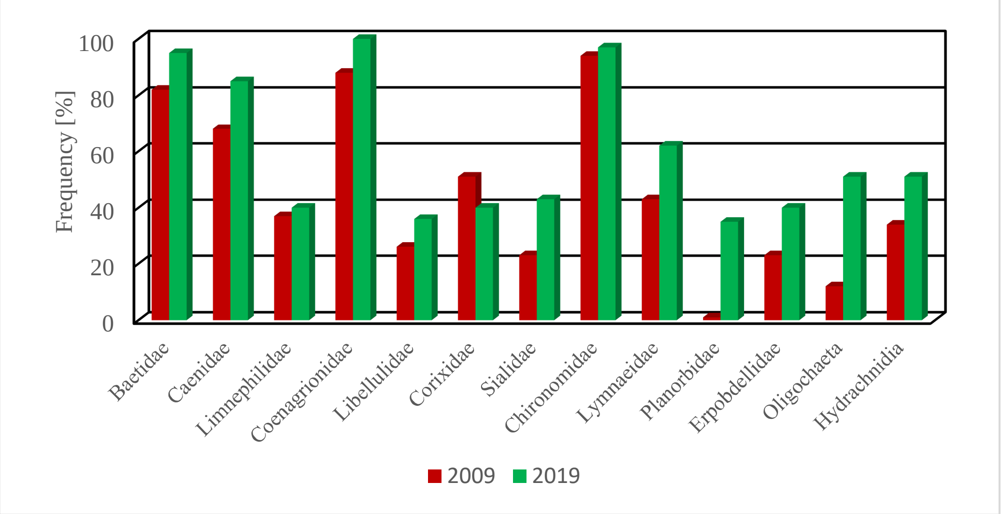

Fig. 3. Frequency of benthic macroinvertebrates in the limestone quarry ponds

Considering individual ponds and seasons in both years of research, 14 taxa had the status of seasonal eudominants (> 10 %), 11 in 2009 and eight in 2019 (Table 4). Within a decade, significant changes in the dominant macroinvertebrate communities were observed in shallow ponds (P1-P2) and the P3 pond. The benthic macroinvertebrates in the P4 pond, which is the oldest and located farthest away from the active part of the limestone excavation and internal roads in the forested area of the quarry, had the most stable community structure.

The RDA analysis revealed that the first two canonical axes accounted for 38.6 % of the macroinvertebrate-environment interaction variance (Fig. 4). Axis 1 explained 13.95 % (eigenvalue 0.14) and axis 2 explained 24.67 % (eigenvalue 0.11) of the variance. The first axis was positively associated with the spring season (r = 0.4188), while negatively correlated with dissolved oxygen content (r = –0.6347) and elodeid development (r = –0.5078). On the other hand, axis 2 was positively correlated with pond margin shading (r = 0.4174) and negatively with spring (r = –0.5151) and depth (r = –0.5102). Most macroinvertebrate taxa were found in the positive part of axis 1, which was associated with spring, and the three families with the highest contribution were Limnephilidae (r = 0.6272), Chironomidae (r = 0.6395), and Chaoboridae (r = 0.5534). Chaoboridae was also the main contributor to the positive part of axis 2 (r = 0.5307), which was related to pond shading, while Coenagrionidae (r = –0.5062) and Polycentropodidae (r = –0.535) were associated with the negative part of axis.

Table 4

Mean relative abundance of macroinvertebrates in the surveyed ponds (P1-P5) in 2009 (I) and 2019 (II) (in bold taxa exceeding 10 % of the assemblage at least in one of the seasons)

Taxa	**P1**		**P2**		**P3**		**P4**		**P5**	
	I	**II**	**I**	**II**	**I**	**II**	**I**	**II**	**I**	**II**
Baetidae	**10.5**	**19.4**	**21.1**	**60.0**	**24.7**	**8.7**	**23.4**	**11.8**	**34.0**	**26.4**
Caenidae	**6.9**	**20.1**		2.5	**16.7**	**9.1**	**17.2**	**14.1**	**12.8**	**23.0**
Leptophlebiidae				0.2			0.4		4.3	1.1
Ecnomidae									0.4	
Leptoceridae	0.3	0.1	0.1	0.2	3.2	1.8	0.4	1.5		0.1
Limnephilidae	0.5	0.1	4.6	1.3	0.4	1.2	0.4	2.0	0.4	0.3
Phryganeidae		0.1	0.1	0.2	0.4	1.2	1.1	0.1	0.1	0.2
Polycentropodidae					0.7	0.1	2.2	1.5	1.1	1.6
Aeschnidae	0.3	1.0		0.2		0.1	1.2	0.2	2.1	0.1
Gomphidae				0.1						
Libellulidae	0.3	1.2	1.1	0.3	0.3	0.1	0.2	4.5	0.6	0.5
Coenagrionidae	**8.9**	**10.2**	9.5	2.4	**10.6**	6.4	**14.0**	**12.9**	**26.1**	**18.6**
Corduliidae			0.4			0.1				0.3
Lestidae	3.6		2.1	0.1			0.1	2.7		
Platycnemididae					0.7				**3.3**	0.1
Corixidae	**7.0**	0.1	3.0	0.4	0.7	0.5	0.6	0.5	1.0	0.8
Naucoridae	**5.6**	1.3	0.2	0.1				0.1	0.9	0.1
Nepidae			0.2		0.4		0.1			0.1
Notonectidae	1.0	1.2	1.5	0.2	0.6	0.1	0.1	0.1		
Pleaidae								0.1		
Curculionidae	0.3	0.1	0.2							
Dytiscidae	2.1	1.1	1.4	0.5	0.3	0.1	0.1	0.1	0.6	
Gyrinidae					0.3		0.1		0.1	
Haliplidae		0.2		0.1	0.1	0.4		0.5	0.2	
Hydrophilidae		0.6		0.1		0.4		0.4		
Noteridae	0.5	0.1	1.1							
Ceratopogonidae	**5.9**	1.0	0.8	1.1		0.2		0.4		0.2
Chaoboridae		0.1	**16.0**	**5.4**		0.8	0.3	0.2	0.1	
Chironomidae	**33.0**	**23.1**	**23.0**	**13.5**	**33.4**	**39.2**	**24.8**	**22.0**	**10.6**	**19.0**
Culicidae	1.0		**11.4**	0.2				0.1		
Dixidae					0.1		0.1		0.1	
Limoniidae		0.1							0.1	0.1
Stratiomyidae				0.1						
Sialidae	1.4	**5.8**	1.1	0.2	0.1	2.0	1.0	1.7	0.3	0.3
Limnaeidae	5.2	**6.2**	0.2	1.0	0.9	**16.7**	1.0	0.7	0.3	
Planorbidae		1.0		2.6		3.7		2.2		
Sphaeriidae		1.0	0.2	1.1			0.1			
Glossiphoniidae			0.2		0.1					
Erpobdellidae	1.4	1.4	0.1	0.1	4.0	1.4		0.1	0.1	0.7
Oligochaeta	4.3	3.2	2.0	4.2		4.7	0.7	3.5		**6.3**
Hydrachnida		0.2	0.6	1.6	1.3	1.0	**10.4**	**15.7**	0.4	0.1

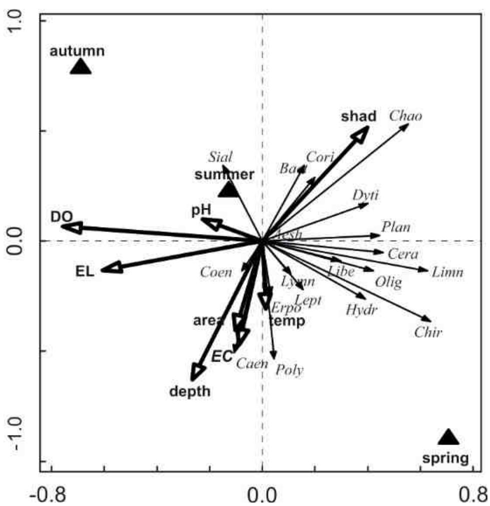

Fig. 4. Redundancy Analysis (RDA) ordination diagram for environmental variables and macroinvertebrates. Variables abbreviations: *Aesh* - Aeshnidae, *Baet* - Baetidae, *Caen* - Caenidae, *Cera* - Ceratopogonidae, *Chao* - Chaoboridae, *Chir* - Chironomidae, *Coen* - Coenagrionidae, *Cori* - Corixidae, *Dyti* - Dytiscidae, *Erpo* - Erpobdelidae, *Hydr* - Hydrachnida, *Lept* - Leptoceridae, *Libe* - Libellulidae, *Limn* - Limnephilidae, *Lymn* - Lymnaeidae, *Plan* - Planorbidae, *Poly* - Polycentropodidae, *Sial* - Sialidae, *Olig* - Oligochaeta, EL - elodeids occurrence, shad - margin shading, DO - dissolved oxygen, *EC* - conductivity

Discussion

The primary goal of this research was to investigate the macroinvertebrate communities inhabiting small water bodies situated in the limestone quarry of Gorazdze, which were constructed to enhance the local ecosystem and support wildlife conservation. The formation of these ponds may have resulted in unique environmental conditions that facilitated the establishment of various macroinvertebrate communities that differed in composition and structure from nearby natural water bodies [28]. The ponds differed in terms of habitat features, vegetation, degree of shoreline shading, and basic water chemistry variables, among others. Despite seasonal variability, which is typical for a temperate climate, the values of water physical and chemical parameters did not differ from those recorded in many other small freshwater ecosystems in mining areas [24, 29]. A significant increase in water temperature was also recorded over the decade, resulting from higher temperatures in the region at that time. According to data from the National Institute of Meteorology and Water Management, 2019 was the warmest year in the last 50 years [30]. Regardless of the harsh and fluctuating environmental conditions of the ponds, they proved to be suitable habitats for numerous invertebrate species, and allowed for the expansion of species range boundaries. In 2010, Buczynski et al. [31] recorded the *Sympecma paedisca* damselfly, the so-called Siberian Winter Damsel, in one of the ponds in the Gorazdze limestone quarry, i.e. 50 km west of the known range of the species. Although the macroinvertebrate assemblages in the studied ponds were similar to those found in other small anthropogenic water bodies, they differed in their spatial and temporal distribution.

Other studies conducted on natural and anthropogenic ponds in different regions of Poland have also collected many of the same families of macroinvertebrates found in this study [24, 32-34]. The number of taxa (42) and average number of taxa per pond (8-16) found in this study likely reflect the impact of nearby exploitation works on the ecological quality of the limestone quarry ponds. In the first year of research, there were no significant differences in the taxa richness and diversity among the ponds, possibly due to high spatial connectivity that allowed for some macroinvertebrates with high dispersal rates to move from one pond to another [18]. Nevertheless, significant differences in assemblage structure parameters have become evident over the decade.

As opposed to taxa richness, macroinvertebrate abundance was much lower, even by a magnitude order, in comparison to the findings of many studies on various ponds, e.g. post-mining, created during marsh restoration and temporary ones [28, 29, 35]. Many interrelated environmental factors, such as the water body size, the diversity of habitats or water chemistry affects the abundance of macroinvertebrates (in general and of individual groups), thus making it difficult to determine precisely which of them is the leading one. However, it can be assumed that a pivotal factor in the surveyed ponds was the specificity of the bottom substrate [36]. The weathering of limestone rock led to the accumulation of a thick layer of unconsolidated clay sediments. These sediments were soft and prone to frequent resuspension due to temperature changes in the water or movements caused by wind and water. Clay-rich deposits show higher compressibility, lower total porosity, and higher vertical permeability [37], thereby making them unfavourable for macroinvertebrate development. The impact of fine sediments, whether they are deposited or suspended, on macroinvertebrates can be both direct and indirect. The mechanisms include bed stability, burial, clogging, and interference with organism respiration or feeding structures. Fine sediments can also affect access to food resources and their nutritional quality. Studies have shown that the degree of clogging has a strong impact on the colonisation of bottom substrates by macroinvertebrates, leading to a lower family richness and reduced abundance of various feeding groups [38-40]. While some taxa are ostensibly adversely affected by increased fine sediment loading, others, such as certain Diptera and Oligochaeta, become more abundant in response to sedimentation and organic enrichment, often associated with increasing levels of anthropogenic disturbance [41]. However, Mahulu et al. [42] found that Diptera was the least abundant group of macroinvertebrates in ponds created in the Wazo Hill limestone quarry in Tanzania. At the same time, this implies how diverse the structure of benthic fauna can be in small water bodies within limestone quarries as dipterans, represented mainly by the Chironomidae family, were one of the dominant groups in the Gorazdze area.

Macroinvertebrate abundance fluctuated annually and monthly during the year. However, except for Coleoptera and Heteroptera, the general pattern was toward increasing abundance in the subsequent surveys. This was primarily attributed to the growing number of mayflies (Baetidae and Caenidae) but also some of the less abundant taxa such as oligochaetes, gastropods (Lymnephilidae and Planorbidae), and water mites. The macroinvertebrates found in the surveyed ponds have diverse ecological preferences and tolerances [24, 43]. The study results confirm the negative impact of clay particles on mayflies and mollusks and the positive effect of a stable substrate on their food and development [43, 44]. The distribution of macroinvertebrates varied greatly between ponds, with mayflies being the dominant group in P2, gastropods in P3 (both ponds had stony elements in the shoreline, with P2 being more shaded than P3), and water mites in P4.

During the summer season of 2019, there was a notable increase in the number of damselflies and dragonflies, although the total number did not differ significantly between the years of the study. Specifically, Coenagrionidae, Aeschnidae, and Libellulidae showed the highest increase, while other families were much less abundant. This trend is consistent with findings by Boix et al. [45] who recorded the highest Odonata abundance in early and mid-summer, a pattern commonly observed in temperate regions. Studies on 36 artificial water bodies in Croatia conducted by Vilenica et al. [46] demonstrated that shallow water bodies with well-developed littoral zones, aquatic vegetation, and low daily and seasonal water level fluctuations provide suitable habitats for diverse Odonata species. The beneficial role of littoral vegetation cover, including submerged plants, has been highlighted in many papers [e.g. 47, 48]. Therefore, pond P2 (a shallow water body with high water level fluctuations and littoral vegetation poverty) was the only one where a declined abundance of odonates was recorded after a decade.

A total of 21 taxa exhibited clear patterns of increased abundance in subsequent study years, and seven taxa declined over time (dipterans Chaoboridae and Culicidae, beetles Noteridae, true bugs Corixidae and Naucoridae, damselflies Lestidae and Platycnemididae). Nevertheless, it is important to consider the inter-annual variation and cyclical nature of macroinvertebrates, which can result from consumer-resource and predator-prey interactions, when interpreting these results [49].

Significant seasonal and spatial variations in the composition of the macroinvertebrate assemblages were apparent. During the course of ten years, the most significant variations were detected in the shallow ponds (P1-2) and the one employed as a water source (P3). The distribution of the dominant taxa (14 in total) was mainly influenced by seasonal and habitat factors. Previous research on pond insects has highlighted that the quality of the habitat within each pond and the inter-pond geometry (isolation) were crucial factors in determining the distribution of invertebrates [18, 50, 51]. However, Bobrek [52] observed that despite a lack of distinct barriers and negligible distances between ponds (with max. 350 m), odonate assemblages differed considerably. In our research, pond margin shading and morphometry affected significantly spatial distribution and abundance of macroinvertebrates, while temperature drove seasonal changes in the assemblage structure. Spring prevailed over the other variables as macroinvertebrate richness and abundance were high even in ponds with low DO or less developed elodeids that season.

Conclusion

To conclude, the presence of fine sediment particles, high water conductivity, and the occasional lack of oxygen were found to adversely impact some macroinvertebrate families, while stable substrates and well-developed littoral zones with aquatic vegetation were positively associated with their abundance and distribution. The variation in macroinvertebrate assemblages over time and among different ponds underscores the importance of long-term monitoring and management of these small water bodies to support their biodiversity conservation and ecosystem functioning. Further research that includes continuous and standardised data collection and analysis at lower taxonomic levels will help to improve our understanding of the factors driving the observed patterns in macroinvertebrate assemblages in small anthropogenic water bodies.

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