limnological review

Article

Diagnosis of the Condition of Aquatic Ecosystems Using a Partial Assessment of Ecological and Trophic States: An Example of Small Lakes in Northern Poland

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Abstract: The current state of aquatic ecosystems was assessed for lakes in two river–lake systems: Święta Struga (Święte and Ocypelek) and Kałębnica (Czarne Południowe and Kałębie). Trophic states were determined using the Vollenweider, Nürnberg, and Carlson methods. Additionally, shoreline changes were analyzed for all lakes concerning their natural character, and physicochemical parameters were utilized as auxiliary elements in the assessment of the ecological state following the guidelines of Directive 2000/60/EC. Supplementary to these methods, the ecological evaluation of the littoral zone utilized meiobenthic organism grouping as an indicator. The results indicate significant differences among the studied reservoirs. Lake Święte is a reservoir bordering mesotrophy and eutrophy, with the ecological state of the littoral zone showing ongoing trophic development. Lake Ocypelek exemplifies a eutrophic reservoir undergoing progressive degradation. The lakes in the Kałębnica system also exhibit advanced trophic conditions, with Lake Kałębie being a eutrophic reservoir. Its shoreline has been significantly altered due to the development of the direct catchment area. In contrast, Lake Czarne Południowe serves as an example of a mesotrophic reservoir, with a substantially changed shoreline. Considering physicochemical elements and chlorophyll a concentration, the water quality for all examined lakes was found to be below the good category. The diagnosis of the condition of lake aquatic ecosystems requires an individualized approach to each of them. Therefore, employing various methods for their assessment, encompassing physico-chemical, biological, and morphological parameters, provides the opportunity to initiate potential remedial actions that will effectively contribute to their improvement. Conducting low-cost research involving a multidisciplinary approach to diagnose the state of aquatic ecosystems is becoming a crucial element in lake monitoring.

Keywords: eutrophication; trophic state; meiobenthos; river–lake system; water quality

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Citation: Markowski, M.; Wojtasik, B. Diagnosis of the Condition of Aquatic Ecosystems Using a Partial Assessment of Ecological and Trophic States: An Example of Small Lakes in Northern Poland. *Limnol. Rev.* **2024**, *24*, 105–125. https://doi.org/10.3390/limnolrev24010006

Academic Editor: Petre Brețcan

Received: 19 December 2023
Revised: 16 January 2024
Accepted: 31 January 2024
Published: 1 March 2024

1. Introduction

The course of processes occurring in a lake informs us about the functioning of a particular reservoir in the natural environment. The compilation of relevant information about these processes provides an answer to the current conditions of aquatic ecosystems in individual reservoirs, especially concerning the trophic and ecological states.

The identification of the current degree of lake water eutrophication and the ecological state is a result of biological, chemical, physical, and morphological factors. Most indicators used for this purpose refer to the entire reservoir. Hence, there are situations in which the waters of one lake may be classified as having different trophic or ecological states.

The assessment of the trophic state of lakes, due to its simplicity and a limited range of physicochemical parameters used for its implementation, is one of the most popular methods for understanding the condition of lake aquatic ecosystems [1,2]. In the literature on the subject, there are numerous studies where the trophic state is determined based on a small number of field measurements, even relying on individual measurement series [3–5]. On the other hand, legal regulations and guidelines of the Water Framework Directive (WFD) make the assessment of the ecological state a decidedly more complex procedure, requiring a significantly broader scope of field research. Consequently, conducting a comprehensive assessment of the ecological state of a hydrological entity necessitates the involvement of a wide range of specialists in hydrochemistry, hydrology, and biology. This, in turn, implies the need for substantial financial resources. As a result, a full assessment of the ecological state is challenging for small research teams with limited financial capabilities. This translates into significant difficulties in conducting monitoring studies for entities not covered by the State Environmental Monitoring. Hence, there is a need for the partial adaptation of the ecological state assessment, based only on selected parameters, to evaluate the condition of individual aquatic ecosystems.

One way to complement the assessment of the ecological state is to employ an alternative method that allows for determining the ecological state of the littoral zone, using the community of meiobenthic organisms as an indicator [6–8]. Meiobenthos (meiofauna) assemblages are composed of small aquatic invertebrates of different systematic assignments. There are many criteria for the size definitions of meiobenthos [6]. The most accepted criterion is given as the limits of dimensions 0.042 to about 1 mm [9]. A part of major meiobenthic taxa is constant (by virtue of size and binding with the water environment throughout the ontogeny), while a part of meiobenthos grows and changes in size (above 1 mm, e.g., Mollusca, Insecta larvae) and/or by the fact of not living in a water environment throughout the lifetime (e.g., larvae—water, adults—terrestrial). The freshwater meiobenthos has various taxonomic ranks of invertebrates: Turbellaria, Rotifera, Gastrotricha, Nematoda, Oligochaeta, Conchostraca, Cladocera, Copepoda, Ostracoda, Insecta larvae (among others: Diptera, Trichoptera, Ephemeroptera, Odonata), small Insecta adults, Arachnida, Tardigrada, Gastropoda, and Bivalvia. Meiobenthos organisms are a separate functional group and a sensitive indicator of change in the aquatic environment [8,10–13]. Meiobenthic assemblages are subject to changes related to the development of the trophy of the aquatic environment (Figure 1) and the degree of anthropogenic pressure, e.g., pollution, hydrotechnical constructions, and reclamation [8]. Due to its specificity, this method (low cost, simple methodology) appears to meet the expectations of analyses conducted for monitoring studies.

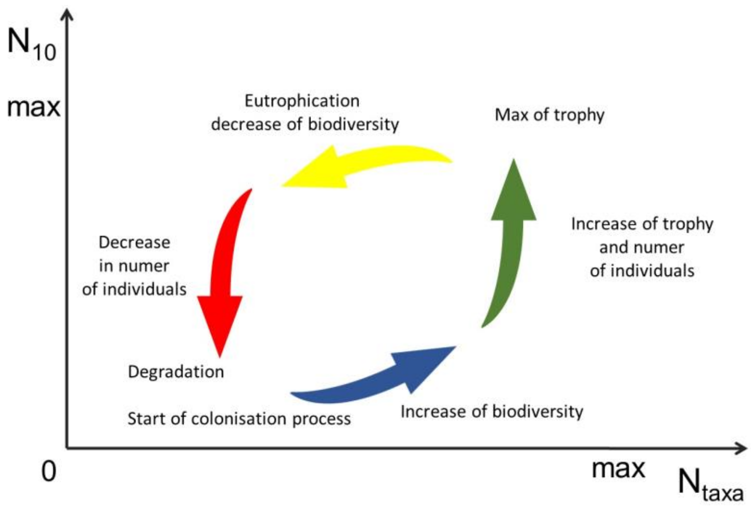


Figure 1. Meiobenthos: changes in abundance and taxonomic diversity of assemblages occurring in different areas: lakes, fresh water reservoir, rivers and, marine environment [7].

In ecological state assessments, the state of hydromorphological elements is also considered, and for lakes, it is determined using the Habitat Modification Score and shoreline transformation indicator adapted to Polish conditions, known as LHMS_PL (Lake Habitat Modification Score PL—LHMS_PL) [14]. Although this method is relatively simple to implement, it is time-consuming and relies on randomly selected measurement points along the shoreline. It is important to note that the shoreline zone is not only a part of the littoral zone but also the immediate hinterland of the lake, often influencing both the conservation status and the degree of transformation of this zone. Therefore, the methodology for determining the degree of shoreline transformation [15] can be utilized as a kind of complementary information for a given reservoir in terms of shoreline hydromorphology.

Conducting research on the assessment of the condition of lake ecosystems requires, therefore, a multidisciplinary approach. It is essential that the measurements performed enable the gathering of a maximum amount of information in a relatively short period, considering the entire group of studied objects.

The aim of this article is to diagnose the conditions of four small lakes located in Northern Poland while minimizing the costs of field measurements and laboratory analyses. It was assumed that field measurements could be carried out by a small research team (3–4 individuals) and would only include a two-day measurement series during the summer. As a result, the collected research material was processed to compile a maximum amount of information on the trophic state, hydromorphological elements, and biological elements of the studied lakes.

2. Methods

Field measurements for four lakes were performed on 14–15 July 2014, during the period of thermal–dynamic stagnation of the lakes. Limnological measurements were carried out within the depth profiles of each lake in accordance with limnological practices [16,17]. As part of these measurements, vertical distributions of characteristics reflecting the features of the lake's aquatic environment were recorded. Vertical profiles of temperature, specific electrical conductivity, pH, oxygen content, and saturation were measured using a YSI-6800 multiparameter probe (YSI Incorporated, Yellow Springs, OH, USA). The concentration of chlorophyll a was measured using a Chelsea Mini Tracka II fluorimeter (Surrey, UK). Secchi disk was used to determine water transparency. Surface and bottom water samples were collected using a Ruttner sampler for laboratory analysis. Ammonium, nitrite, nitrate, and total nitrogen, as well as total phosphorus, were determined using a quantitative colorimetric analysis method based on the Lambert–Beer law, with a Spectroquant Pharo 300 spectrophotometer (Merck, Darmstadt, Germany). Chemical analyses were conducted in the hydrochemical laboratory at the Limnological Station in Borucino.

The analysis of the gathered research material was supplemented by selected indicators providing information on the degree of eutrophication of lake waters. For this purpose, the trophic assessment of the lake was based on the methods proposed by Vollenweider [18] and Nürnberg [19], and the trophic state assessment was performed using the Carlson Trophic State Index [20].

The partial assessment of the ecological state of the lakes was primarily based on physicochemical elements specified in the Regulation of the Minister of Infrastructure of 25 June 2021 (Dz.U. 2021 poz. 1475), implemented in accordance with the Water Framework Directive (WFD) [21]. Due to incomplete measurements of biological elements, only the concentration of chlorophyll a, a component of the Phytoplankton Index for Polish Lakes (PMPL) [22], was used for the assessment. Water samples for the partial assessment of the ecological status were collected from two measurement stations at each reservoir, with one of them being located at the deepest point of the lake (Figure 2).

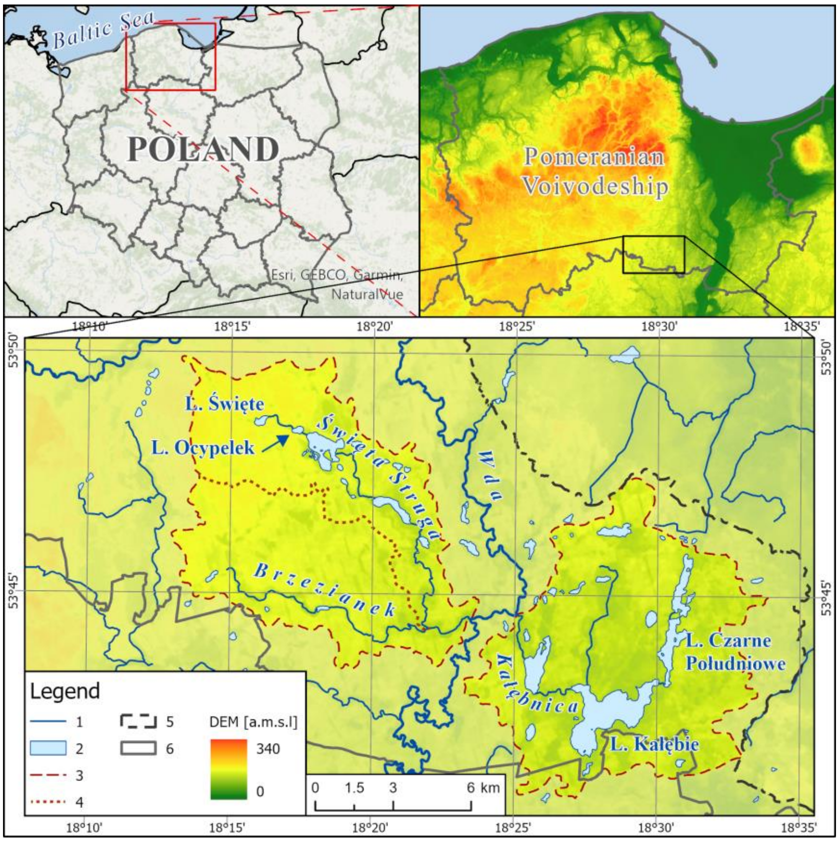


Figure 2. Location of the research area, where 1—streams/rivers, 2—lakes, 3—catchment III order, boundary, 4—catchment IV order, 5—mesoregions boundary, 6—voivodeship boundary.

The transformation degree of the lake's shoreline zone (B_a) was determined in accordance with the methodology outlined by the Institute of Meteorology and Water Management (IMGW) [23]. However, this methodology broadly defines the classification of a given section of the shoreline into one of three designated classes of shoreline management. Therefore, the transformation degree of a specific segment of the shoreline of the studied lake was assessed based on criteria defined in the study by Bajkiewicz-Grabowska [15]. Using these criteria, the length of classified shoreline segments was aggregated into four classes:

(a) Class 1—adverse transformation or development of the shoreline zone, involving permanent soil sealing, restricting water infiltration (recreational centers, dense holiday and residential construction, industrial facilities, urbanized areas, asphalt road running along the shoreline);
(b) Class 2—transformation or development of the shores allowing for the preservation of a relatively natural hydrological regime, characterized by permanent but not eliminating changes in the morphological structure of the shores (farmlands, beaches, scattered holiday and residential construction, hardened road along the shoreline, forests, and green areas, including fallow lands separated from the lake by a hardened surface road);
(c) Class 3—sections resembling natural ones with artificially disrupted continuity of macrophytes (meadows and fallow lands, as well as forests with a macrophyte zone, where continuity is interrupted by paths and fishing piers);
(d) Natural shoreline (Class 4–5)—meadows and fallow lands, as well as forests, with both imperceptible and visibly preserved continuity of the macrophyte zone.

To assess the variability of the meiobenthos community in the littoral zone of the studied lakes, sampling locations were determined based on an analysis of the shoreline. This analysis took into account environmental components influencing the migration of pollutants into the lake, including plant cover, land use, topography, inflow, and the occurrence of point source pollution.

Samples for meiobenthic analysis were collected on July of 2014 through tests for quantitative and qualitative analyses. Samples were preserved in 70% ethanol and stained with rose bengal (Rose bengal sodium salt, Sigma No. R3877-5G). The prepared material after washing on a sieve with a mesh of 0.042 mm was subjected to detailed analysis in terms of which are the major meiobenthic invertebrates. The analyzed material was flushed out of the frame using a mesh of 1.0 mm to separate meiobenthos of macrobenthos. The samples were analyzed using a stereomicroscope. To assess the size of the animals, Petri dishes with grids of 1 and 2 mm were used. Analyses of meiobenthic assemblages conducted: relative abundance of major meiobenthic taxa of studied lakes, frequency (F) of major meiobenthic taxa, mean and median, and Bray–Curtis faunistic similarity (cluster and MDS). Analyses were performed based on the developed methodologies for assessing the ecological state MeioEco by meiobenthos assemblages [6].

Analyses in 2D and 3D were conducted for the relative scale, taking into account the minimum and maximum values of the parameters in the obtained results: N_{10}—the number of individuals per 10 cm^2, N_{taxa}—number of identified major meiobenthic taxa. Arithmetic means were calculated for the maximum and minimum values of both parameters to obtain the boundaries of the intervals. Then, a 3D analysis also included was a new algorithm B_W [7,8] to calculate the balance of taxa present in the assemblage. The maximum value was 1, while the minimum was 0 for one taxon in the assemblage, or greater than 0 if the value of the B_W ratio was in the range of 0 to 1. The B_W factor is described by the following formula:

$$B_W = 1 - \sum_{\substack{i,j\,\epsilon\,(N)\\ j\geq i\\ 0<\cdots\leq i\leq j\leq\cdots.M\leq N\\ k=1;2;\ldots;M-1}}^{N} \frac{(n_j - n_i)}{kN}$$

where

N—number of all individuals in the sample,
n_i, n_j—number of individuals of the i-th and j-th taxa.

Taxa are ranked in the order of increasing number of individuals in the following groups in order to distinguish them from N—number of individuals; in this, case (N) denotes a natural number.

M—number of taxa in one sample
k = 1 for n_M; k = 2 for n_{M-1}; . . .; k = M − 1 for n_1

The B_W indicator assumes a maximum value equal to 1 when all the taxa present are represented by the same number of individuals. The lower the ratio, the stronger the dominance of one of the taxa. The maximum and minimum values of B_W are the extent of our study. The arithmetic average of the maximum and minimum values of the border ranges between equilibrium and its absence in the meiobenthic assemblages. And Bray–Curtis faunistic similarity analysis was performed by using Primer in version 6.

The assessment of the variability of meiobenthic communities for individual lakes was presented in the form of a 2D analysis expressed through an ecological state map. This map is the result of interpolating point values within a 30 m buffer along the shoreline. The interpolation process and other spatial analyses were conducted using GIS software (ArcGIS Pro v. 3.0). The 'Topo to Raster' tool was utilized as the interpolation method, considering the limited number of measurement points.

3. Study Area

The analysis of the eutrophication levels was conducted for lakes located in two river–lake systems. Lake Święte and Lake Ocypelek belong to the Święta Struga river–lake system, while Lake Czarne Południowe and Lake Kałębie are part of the Kałębnica system.

In the updated physical–geographic classification [24], the Święta Struga catchment is part of the South Pomeranian Lakeland macro-region (314.6-7) and the Bory Tucholskie mesoregion (314.71). On the other hand, the Kałębnica catchment is mostly located within the Bory Tucholskie mesoregion, with only its northeastern part situated in the Pojezierze Starogardzkie mesoregion (314.52), which is part of the East Pomeranian Lakeland macroregion (314.5). Administratively, the research area is almost entirely located in the southern part of the Pomeranian Voivodeship, with only a small fragment of the Kałębnica catchment situated in the northern part of the Kuyavian–Pomeranian Voivodeship.

The Święta Struga catchment covers an area of 44.2 km^2. It is a fourth-order catchment (Figure 2), constituting an elementary catchment of the Brzezianek stream (third-order), which, in turn, is a right-bank tributary of the Wda River (second-order catchment). This area has an elongated shape, and its terrain slopes from the northwest to the southeast. Święta Struga originates from Lake Święte and flows successively through the lakes: Ocypelek, Ocypel Wielki, Długie, and Babskie. The selected lakes for analysis, Święte and Ocypelek, mark the beginning of the Święta Struga system and are connected by a river segment measuring 1.4 km in length. The surface area of the catchment, enclosed by the profile at the outlet of Lake Ocypelek, is 17.4 km^2 and represents 40% of the total Święta Struga catchment. This system has formed in a wide subglacial trough, expanding in the southeast direction. The edges of the subglacial trough in the upper part of the Święta Struga system reach directly to Lake Święte and partially to Lake Ocypelek. The land use structure in the direct catchments of Lakes Święte and Ocypelek is uniform, with forests dominating and covering nearly 99% of their combined area (excluding lakes) (Table 1).

Table 1. The land use structure of the direct catchments of the examined lakes.

Lake	Catchment			Land Use Structure w/o Lake				
	Total	Direct		Agriculture	Forsests	Green Areas	Built-Up Areas	Water Bodies
		with Lake	w/o Lake					
	(km^2)	(km^2)	(km^2)	(%)	(%)	(%)	(%)	(%)
Święte	11.69	11.69	11.56	0.4	99	0.8	0	0
Ocypelek	17.49	3.36	3.27	0.7	99.3	0	0	0
Czarne Południowe	21.69	5.65	4.66	16.0	58	14.3	6.8	4.5
Kałębie	47.90	26.28	21.62	18.5	51	26.8	3.4	0.8

The river–lake system of the Kałębnica River, according to the Hydrographic Division Map of Poland at a scale of 1:50,000, is designated as a third-order catchment. It constitutes a left-bank elementary catchment of the Wda River catchment (second-order). The term "Kałębnica" appears on hydrographic maps for the stream from the outflow of Lake Kałębie to the point where it flows into the Wda River. Due to the fact that a stream flows into Lake Kałębie, which passes through two lakes (Czarne Południowe and Czarne Północne) before reaching Lake Kałębie, the name "Kałębnica" in this study refers to the stream flowing from Lake Czarne Północne. The confluence of Kałębnica into Wda is located 2 km above the Brzezianek River mouth, which is the recipient of the waters from the Święta Struga.

The total Kałębnica catchment covers an area of 72.2 km^2, and the catchment defined by the closing profile at the outlet of Kałębnica from Lake Kałębie constitutes over 66% of the total catchment (47.9 km^2). In the upper course, Kałębnica flows in a subglacial trough with a north–south direction, occupied by the lakes Czarne Północne and Czarne Południowe. Denivelations on the slopes of subglacial troughs in this area can reach up to 15–20 m (eastern part of Lake Czarne Południowe), and the terrain drops exceed 12%. In the middle course of the Kałębnica, there is Lake Kałębie, situated in a depression with gentler slopes. The direct catchment of Lake Kałębie (26.3 km^2) is nearly five times larger than the direct catchment of Lake Czarne Południowe (5.6 km^2). The land use structure in these catchments is significantly more diverse than for the analyzed lakes of the Święta Struga system. Forests dominate, constituting 58% of the direct catchment of Lake Czarne Południowe and nearly 50% of the direct catchment of Lake Kałębie (Table 1). Additionally, arable land (Czarne Południowe—16.0%; Kałębie—18.5%) and green areas (Czarne Południowe—14.3%; Kałębie—26.8%) have a relatively large share in both catchments.

The examined lakes, in terms of morphometry, can be divided into two groups. Lake Święte and Ocypelek (Święta Struga system) are reservoirs with a small surface area, and consequently, a short shoreline. According to [25], which takes into account maximum and mean depths, they belong to the group of deep lakes (Table 2). On the other hand, lakes in the Kałębnica system are moderately shallow but very large with a long shoreline.

Table 2. Basic morphometric parameters of the studied lakes.

Lake	River–Lake System	Elevation	Depth		Volume	Surface Area
			Max	Average		
		(m a.m.s.l.)	(m)	(m)	(10^3 m^3)	(ha)
Święte	Święta Struga	103.6	10.5	4.2	552.64	13.1
Ocypelek	Święta Struga	100.3	13.0	4.2	397.89	9.4
Czarne Południowe	Kałębnica	87.8	7.6	2.8	2799.50	98.4
Kałębie	Kałębnica	87.6	6.4	2.4	11,056.40	466.3

4. Results and Discussion

4.1. The Transformation Index of the Littoral Zone (B_a)

The lake ecosystem along with the catchment area constitutes a natural landscape system, which can be termed as the lake geoecosystem [26–28]. The structure of this geoecosystem influences the course of eutrophication processes [29]. The trophic state of water bodies is significantly influenced by the land use practices in the immediate catchment area. Therefore, the critical area in the eutrophication process becomes the lake's shoreline zone and its degree of transformation. The degree of transformation of the lake's shoreline zone (B_a) has been classified as one of the key indicators for assessing the morphological state of Uniform Surface Water Bodies (USWB—JCWP in Polish) in designating Heavily Modified Water Bodies (HMWB—SZCW in Polish). It allows for the determination of different land use classes for shoreline sections as well as an assessment of the shoreline zone for the entire catchment.

As a result of the conducted analysis, the lake from the Święta Struga system is classified as a water body with a natural shoreline character (Table 3). The only variation in the shoreline is associated with existing roads and forest paths. The low values of the Ba coefficient are primarily due to the fact that their relatively small direct catchments (Święte—11.7 km^2; Ocypelek—3.3 km^2) are 99% covered by forests. Therefore, they still represent an example of a natural landscape. The anthropogenic impact on the lake in such a landscape usually is limited to direct point-source activities, including fishing, recreation, littering, or illegal discharges of polluted water. The identification of areas subjected to human pressure is possible, among other things, through the assessment of the variability of the meiobenthic community.

The character of the lake shorelines belonging to the Kałębnica river–lake system is markedly different. The length of the shorelines of both lakes is noteworthy, especially in the case of Lake Czarne Południowe, which is 4.5 times longer than the shoreline of Lake Święte and over 6 times longer than that of Lake Ocypelek. In Lake Kałębie, due to its twice-as-long shoreline as Lake Czarne Południowe's, these disparities are doubled. The shoreline transformation for both lakes is not as homogeneous as in the case of the analyzed Święta Struga lakes. The shoreline of Lake Czarne Południowe has a dual character. The eastern part is a natural shoreline (classes 4–5) or close to natural (class 3). In contrast, the western part is primarily classified as class 2—33%. Only in the southern part is there a small section of shoreline classified as class 1—4%. The development of the shoreline of Lake Kałębie is also diverse. However, a dominant feature can be identified, with segments of the shoreline classified as class 2 accounting for 69%. The least numerous segments are of the natural shoreline, representing only 7.5%. Considering the classification based on the Ba index, both Lake Kałębie and Czarne Południowe are water bodies with altered shorelines. The least favorable situation occurs in Lake Kałębie, which, based solely on the Ba index, could be classified as a strongly modified part of surface waters (B_a = 49). Meanwhile, Lake Czarne Południowe is an example where the shoreline has been significantly altered (B_a = 28).

Table 3. The length of the lake's shoreline according to the adopted classes of its transformation considering the correction coefficient and the transformation degree index of the lake's shoreline, Ba.

Lake	River–Lake System	Shoreline Length L	Class 1 L_1	Class 2 L_2	Class 3 L_3	Class 4–5 L_{4-5}	B_a
		(km)	(km)	(km)	(km)	(km)	(km)
Święte	Święta Struga	1.644	0	0.443	0	1.201	13.5
Ocypelek	Święta Struga	1.210	0	0	0.330	1.210	5.5
Czarne Południowe	Kałębnica	7.643	0.300	2.530	2.843	1.970	27.9
Kałębie	Kałębnica	15.200	1.960	10.458	1.633	1.149	49.4

4.2. Physicochemical Parameters—Selected Aspects

During the conducted research, basic physicochemical measurements were carried out, reflecting the characteristics of the aquatic environment in which the lakes operate.

The lakes of the Kałębnica system (Kałębie and Czarne Południowe) are large reservoirs with relatively shallow maximum and average depths (Table 2). The morphometry of these reservoirs facilitates the mixing of entire water masses several times a year, making them polymictic lakes. The vertical profiles of temperature, conductivity, chlorophyll a, and pH (Figure 3) confirm their polymictic nature, and for both lakes, they exhibit a similar pattern. In the case of oxygen concentration, the differences between Lake Kałębie and Lake Czarne Południowe are not as subtle. Oxygen concentration measurements in Lake Czarne Południowe indicate a significant decline with increasing depth (from 98.6% to 10.0%). At the lake bottom, this decline is pronounced, and the oxygen content of 0.95 mg L^{-1} suggests the development of anaerobic conditions (anoxia). The causes of such a situation can be attributed to the amount of biogenic substances dissolved in the bottom water. The oxygen conditions in Lake Kałębie are significantly better, with only a 30% decrease in oxygen extending to the lake bottom.

The location and morphometry of the lakes in the Święta Struga system (Święte and Ocypelek) favor the development of significant vertical temperature gradients during the summer. The small surface areas of these reservoirs and the deep embedding of lake catchment into the subglacial trough create conditions that limit the role of wind in turbulent mixing, thereby promoting the development of summer thermal stratification of an anothermal nature. The circulation processes classify both reservoirs as lakes with a dimictic type of a thermal–dynamic regime. During the summer thermal stagnation, distinct layers of epilimnion, metalimnion, and hypolimnion are observed. The depth of the boundary layers between these structures and their thermal characteristics allow for the assessment of subtypes of the thermal–dynamic regime. The low water temperature in the near-bottom layer (approximately 4.7 °C), a shallow epilimnion reaching 2–3 m, and a hypolimnion with significant thickness (4–7 m), preliminarily categorize Lake Święte and Lake Ocypelek as bradymictic lakes. The anothermal water stratification is reflected in the vertical oxygen distributions of the studied lakes, which take on a clinograde form.

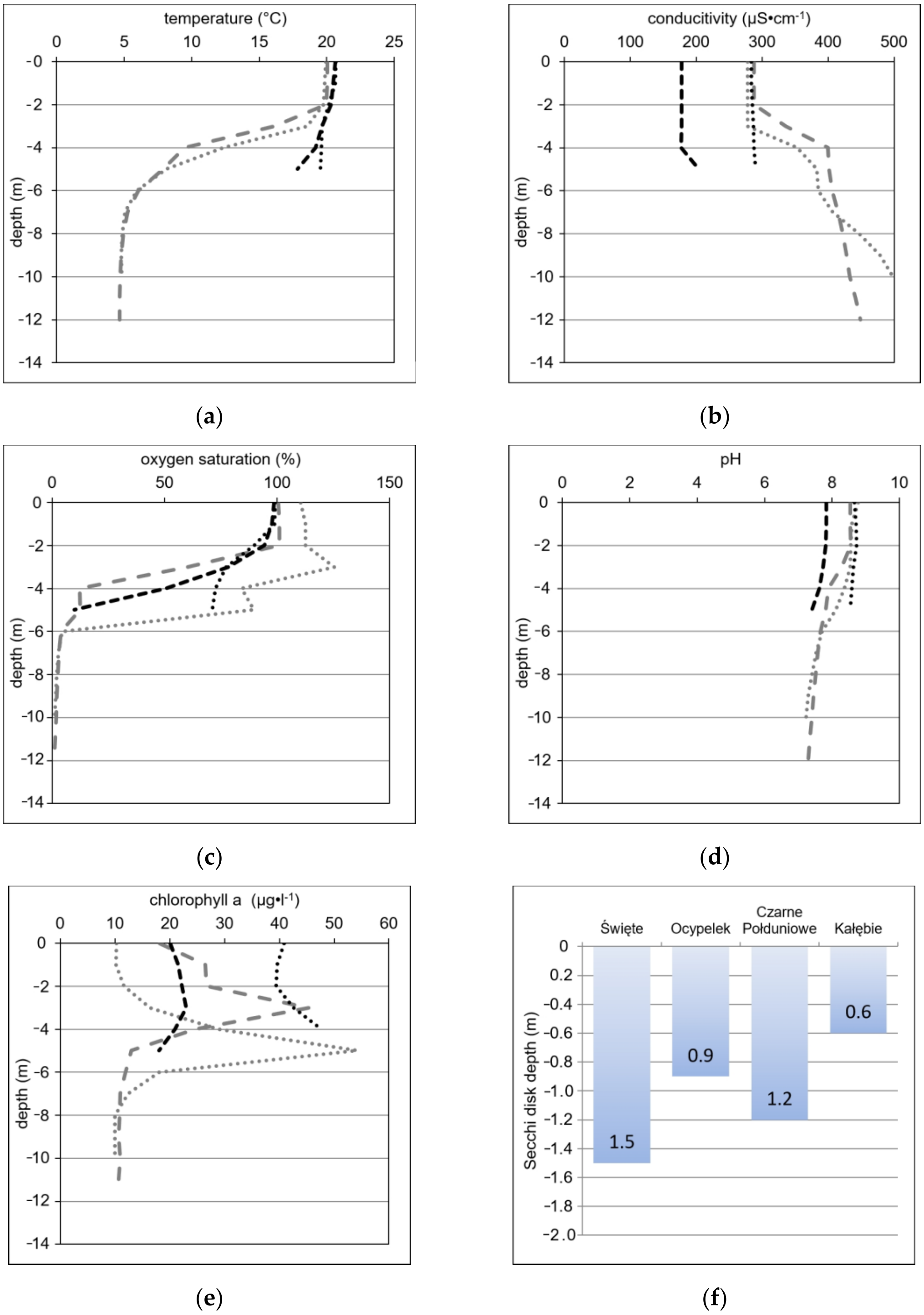


Figure 3. Vertical profiles: (**a**)—temperature, (**b**)—conductivity, (**c**)—dissolved oxygen, (**d**)—pH, (**e**)—chlorophyll a, and Secchi disk visibility (**f**) in the studied lakes. Where: Lake Święte—grey dotted line, Lake Ocypelek—grey dashed line, Lake Kałębie—black dotted line, Lake Czarne Południowe—black dashed line.

The noteworthy occurrence is the presence of a strong oxygen saturation in the epilimnion layer of Lake Święte, with its maximum at a depth of 3 m (125.3%). Below the epilimnion, a dramatic decrease in oxygen content with depth was observed. Conditions approaching anoxia in Lake Święte occurred at a depth of 6 m (0.55 mg L^{-1}), while in Lake Ocypelek, it occurred already at 4–5 m (1.39 mg L^{-1}). Oxygen deficits in surface waters often occur in lakes with intense primary production in the trophogenic layer [30].

Oxygen deficits in the tropholytic layer, resulting from the decomposition of organic matter, along with simultaneous frequent saturations in the trophogenic layer due to increased biomass production, indicate ongoing and significantly accelerated eutrophication of the reservoir [31].

The vertical distribution of conductivity in the case of polymictic lakes (Kałębie and Czarne Południowe) is similar to the homogeneous. In deep bradymictic lakes (Święte and Ocypelek), the variation in specific water conductivity is associated with thermal–density stratification. Lower values in the near-surface layer of water are related to the absorption of dissolved mineral matter by developing biomass. The increase in conductivity in surface waters is primarily due to groundwater input and the penetration of mineral compounds from the bottom sediments [31].

4.3. Biogenic Substances

The content of biogenic substances in the aquatic environment is particularly significant for the functioning of lake reservoirs. The concentration of biogenic compounds in water results from their inflow from the catchment area and internal supply from bottom sediments. The types of thermal–dynamic regimes, as well as affiliation with specific river–lake systems, determine the diversity of biogenic compounds in the studied reservoirs. The presence of nitrogen compounds in surface waters influences the intensity of biomass production in lakes. In the polymictic waters of the Kałębnica system, concerning the total nitrogen content throughout their volume, they are homogeneous. The concentrations of this element at the surface and near the bottom vary in the range of 1.45 to 1.55 mg L^{-1} (Table 4). Lower values of total nitrogen are present in the surface waters of Lake Ocypelek (0.59 mg L^{-1}) and Lake Święte (0.42 mg L^{-1}). Therefore, during the summer, the intensity of biomass production in these reservoirs is lower. The dimictic nature of these lakes results in significant disparities in total nitrogen concentrations at the surface and near the bottom.

Table 4. The concentrations of key biogenic substances in the water of the studied lakes.

Lake		Nitrogen			Total Phosphorus
Name	Sampling Location	Total	NO_2	NH_4	
		(mg L^{-1})	(mg L^{-1})	(mg L^{-1})	(mg L^{-1})
Święte	surface	0.420	0.009	0.057	0.031
	bottom	0.720	0.011	0.043	0.046
Ocypelek	surface	0.590	0.010	0.045	0.045
	bottom	4.320	0.010	4.080	0.488
Czarne Południowe	surface	1.500	0.015	0.018	0.034
	bottom	1.450	0.015	0.024	0.060
Kałębie	surface	1.550	0.023	0.044	0.048
	bottom	1.550	0.023	0.048	0.046

In the case of Lake Święte, the ratio of nitrogen content in the near-bottom and near-surface waters is close to 2:1, while for Lake Ocypelek, it exceeds 7:1. The very high amounts of this element near the bottom are associated with the occurrence of anoxic conditions, which intensify ammonification processes. Hence, the amounts of ammonium nitrogen in this reservoir are also very high, reaching up to 4.08 mg L^{-1}, which constitutes over 94% of the total nitrogen content (4.32 mg L^{-1}). The ratio of ammonium nitrogen amounts near the bottom to those at the surface is 90:1, and for Lake Święte, this ratio is less than 1. The causes of abnormal concentrations of ammonium nitrogen in Lake Ocypelek can be primarily attributed to bottom sediments, which introduce this form of nitrogen into isolated near-bottom layers of water. In terms of the quantity of nitrate nitrogen, which is also a form of mineral nitrogen, there are no significant differences between the waters of

Lake Święte and Lake Ocypelek. For both reservoirs, the concentrations of this element throughout the water mass range from 0.009 to 0.011 mg L^{-1}. Vertical homogeneity in terms of nitrate nitrogen content is also maintained in the waters of Lake Kałębie (0.015 mg L^{-1}) and Lake Czarne Południowe (0.023 mg L^{-1}).

Among the mineral forms of nitrogen, ammonium nitrogen dominated, with higher concentrations observed in near-bottom waters (Kałębie—0.048 mg L^{-1}, Czarne Południowe—0.024 mg L^{-1}). Summer concentrations of total phosphorus in all studied lakes were relatively consistent, ranging from 0.031 (Święte) to 0.048 mg L^{-1} (Kałębie) (Table 4). For lakes characterized by oxygen deficits near the bottom, an increase in phosphorus levels with depth was noted. Consequently, a twice-as-high phosphorus concentration was recorded at the bottom of the shallow polymictic lake Czarne Południowe (0.060 mg L^{-1}). In the well-oxygenated Lake Kałębie, the total phosphorus concentration at the bottom is similar to that at the surface, amounting to 0.046 and 0.048 mg L^{-1}, respectively. In the stratified lakes of Święta Struga, characterized by significant oxygen deficits in the hypolimnion zone, the total phosphorus content at the bottom is higher than at the surface. In Lake Święte, these differences are relatively small (surface—0.036 mg L^{-1}, bottom—0.046 mg L^{-1}). Conversely, in Lake Ocypelek, similar to ammonium nitrogen, phosphorus concentrations at the bottom (0.488 mg L^{-1}) are significantly higher than at the surface (0.045 mg L^{-1}). The high phosphorus levels at the bottom result from the release of this element from bottom sediments, especially under anoxic conditions [31].

4.4. Meiobenthos Assemblages

The analyses of the meiobenthos assemblages performed using the MeioEco method indicate the diverse nature of the littoral zone of the studied lakes. The most strongly developed trophy is found in the Czarne Południowe Lake; moreover, the range of changes in the examined parameters has the greatest spread here. This indicates significant fluctuations in the development of trophies in individual areas of the lake; from the level of developing trophy, the through strongly developed trophy to an area with progressive degradation.

In the samples, 2900 meiobenthic invertebrates were identified. The most numerous taxon was Nematoda. The highest frequency was calculated for Turbellaria. The relative abundance values of the major meiobenthic taxa of the studied lakes are shown in Figure 4 (detailed information—Supplementary Materials—Table S1). The mean and median of the meiobenthic assemblages of the studied lakes are shown in Figure 5.

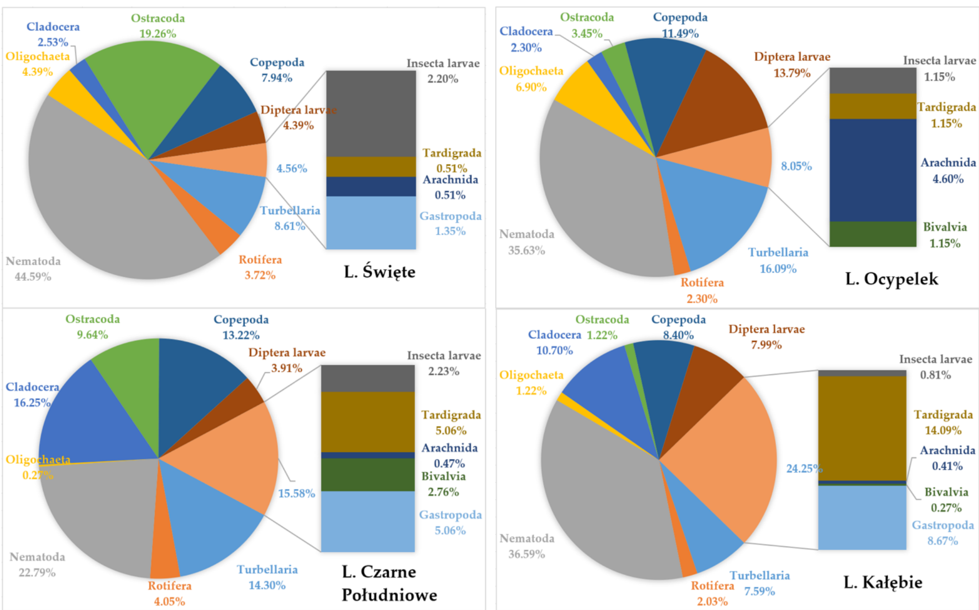


Figure 4. Relative abundance of major meiobenthic taxa of studied lakes.

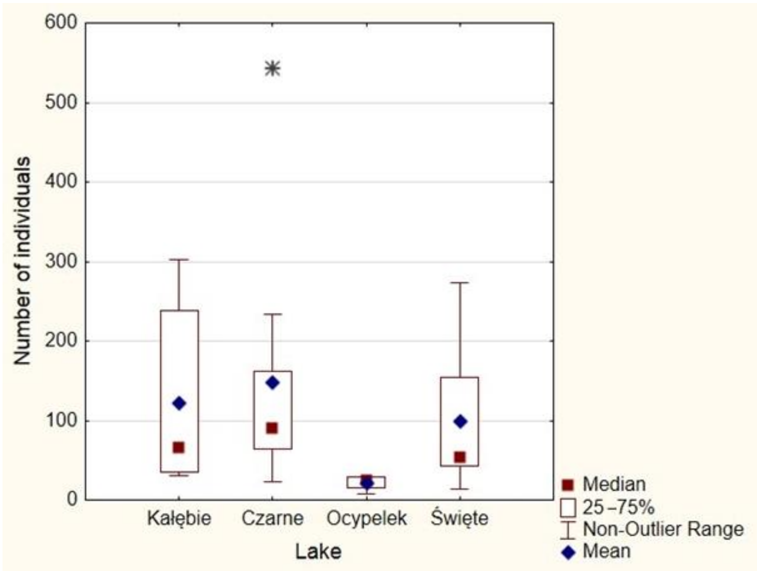
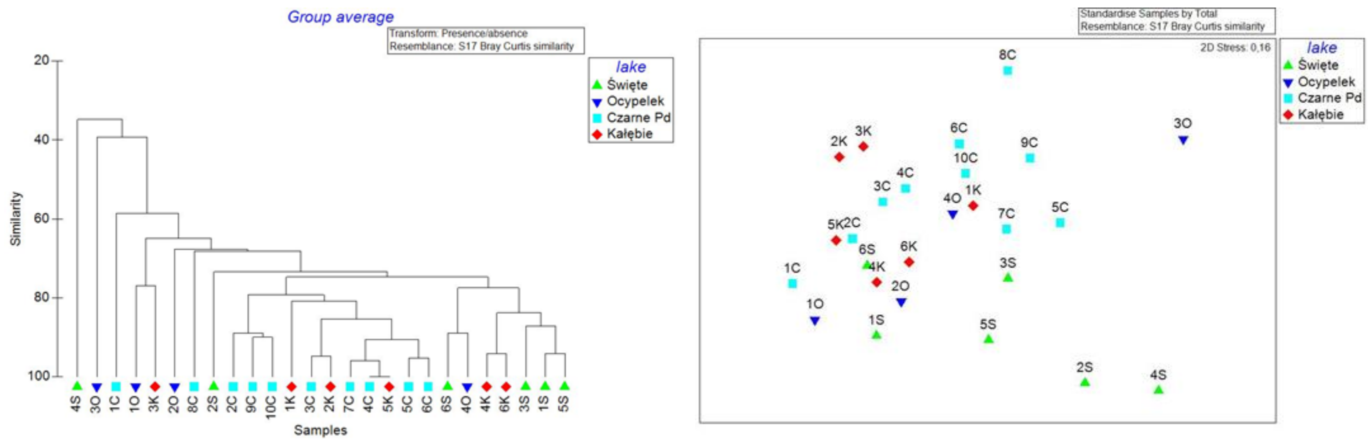


Figure 5. Mean and median of meiobenthic assemblages of studied lakes. Where: *—upper extreme.

The Bray–Curtis faunistic similarity (Figure 6) graphs show that stations Święte Lake No. 4 and Ocypelek Lake No. 3 have the greatest difference (approximately 40% similarity). All others are similar with a probability of about or greater than 60%. The sites of individual lakes do not form specific groups, but they rather constitute a common group characteristic of the study area.



(**a**) (**b**)

Figure 6. The Bray–Curtis faunistic similarity: (**a**)—cluster, (**b**)—MDS analyses.

Using the methodology of assessing the variability of the meiobenthic assemblages proposed by Wojtasik [6–8], a comparative 2D analysis of the ecological state of the lakes was carried out, and data interpolation was performed to create maps of the ecological state of the littoral (Figure 7). The values of parameters N_{10} and N_{taxa} are presented in Table 5.

The Święte and Kałębie lakes have a similar distribution for the N_{10} and N_{taxa} values, although a more highly developed trophy with richer biodiversity occurs in Lake Kałębie (Figure 7b). Lake Ocypelek has the least diversified littoral area in terms of ecological state (low values of N_{10} and N_{taxa} parameters). The littoral zone of the studied lakes (outside the area of site no. 4 of Lake Czarne Południowe) indicates the possibility of further development. A specific situation was found for Lake Święte (Figure 7c). Despite the fact that it is located in the vicinity of a forest, the obtained results indicate a progressive degradation of the lake. There is a poor grouping of meiobenthos with a disturbed taxonomic balance (B_w index).

Particular attention should be paid to points marked as subject to degradation (Czarne Południowe and Kałębie). These areas may have a decisive impact on the further development of lakes, which may consequently lead to their degradation. The location of the risk areas in the vicinity of buildings, farmlands, and roads suggests the possibility of an inflow of pollutants to the lakes as a result of anthropogenic activities [32,33].

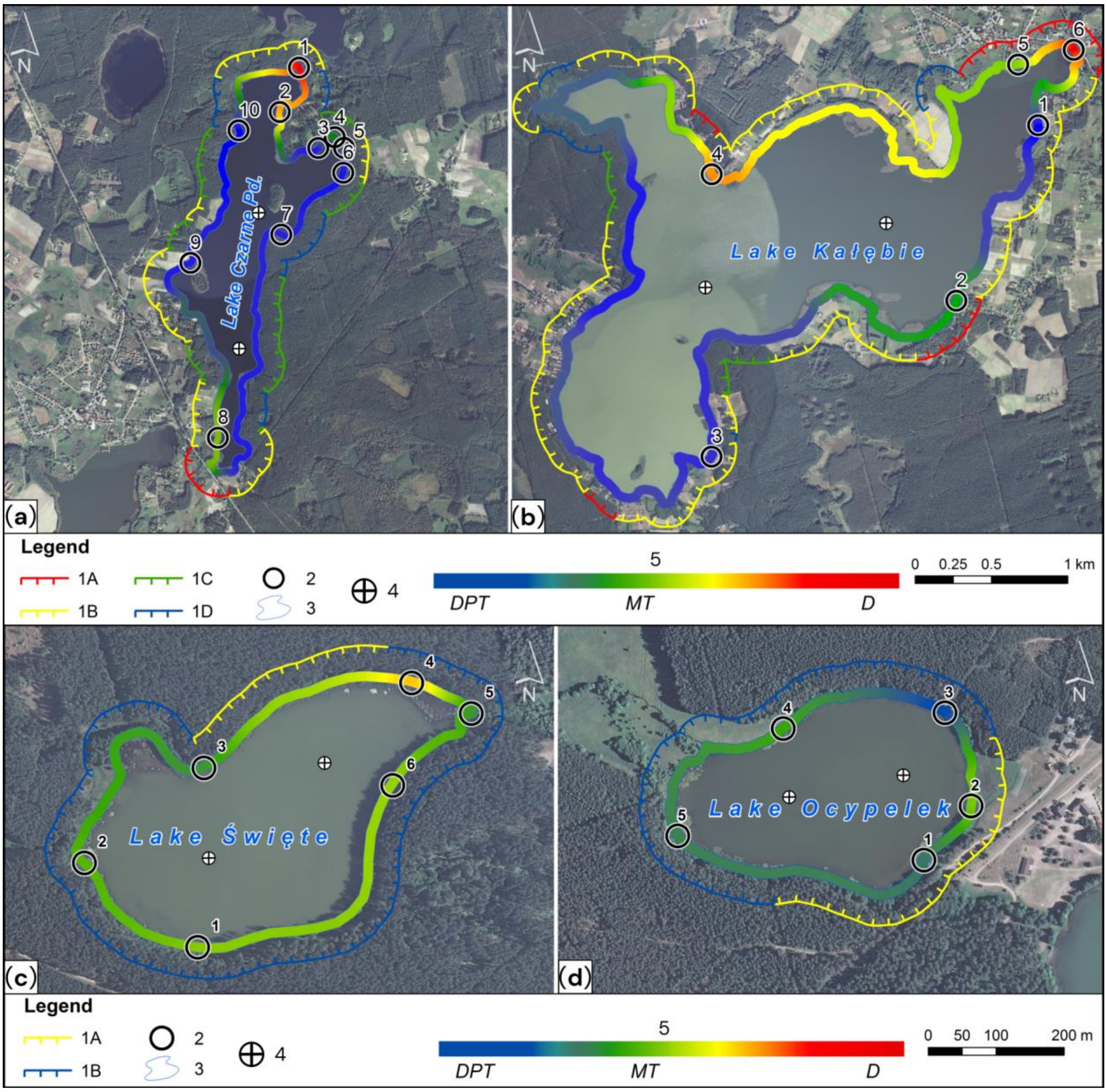


Figure 7. Ecological state of littoral of studied lakes and shoreline transformation: (**a**)—Lake Czarne Południowe, (**b**)—Lake Kałębie, (**c**)—Lake Święte, (**d**)—Lake Ocypelek. Where 1—classes of shoreline transformation (A—Class 1, B—Class 2, C—Class 3, D—Class 4–5), 2—meiobenthos sampling stations, 3—30 m boundary for lake shoreline, 4—lake sampling stations, 5—lake ecological state: DTP—Development Phase of Trophy; MT—Maximum Trophy; D—Degradation.

A comparative analysis of the results obtained for four lakes shows a clear differentiation of the littoral characteristics (Figure 8). The area of variability of the N_{10} and N_{taxa} parameters of Lake Kałębie is almost entirely within the area of variability of Lake Czarne Południowe, and to a lesser extent, it concerns Lake Święte. On the other hand, the area of variability of the examined N_{10} and N_{taxa} parameters for Lake Ocypelek is outside the areas of variability of other lakes. This indicates a different and not very differentiated nature of the littoral of Lake Ocypelek compared to lakes Czarne Południowe, Kałębie, and Święte.

Table 5. The MeioEco analyses of all stations: calculated parameters N_{10}, N_{taxa}, and B_w of meiobenthic assemblages for sampling stations.

Lake	Station Number	N_{10}	N_{taxa}	B_w
Święte	S1	156.98	9	0.489
	S2	45.87	8	0.507
	S3	43.83	11	0.904
	S4	14.27	3	0.536
	S5	64.22	8	0.821
	S6	278.29	10	0.514
Ocypelek	O1	29.56	6	0.687
	O2	28.54	8	0.665
	O3	8.15	3	0.750
	O4	22.43	8	0.839
Czarne Południowe	C1	23.45	5	0.348
	C2	85.63	8	0.575
	C3	98.88	10	0.834
	C4	554.54	13	0.880
	C5	237.51	11	0.790
	C6	153.92	10	0.859
	C7	53.01	12	0.842
	C8	74.41	7	0.632
	C9	65.24	10	0.652
	C10	165.14	10	0.857
Kałębie	K1	63.20	8	0.858
	K2	242.61	10	0.895
	K3	31.60	7	0.892
	K4	71.36	9	0.730
	K5	307.85	13	0.615
	K6	35.68	8	0.790

The calculation of the arithmetic mean value of the three parameters N_{10}, N_{taxa}, and B_w for the sites of the individual lakes studied and the determination of extreme values among all the measured values of N_{10}, N_{taxa}, and B_w allowed us to determine the average ecological state of the littoral and compare these values for the analyzed reservoirs (Figure 9). The obtained results indicate the similarity of the ecological state of the littoral of Lake Czarne Południowe and the Kałębie Lakes. Their ecological state can be described as a developing trophy. On the other hand, lakes Święte and Ocypelek are in the early stage of development compared to lakes Kałębie and Czarne Południowe. Lake Ocypelek shows a low level of trophic development. On the other hand, Lake Święte has a state of taxonomic equilibrium (B_w) on the border of an imbalance (Figure 8). This indicates a disturbed structure of the meiobenthos community of this lake.

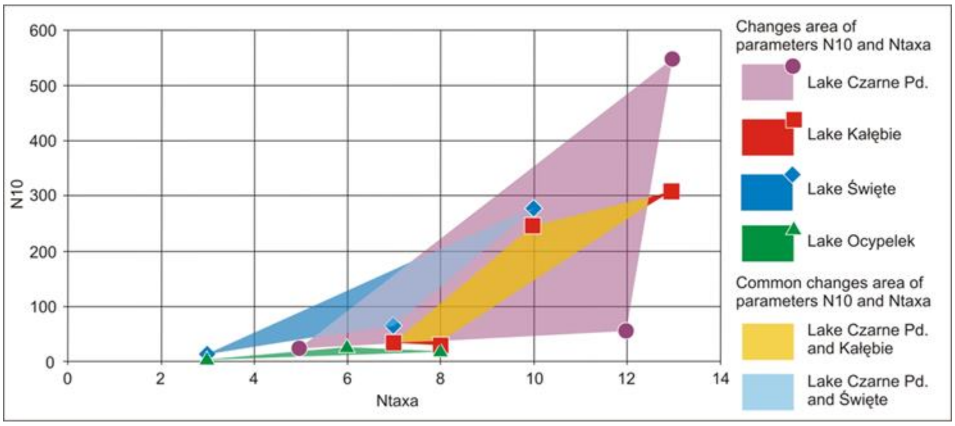


Figure 8. Range of variability of the ecological state (min, max, and area of variability of N_{10} and N_{taxa} parameters) of the studied lakes.

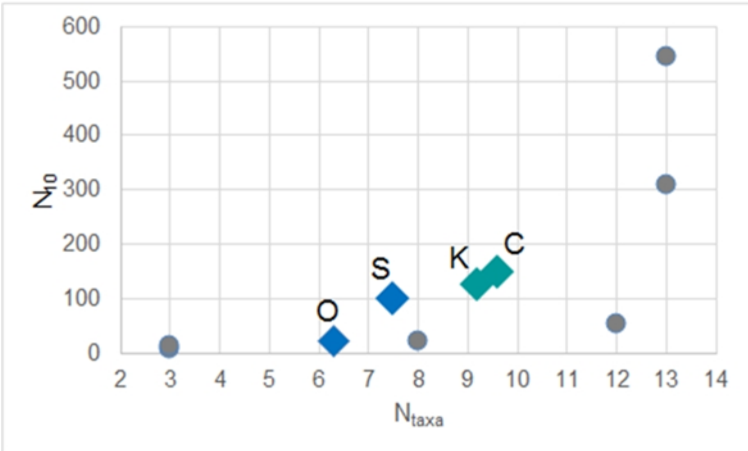


Figure 9. Arithmetic mean values of N_{10}, N_{taxa} parameters calculated for the lakes: Czarne Południowe (C), Kałębie (K), Święte (S), and Ocypelek (O) determining the mean ecological state of the littoral; gray dots represent points with extreme values of N_{10} and N_{taxa} in the entire analyzed material, blue rectangles represent initial phase of trophy, green rectangles represent growth of trophy.

When analyzing the ecological state of the littoral zone of the studied lakes (Figure 7), a relative scale was adopted, including the independently tested lakes:

Lake Czarne Południowe—a strongly developed trophy with a tendency to degrade in a small section, outside the forest areas, the northern part of the shoreline, a developing trophy in a long forest section. Ecological state for the whole lake—strong differentiation of trophies between development and degradation

Lake Kałębie—developed trophy with a tendency to degrade over a large stretch outside forest areas. Ecological state for the whole lake—strong differentiation of trophies between development and progressive degradation.

Lake Ocypelek—a developing trophy in the forest section, a tendency for degradation in the section adjacent to the arable fields. Ecological condition for the whole lake—progressive trophy development partially disturbed with sections of progressive degradation.

Lake Święte—development of a disturbed trophy (disturbed taxonomic balance for most sites, B_w index) and a developed trophy with a tendency for degradation in a small forest section. Ecological state for the entire lake—progressive development of the trophy.

A comparative 3D MeioEco analysis for the results obtained from all lakes (Figure 10) indicates a different degree of trophy development (N_{10} and N_{taxa}—Table 5). Lake Ocypelek remains in the initial stage of trophy development compared to other reservoirs. Lake Święte, on a large part of the littoral, has a trophy in the development stage, but with taxonomic imbalance. The northeastern section of the lake is in the trophic degradation phase. The southern and northeastern sections of the littoral of Lake Kałębie have a trophy in the initial stage of development, while on a short fragment of the northern part was indicate degradation. Lake Czarne Południowe has the most diversified ecological state, from the state of degradation (northern area), through a very well-developed trophy (the most developed of all four lakes) in the north-eastern region and the phase of sustainable development (middle part of the lake), to the phase of initial trophy development (southern part of the littoral).

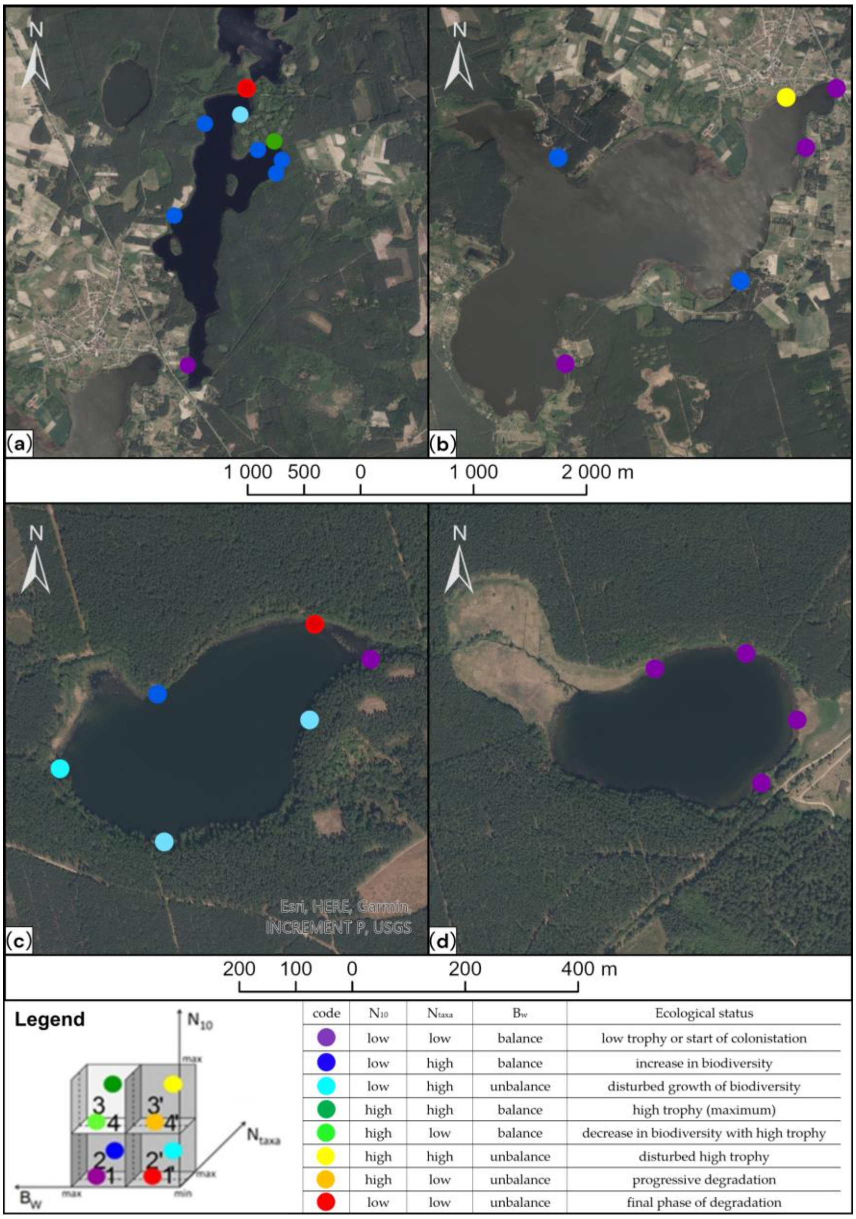


Figure 10. Comparative analysis of the ecological state of the studied lakes using MeioEco: (**a**)—Lake Czarne Południowe, (**b**)—Lake Kałębie, (**c**)—Lake Święte, (**d**)—Lake Ocypelek. Where: N_{10}—density of meiobenthic organisms (number of individuals/10cm^2), N_{taxa}—number of major meiobenthic taxa, B_w—balance index.

The analyses of the meiobenthos assemblages indicate the diverse nature of the littoral zone of the studied lakes. The most strongly developed trophy is found in the Czarne Południowe Lake; moreover, the range of changes in the examined parameters has the greatest spread here. This indicates significant fluctuations in the development of trophies in individual areas of the lake, from the level of developing a trophy, through a strongly developed trophy, to an area with progressive degradation.

A comparative analysis of the ecological state using the MeioEco method with other examined reservoirs in Poland, showing varying degrees of anthropogenic pressure, including the Czorsztyński and Sromowiecki reservoirs in the south of Poland [34], a degraded water environment near the phosphogypsum heap in Wiślinka in Northern Poland, natural and pristine water reservoirs in Roztocze in Southeastern Poland, and small reservoirs in the Kashubian Lakeland in Northern Poland [8], indicates well-developed trophic conditions and rich communities for both entire lakes and most study sites. Degraded regions are an exception, but they are relatively scarce (Figure 7).

4.5. Ttrophic State and Partial Assessment for Ecological State (WFD)

The gathered research material, based on a wide range of applied classifying elements, enabled the analysis of the trophic and partial assessments for the ecological state of the studied lakes. The assessment of the trophic state, based on the indicators of Vollenweider and Nurnberg, was fully applied only to dimictic reservoirs (Święte, Ocypelek). In addition to the universal measurement of the Secchi disk visibility, the percentage saturation of the hypolimnion with oxygen was also considered. Due to significant oxygen deficits recorded in the hypolimnion layer, these reservoirs can be classified as eutrophic or even polytrophic lakes (Table 6). Trophic state assessment criteria based on Carlson's indicators (TSI) allowed for the analysis of this state for all studied lakes. The calculated Carlson index values indicated that the trophic state of the reservoirs generally fell on the border between mesotrophy and eutrophy (Table 6). The variability of individual TSI indicators within the studied lakes was small (from 0.7—Lake Święte to 7.4—Lake Kałębie), indicating a consistency in the classification of this method. The indicator based on phosphorus content in the water (TSI_{TP}) for all lakes assumed values typical of mesotrophy (from 53.7 to 60.0). Indicators calculated based on Secchi disk visibility (TSI_{SD}) and chlorophyll a content (TSI_{Chl}) played a decisive role in classifying Lake Kałębie as a eutrophic reservoir.

Table 6. Evaluation of the trophic and ecological states (partial assessment) using selected methods.

Lake	River–Lake System	Trophic State		Shoreline State (Transformation)	Ecological State	
		Vollenweider	Carlson		WFD (Partial Assessment)	Meiobenthos
Święte	Świeta Struga	eutrophy	mesotrophy	natural shoreline	moderate	developing trophy with disturbed balance
Ocypelek	Święta Struga	eutrophy	eutrophy	natural shoreline	moderate	initial phase of developing trophy
Czarne Południowe	Kałębinica	-	mesotrophy	transformation of the natural shoreline is significant	moderate	developed trophy with area of high trophy and degradation
Kałębie	Kałębinica	-	eutrophy	heavily transformed shoreline	moderate	developed trophy

The diversity in the index of the shoreline transformation degree (B_a) clearly distinguishes lakes belonging to the Święta Struga system from those in the Kałębnica system. Lakes within the Święta Struga system exhibit a shoreline with a natural character. In contrast, lakes within the Kałębnica system are characterized by a significant or strong transformation of the shoreline zone.

Available biological elements were utilized to assess the ecological state of the studied lakes using information on chlorophyll a content and its threshold values for water quality classes assigned according to the "Chlorophyll-a" metric [8]. Based on this, Lake Święte and Czarne Południowe were classified as water bodies with a good ecological state. The other two reservoirs (Ocypelek and Kałębie) were preliminarily classified as lakes with a moderate ecological state. However, the final partial assessment of the ecological state was made with the support of physicochemical elements characterizing the eutrophication process (conductivity, Secchi disk visibility, dissolved oxygen, total nitrogen, and phosphorus content in the water). Water quality based on these elements is rated as above good and below good (according to Dz.U. 2021 poz. 1475), in reference to the surface water category for lakes. A state below good for physicochemical elements was observed only for Secchi disk visibility (Święte, Ocypelek, Kałębie) and dissolved oxygen content in the water (Święte, Ocypelek, Czarne Południowe). As a result, all examined lakes were classified as water bodies with a moderate ecological state.

For the investigated group of lakes, monitoring data are available only for Lake Kałębie. Based on the water quality assessment for this lake in 2005 [35], the waters were classified as Class III purity. However, the monitoring assessment for the periods of 2010–2015 and 2016–2021 [36] indicates that Lake Kałębie has a poor ecological status. These results correspond with the overall assessment of the trophic state and partial assessment of the ecological states for this lake. The water quality assessment for Lake Czarne Południowe in 2005 [37] was classified as a Class III purity lake, which is also reflected in the trophic state of this reservoir. However, it is presumed that due to significant pressure from the catchment and a low resistance to eutrophication, this lake will undergo further degradation. Unfortunately, for the remaining reservoirs, there is a lack of publicly available studies of a similar scope.

5. Conclusions

Lakes are territorial natural systems; thus, they should be regarded as elements whose functioning results from the interplay of various natural factors [26]. A detailed analysis of biological, chemical, physical, and morphological indicators, along with their synthetic compilation using applied methods for assessing trophic and ecological state, provides insights into the functioning and state of the lake ecosystem.

The diagnosis of the ecological and trophic states of selected lakes within the river-lake system of Święta Struga and Kałębnica indicates distinctions between the studied reservoirs. Lake Święte is a water body bordering on mesotrophy and eutrophy, where the ecological state (meiobenthic assessment) of the littoral zone suggests progressive trophic development. The water quality in this lake is classified as below good (moderate ecological state). Lake Ocypelek serves as an example of a eutrophic reservoir undergoing progressive degradation, with water quality also falling below good. Both lakes within the Święta Struga system are characterized by a natural shoreline and a forested direct catchment. Consequently, questions arise regarding the sources of their poor trophic state, answers to which lie beyond the scope of this study.

The lakes of the Kałębnica system are also characterized by a third quality water class, but in both reservoirs, advanced trophic conditions were diagnosed. Lake Kałębie is a eutrophic water body with a significantly transformed shoreline due to the development of the direct catchment. On the other hand, Lake Czarne Południowe is an example of a mesotrophic reservoir with a significantly transformed shoreline.

The progress of eutrophication in small lakes of the Święta Struga system and the poor trophic state in the large lakes of the Kałębnica system underscore the importance of employing various methods for assessing trophic and ecological states as a cohesive whole. The primary goal of a multi-analytical approach to such analyses is an attempt to indicate not only the trophic or ecological states of the entire reservoir but, above all, areas where actions should be taken to identify the causes of eutrophication and the deteriorating ecological conditions of the lakes.

The advantages of using meiobenthic organisms to assess water pollution were recognized as early as the 1990s [10,11,38]. However, the method of analyzing meiobenthic assemblages (MeioEco), along with its dedicated application, represents an innovative approach to assessing the ecological status and trophic development of water reservoirs, rivers, and marine areas [39]. It allows for the rapid classification of study sites in terms of quality or the comparison of analyzed water areas. The method is based on relative analysis, making it possible to identify subtle differences (newly formed or impoverished sites) and pinpoint locations particularly vulnerable to anthropogenic pressure.

The choice of a method for diagnosing the current trophic and ecological states of a given reservoir should take into account a preliminary assessment of the conditions in which the lake exists. This, in turn, requires an individual approach to each lake, making it advisable to use various available methods for assessing the trophic and ecological states of lakes. Consequently, potential corrective actions have the chance to effectively contribute to improving their condition. The limited or complete absence of results from individual or monitoring measurements in the water quality domain suggests that the use of simple, utilitarian tools and methods for monitoring the state of aquatic ecosystems is even more crucial, following the principle of 'Citizen Science' [40,41]. So, conducting low-cost research involving a multidisciplinary approach to diagnose the state of aquatic ecosystems is becoming a crucial element in lake monitoring.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/limnolrev24010006/s1, Table S1: Individuals of major meiobenthic taxa for sampling stations, N—all individuals of sampling stations, F—frequency of sampling stations of the lake, Ft—frequency of all stations.

Author Contributions: Conceptualization, M.M.; methodology, M.M. and B.W.; software, M.M. and B.W.; validation, B.W.; formal analysis, M.M. and B.W.; investigation, M.M. and B.W.; resources, M.M. and B.W.; data curation, M.M. and B.W.; writing—original draft preparation, M.M. and B.W.; writing—review and editing, M.M.; visualization, M.M. and B.W.; supervision, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article and Supplementary Materials.

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

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