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Article

Long-term phytoplankton and periphyton dynamics as indicators of ecological recovery in a hypertrophic lake: lake Durowskie, Poland

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Abstract. Long-term eutrophication remains one of the major pressures affecting freshwater lake ecosystems in Europe. Lake Durowskie (north-western Poland) has experienced sustained nutrient loading from agricultural runoff, urban activities, and hydrological connections with upstream lakes, resulting in a hypertrophic state. Since 2009, restoration measures combined with systematic ecological monitoring have been implemented to improve the lake's ecological condition. This study evaluates long-term phytoplankton and periphyton dynamics as indicators of ecological recovery in Lake Durowskie during 2008–2025. Samples were collected from multiple lake and inflow sites and analysed in terms of taxonomic composition, abundance, biomass, and ecological characteristics. Ecological status was assessed using biological indices, including the Shannon–Wiener diversity index (H′), Pielou evenness index (E), Jaccard similarity index, Nygaard mixed trophic index, and the diatom index (DI). The results indicate relatively high phytoplankton diversity and evenness across the lake. Chlorophyta and Bacillariophyceae contributed most to species richness, whereas total biomass was largely influenced by dinoflagellates, particularly Ceratium hirundinella and Peridiniopsis berolinense. Long-term observations revealed increasing algal species richness since 2022 and low Jaccard similarity values (17–25%), indicating significant community restructuring. Although the Nygaard index consistently classified the lake as hypertrophic, improvements in the periphyton diatom index at several sites suggest gradual ecological improvement. Overall, the results indicate a transitional recovery phase under persistent eutrophic pressure and confirm the value of phytoplankton and periphyton as indicators for long-term monitoring of hypertrophic lake ecosystems.

Keywords: phytoplankton; periphyton; eutrophication; ecological recovery; long-term monitoring; bioindicators; diatom index; hypertrophic lake; Lake Durowskie

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1. Introduction

Eutrophication remains one of the most widespread and persistent pressures on freshwater ecosystems worldwide, particularly in temperate regions of Europe (Xu et al., 2022). Excessive nutrient inputs from agricultural runoff, urbanisation, and altered hydrological connectivity promote high primary production, frequent algal blooms, and long-term degradation of ecological status in lakes (Xu et al., 2022; Yan et al., 2024).

Even when restoration measures are implemented, the ecological response of eutrophic and hypertrophic lakes is often non-linear, requiring long-term biological monitoring to reliably assess recovery trajectories (Jeppesen et al., 2005; Reyjol et al., 2014).

Algal communities, including phytoplankton and periphyton, are widely recognised as sensitive bioindicators of environmental change in freshwater ecosystems (Jakovljević et al., 2021; Messyasz & Wu, 2017). Due to their short life cycles and direct dependence on nutrient availability, light conditions, and water chemistry, algae respond rapidly to both anthropogenic pressures and restoration efforts. Changes in algal taxonomic composition, biomass distribution, and diversity indices provide valuable insights into trophic status, ecosystem stability, and successional processes (Reynolds, 2006; Padisák et al., 2009; Karpowicz et al., 2025). Consequently, algal-based indices, such as diversity metrics, trophic indices, and diatom-based indicators, are increasingly applied in ecological status assessments and water management frameworks (Tokatlı et al., 2020; European Commission, 2000; Birk et al., 2013; Blanco, 2024).

Long-term datasets are particularly valuable for distinguishing between short-term variability and genuine ecological recovery (Li et al., 2025; Reynolds, 2006). Recent studies highlight the importance of long-term ecological monitoring in evaluating restoration success in eutrophic lakes, particularly under conditions of persistent nutrient loading (Poikane et al., 2016; Carvalho et al., 2020; Hilt et al., 2017). While reductions in nutrient concentrations may occur relatively quickly, biological communities often respond with a delay, exhibiting complex restructuring processes rather than simple linear improvement (Li et al., 2025; Karpowicz et al.,2025). Declining community similarity, shifts in dominant functional groups, and divergence between abundance- and biomass-based patterns are frequently observed during transitional phases of recovery. Therefore, integrating phytoplankton and periphyton analyses over extended time periods is essential for understanding ecosystem trajectories in hypertrophic lakes.

Lake Durowskie, located in north-western Poland, represents a characteristic example of a small urban lake subjected to long-term eutrophication driven by agricultural inflow, urban pressure, and hydrological connections with upstream lakes (Xu et al., 2022; Reyjol et al., 2014). Since 2009, the lake has been the focus of continuous ecological monitoring combined with restoration measures aimed at improving water quality. This unique long-term dataset provides an opportunity to evaluate how algal communities respond to sustained management efforts under persistent eutrophic conditions (Li et al., 2025; Reynolds, 2006).

The present study aims to assess long-term phytoplankton and periphyton dynamics as indicators of ecological recovery in Lake Durowskie over the period 2008–2025. By combining taxonomic analyses with multiple algal-based indices, this study seeks to characterise spatial and temporal changes in algal community structure, evaluate trends in ecological status under continued hypertrophic pressure (Xu et al., 2022; Bennion et al., 2004; Li et al., 2025; Birk et al., 2013), and assess the usefulness of phytoplankton and periphyton as complementary bioindicators in long-term lake monitoring and sustainable ecosystem management (Li et al., 2025; Tokatlı et al., 2020; Blanco, 2024; Van den Brink et al., 2011).

2. Materials and Methods

2.1. Study area

The study was conducted in Lake Durowskie, located in north-western Poland within the town of Wągrowiec (52°49′06″ N, 17°12′01″ E) (Figure 1). Lake Durowskie is a post-glacial, lowland lake strongly influenced by anthropogenic pressure due to intensive agriculture in the catchment area, urban development along the shoreline, and hydrological connectivity with upstream lakes. This connectivity promotes continuous nutrient inflow and contributes to the lake’s long-term hypertrophic condition.

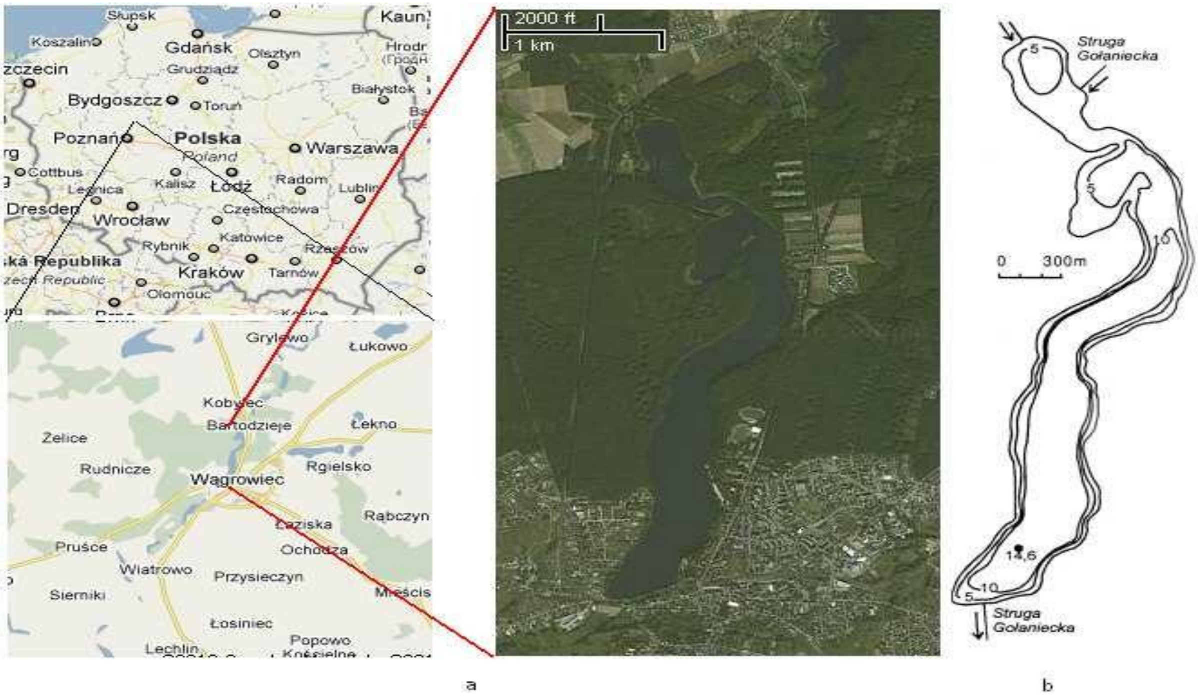


Figure 1. Location of Lake Durowskie (north-western Poland) and satellite view of the study area (Source: authors)

The morphometric and hydrological characteristics of Lake Durowskie are presented in Table 1, while the land-use structure of the direct catchment area is summarized in Table 2. The dominance of agricultural and forested areas indicates a mixed-type catchment, where diffuse pollution plays a key role in shaping the trophic status of the lake.

Table 1. Morphometric and hydrological characteristics of Lake Durowskie

Parameter	Value
Surface area	143.7 ha
Volume	11.32×10^6 m^3
Maximum depth	14.6 m
Mean depth	7.9 m
Total catchment area	23.610 ha
Direct catchment area	1.581 ha

Table 2. Land-use structure of the direct catchment area

Land use type	Share (%)
Urban	8.25
Agriculture	33.52
Forest	58.26

2.2. Sampling and monitoring

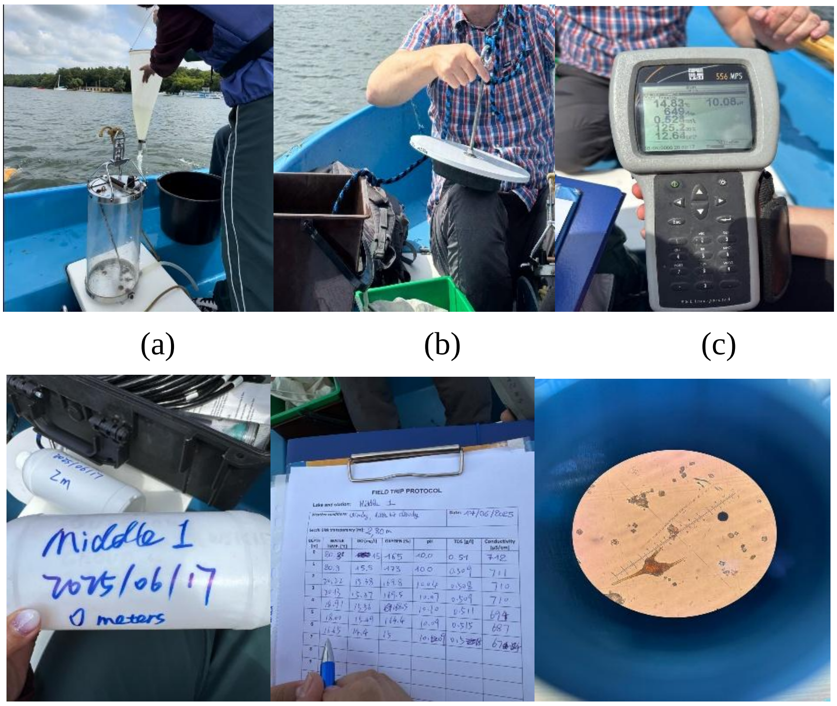
Field investigations were carried out in June 2025 as part of the long-term ecological monitoring program. The sampling design ensured coverage of inflow, central, aeration, and littoral zones.

Phytoplankton: 8 sampling stations

Periphyton: 12 sampling stations

Water samples (30 L) were collected from the epilimnion layer (0–3 m) and concentrated using plankton nets. Periphyton samples were obtained by scraping submerged stones along the shoreline. All samples were preserved with Lugol's iodine solution(Figure 2).

Physicochemical parameters (temperature, pH, electrical conductivity, dissolved oxygen) were measured in situ using a YSI 556 multiparameter probe. Water transparency was determined with a Secchi disk.



(a) (b) (c)

(d) (e) (f)

Figure 2. Field sampling procedures and *in situ* measurements during the monitoring campaign

(a) Water sampling for phytoplankton analysis (Source: authors)
(b) water transparency measurement using Secchi disk;
(c) in situ measurements of physicochemical parameters using a multiparameter probe (YSI 556);
(d) sample labeling;
(e) field protocol documentation;
(f) representative phytoplankton taxa under light microscopy.

2.3. Laboratory analysis

Algal taxa were identified to the lowest possible taxonomic level using light microscopy and standard taxonomic keys(Rimet & Bouchez, 2012). Quantitative analysis was conducted by counting individual algal cells in subsamples. Phytoplankton abundance was expressed as individuals per litre (ind. L^{-1}) using appropriate concentration factors.

Biomass was estimated based on species-specific biovolume calculations, where algal cells were approximated using geometric models. Biomass values were expressed in mg L^{-1} and rounded to three decimal places.

2.4. Biological indices

Biological assessment followed the principles of the EU Water Framework Directive, with emphasis on biological quality elements (Scott et al., 2005).

2.4.1. Phytoplankton indices

The following indices were applied:

Shannon–Wiener diversity index (H′) – assessment of species diversity;

Evenness index (E) – evaluation of species distribution uniformity;

Jaccard similarity index (SJ) – long-term comparison of species composition (2008–2025);

Nygaard trophic index – determination of trophic state, with trophic status classification based on threshold values presented in Table 3.

Table 3. Classification of trophic status based on Nygaard index

Trophic status	Index value
Oligotrophic	< 1.0
Mesotrophic	1.0–3.0
Eutrophic	3.0–5.0
Hypertrophic	> 5.0

The Nygaard index classification was used to interpret phytoplankton-based trophic status.

2.4.2. Periphyton and diatom index

The ecological status was assessed using the Diatom Index (DI), based on species-specific sensitivity, tolerance ranges, and relative abundance (Poikane et al., 2016), with ecological status classes defined according to the classification scheme presented in Table 4.

Table 4. Ecological status classification according to diatom index

Ecological status	Diatom index
Very good	> 0.83
Good	0.55–0.83
Moderate	0.30–0.55
Poor	0.15–0.30
Bad	< 0.15

This classification was applied to interpret diatom-based ecological status across sampling sites.

2.5. Data analysis framework

Data processing included quantitative and qualitative analysis of phytoplankton and periphyton communities. Phytoplankton density (ind. L^{-1}) and biomass (mg L^{-1}) were calculated using species-specific biovolume estimates.

Descriptive statistical analysis was applied to summarize spatial patterns in species richness, abundance, and biomass. Diversity indices were calculated for each sampling station. Long-term trends in species richness and trophic indices were interpreted using comparative analysis of monitoring data collected between 2008 and 2025.

3. Results

3.1. Phytoplankton structure and diversity

Phytoplankton communities of Lake Durowskie in 2025 exhibited high taxonomic richness and pronounced spatial heterogeneity. In total, 86 phytoplankton taxa belonging to seven major algal groups were identified, including *Bacillariophyceae*, *Chlorophyta*, *Cyanobacteria*, *Cryptophyta*, *Dinophyta*, *Euglenophyta*, and *Chrysophyceae.*

Species richness was highest in the inflow zone, where 46 taxa were recorded, whereas central pelagic stations showed lower values ranging from 13 to 27 taxa. This pattern indicates that the inflow acts as an important source of phytoplankton diversity, continuously supplying taxa to the lake ecosystem.

Chlorophyta and *Bacillariophyceae* dominated the phytoplankton community at all sampling sites, together accounting for more than 65% of the total species pool (Figure 3). This taxonomic structure is characteristic of eutrophic lowland lakes exposed to sustained nutrient loading.

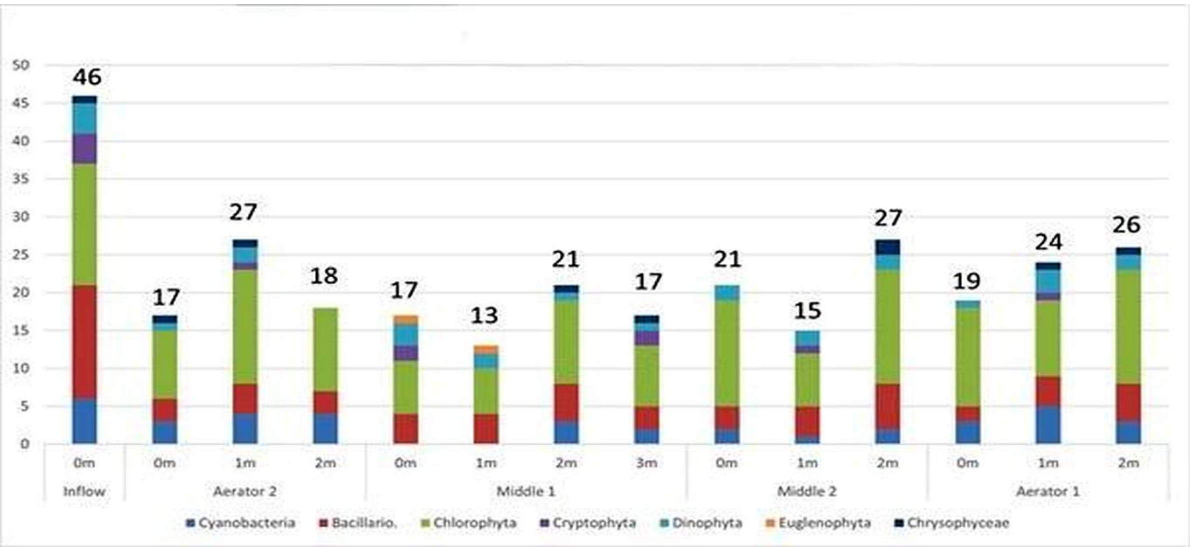


Figure 3. Number of Phytoplankton Species at each site and depth. The belonging group of the species is indicated with different colors (Source: authors)

Figure 3 shows a higher number of species in the inflow (46) than in the lake (13-27). This indicates that the inflow acts as an additional source of phytoplankton species for the lake ecosystem. *Chlorophyta* and *Bacillariophyceae* groups contribute to more than 65% of the number of the phytoplankton species at every site.

Phytoplankton diversity, expressed by the Shannon–Wiener index, varied among sampling zones. The highest values were observed in the inflow (approaching 5.0), whereas lake stations showed moderate to high diversity levels ranging from 2.5 to 3.5 (Figure 4). Elevated diversity in the inflow reflects reduced dominance and higher environmental heterogeneity compared to the central lake basin. Evenness index values were consistently high across all sites (0.63–0.83), indicating a relatively balanced distribution of species abundances and the absence of strong dominance patterns. Overall, these results suggest a structurally complex phytoplankton community despite the persistence of eutrophic conditions.

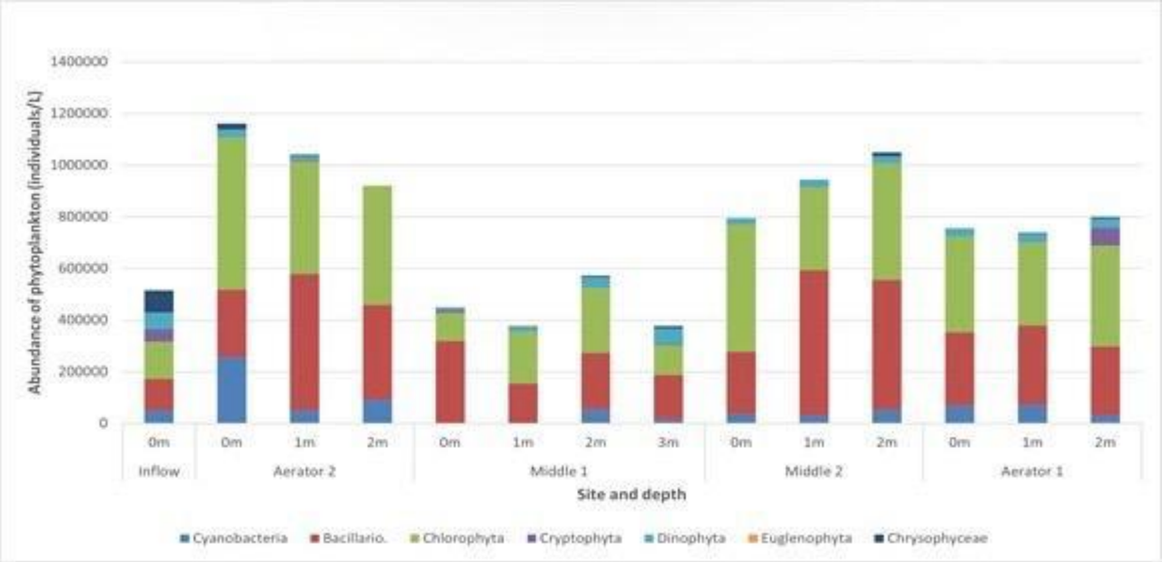
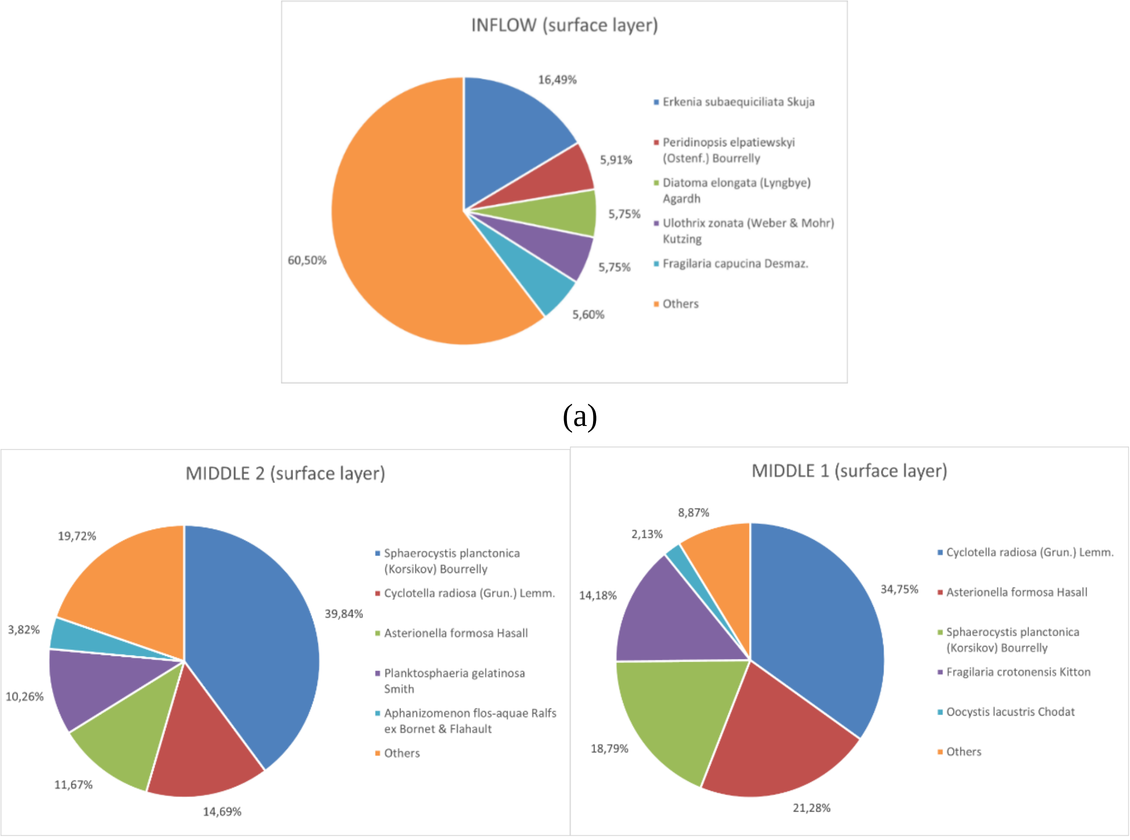


Figure 4. Phytoplankton group abundance for each site and depth (Source: authors)

Figure 4 shows that the most abundant phytoplankton groups are *Bacillariophyceae* and *Chlorophyta* at lake stations, whereas no single dominant group was observed in the inflow.

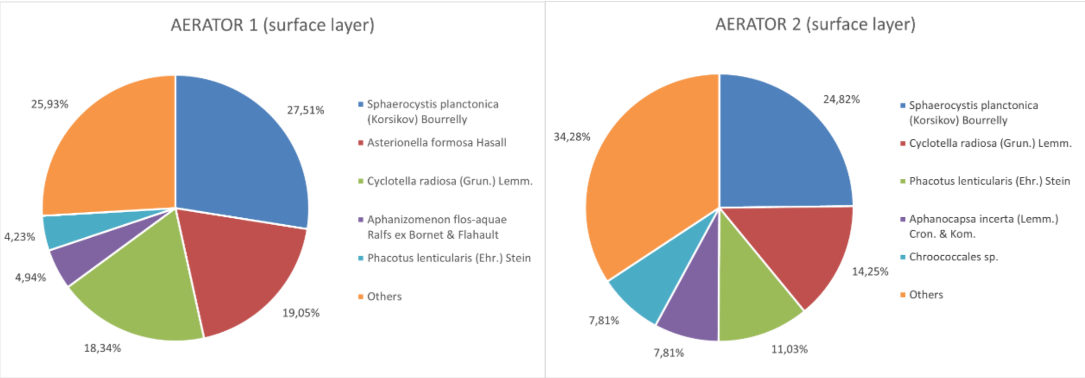
As illustrated in Figure 5, at the inflow station, phytoplankton abundance was characterised by the dominance of a limited number of taxa, while the remaining species together accounted for more than 60% of the total abundance.



(a)

(b)

(c)



(d) (e)

Figure 5. Relative abundance of the five dominant phytoplankton species at different sampling sites in the surface layer (0 m depth): (a) inflow station; (b) site 2; (c) site 3; (d) site 4; (e) site 5 (Source: authors)

3.2. Periphyton and diatom index

Periphyton communities of Lake Durowskie in June 2025 were dominated by benthic diatoms, demonstrating clear spatial variation in species composition and dominance patterns among sampling sites (Table 5). The assemblages were characterised by a limited number of dominant taxa accompanied by a diverse group of less abundant species.

Table 5. Relative abundance (%) of dominant diatom taxa in periphyton communities of Lake Durowskie in June 2025. No diatoms were recorded at site 12

Taxon	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**Site 7**	**Site 8**	**Site 9**	**Site 10**	**Site 11**	**Site 12**
1	2	3	4	5	6	7	8	9	10	11	12	13
Achnanthes lanceolata	–	–	–	–	6.77	–	–	–	–	–	–	–
Achnanthes laterostrata	–	–	–	–	–	–	–	–	–	–	–	–
Achnanthes minutissima Kütz.	35.00	32.77	44.03	38.14	37.00	39.80	38.84	43.10	48.00	39.43	14.00	–
Amphora pediculus (Kütz.) Grunow	–	–	–	1.93	5.01	–	28.76	3.47	–	–	–	–
Cocconeis pediculus	3.75	7.60	–	–	–	3.56	–	–	–	–	–	–
Cocconeis placentula Ehr.	20.50	18.29	15.34	13.96	15.54	11.60	13.17	21.88	17.00	29.43	18.00	–
Gomphonema mesodon (Ehr.) Kütz.	–	–	–	–	–	–	–	–	7.00	9.30	–	–
Diatoma tenuis	16.00	10.68	11.93	8.47	5.01	8.92	–	–	–	–	–	–

Continuation of the Table 5

1	2	3	4	5	6	7	8	9	10	11	12	13
Diatoma vulgaris	6.65	7.05	7.06	–	–	–	–	–	–	–	–	–
Fragilaria capucina (Desm.) Rabenhorst	–	–	5.68	–	–	–	–	–	6.00	–	–	–
Fragilaria capucina var. vaucheriae	–	–	–	–	8.02	–	4.05	–	–	–	8.00	–
Fragilaria virescens	–	–	–	–	–	5.56	–	–	–	–	–	–
Gomphonema parvulum	–	–	–	–	–	–	–	–	–	–	6.00	–
Gomphonema pumilum	–	–	–	–	–	–	–	–	–	–	–	–
Navicula cari	10.75	–	–	–	–	–	–	–	–	–	–	–
Witzschia dissipata	–	–	–	–	–	5.56	–	3.47	–	–	7.00	–
Witzschia palea (Kütz.) W. Sm.	–	–	–	–	–	–	–	–	–	–	–	–

Across most sites, *Achnanthes minutissima* represented the most abundant diatom species, reaching particularly high relative contributions at sites 3-9, where its share exceeded 35–48%. This widespread dominance reflects the high ecological tolerance of this species and its adaptability to eutrophic and environmentally variable conditions. *Achnanthes lanceolata* and *Achnanthes laterostrata* occurred sporadically with low relative abundance.

Cymbella microcephala was another frequent and ecologically important taxon, contributing between approximately 12% and 27% at several sites, suggesting relatively stable littoral habitats with sufficient oxygen availability. Other taxa, including *Diatoma tenuis*, *Fragilaria capucina*, *Gomphonema parvulum*, *Gomphonema pumilum*, *Navicula cari*, and *Nitzschia* spp., occurred with moderate to low relative abundance and contributed to local-scale differentiation of periphyton communities.

No diatom species were recorded at site 12, indicating unfavourable conditions for periphyton development at this station.

Diatom Index values revealed pronounced spatial variability in ecological status along the littoral zone. In 2025, several stations achieved good ecological status, while other sites remained within moderate or poor classes, indicating partial improvement of benthic ecological conditions under persistent eutrophic pressure.

3.3. Long-term dynamics (2008–2025)

Long-term analysis revealed pronounced temporal changes in the phytoplankton communities of Lake Durowskie over the period 2008–2025. Total species richness increased markedly after 2022, with 2025 exhibiting the highest number of recorded taxa since the beginning of the monitoring programme (Figure 6). This trend indicates a gradual increase in community complexity and may reflect the cumulative effects of restoration measures implemented in the lake since 2009. This increase indicates an ongoing restructuring of phytoplankton assemblages rather than a return to earlier community states.

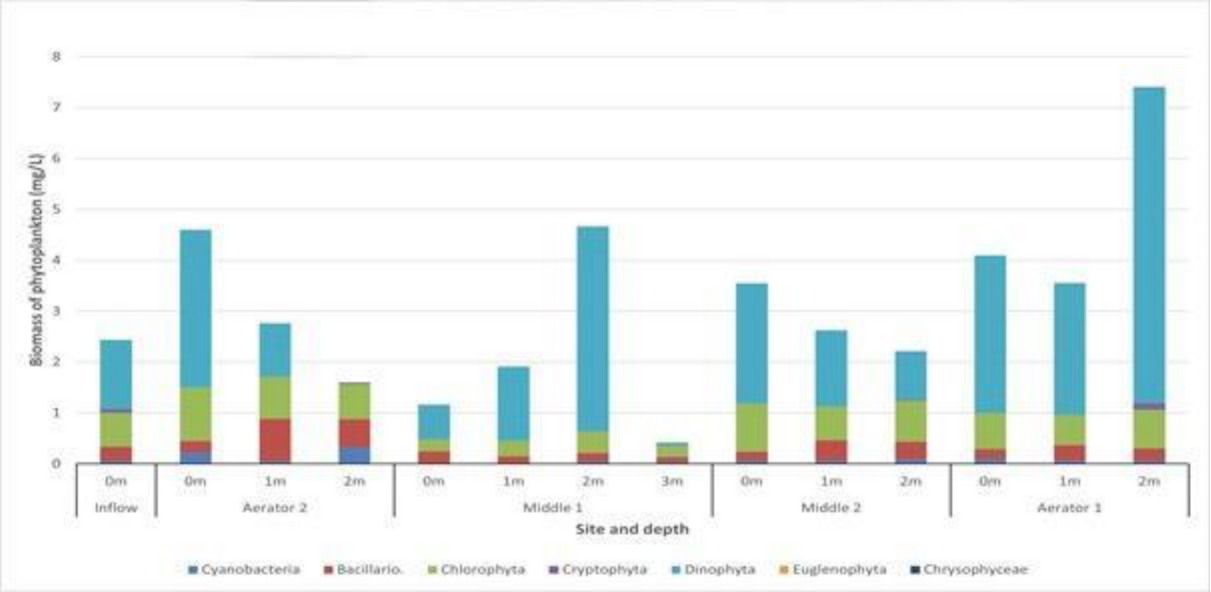


Figure 6. Shows that Dinophyta and Chlorophyta dominate phytoplankton biomass across all sites and depths (Source: authors)

In particular, dinoflagellates contributed disproportionately to total biomass, reflecting their large cell size and high biovolume, despite relatively moderate numerical abundance. This divergence between abundance- and biomass-based patterns highlights the importance of considering multiple metrics when assessing ecological change.

Community similarity analysis further confirmed the dynamic nature of phytoplankton succession. Jaccard similarity values between 2025 and earlier monitoring years ranged from 17% to 25%, indicating low resemblance to historical assemblages and high species turnover. Such low similarity suggests continuous species replacement and adaptive reorganisation under sustained environmental pressure.

Despite increasing taxonomic richness, the Nygaard mixed trophic index remained consistently high across all stations in 2025, with values ranging from 5.7 to 11.5 (Table 6), corresponding to eutrophic and hypertrophic conditions. These values were comparable to those observed in 2023–2024, demonstrating that nutrient enrichment continues to exert strong control over phytoplankton structure and ecosystem functioning.

Table 6. Nygaard mixed trophic index values at sampling sites in Lake Durowskie in 2025

Methods	Cyanobacteria	Chlorococcales	Centric diatoms	Euglenoids	Desmids	Mixed Index
Inflow	6	10	1	0	3	5,7
Aerotor 2	7	14	1	0	3	11,0
Middle 1	4	9	1	1	3	5,0
Middle 2	3	13	2	0	4	9,0
Aerotor 1	6	15	2	0	2	11,5

Overall, the long-term dynamics of phytoplankton in Lake Durowskie indicate a transitional ecological state, characterised by increasing biodiversity, high species turnover, and persistent eutrophic conditions. These patterns suggest that biological reorganisation is occurring under long-term management, although full trophic recovery has not yet been achieved.

4. Discussion

4.1. Phytoplankton

The phytoplankton community of Lake Durowskie exhibits clear spatial and temporal patterns typical of eutrophic to hypertrophic lake ecosystems undergoing long-term management. One of the most prominent features is the role of the inflow as a major biodiversity source. Significantly higher species richness and diversity at the inflow compared to pelagic lake stations indicate continuous introduction of taxa into the lake, promoting spatial heterogeneity and contributing to community complexity.

A marked discrepancy between numerical dominance and biomass dominance was observed. While Chlorophyta and *Bacillariophyceae* dominated phytoplankton assemblages in terms of species richness and abundance, phytoplankton biomass was largely controlled by dinoflagellates, particularly *Ceratium hirundinella* and *Peridiniopsis berolinense*. This pattern reflects the large cell size and high biovolume of dinoflagellates, allowing them to dominate biomass despite relatively low abundance. Such divergence between abundance- and biomass-based metrics is well documented in eutrophic lakes and has important implications for energy flow and trophic interactions (Reynolds, 2012).

Long-term analysis revealed increasing phytoplankton biodiversity since 2022, with 2025 showing the highest total number of recorded taxa since the beginning of monitoring. At the same time, declining Jaccard similarity values indicate substantial species turnover and ongoing community restructuring rather than recovery toward historical assemblages. This combination of increasing diversity and low similarity suggests a transitional ecological state characterized by dynamic reorganization under persistent environmental pressure.

Similar transitional dynamics have been reported in other European lakes undergoing restoration, where biological communities often respond more slowly than physicochemical parameters (Jeppesen et al., 2005; Carvalho et al., 2020). These findings confirm that biological indicators provide essential information on ecosystem recovery processes.

Despite these biological changes, the Nygaard mixed trophic index consistently classified the lake as eutrophic to hypertrophic. This confirms that nutrient enrichment remains a dominant driver of ecosystem functioning. The coexistence of high biodiversity with persistent eutrophy highlights the non-linear response of phytoplankton communities to management measures and emphasizes that biological recovery may precede detectable improvements in trophic status (Reynolds, 2012).

4.2. Periphyton

Periphyton communities provided complementary insights into ecological conditions, particularly in littoral zones. The dominance of *Achnanthes minutissima* and *Cymbella microcephala* across most sampling sites reflects the prevalence of taxa tolerant to eutrophic conditions and variable environmental stress. Nevertheless, spatial differences in dominance patterns indicate local-scale habitat differentiation (Van den Brink et al., 2011)

Diatom index values demonstrated a clear improvement in ecological status at several littoral sites in 2025 compared to previous years, with multiple stations shifting from moderate or poor to good ecological classes. These changes suggest that benthic communities may respond more rapidly to environmental improvement than pelagic phytoplankton, making periphyton a sensitive early indicator of ecological recovery.

Ecological preference analyses showed persistent dominance of eutrophic indicator species, confirming sustained nutrient enrichment. However, the increasing contribution of mesotrophic taxa suggests partial alleviation of eutrophication pressure. High proportions of oxygen-demanding species across sites indicate favourable oxygen conditions, while dominance of alkaliphilous taxa reflects stable alkaline pH typical of productive eutrophic lakes.

Overall, periphyton-based assessment indicates gradual improvement of nearshore ecological conditions, even though eutrophication remains the defining characteristic of the lake (Feio & Dolédec, 2012; Ma et al., 2019; Ramezani et al., 2014).

Descriptive statistical analysis and comparative evaluation of long-term monitoring data revealed a gradual increase in phytoplankton species richness after 2022, accompanied by substantial community turnover. These trends suggest that biological restructuring is occurring despite the persistence of hypertrophic conditions.

5. Conclusion

Phytoplankton communities of Lake Durowskie are characterized by high taxonomic diversity, with diatoms and green algae dominating in terms of abundance, while dinoflagellates - particularly *Ceratium hirundinella* - control phytoplankton biomass. Diversity and evenness indices indicate structurally complex communities with limited dominance, despite persistently high nutrient levels.

Periphyton-based diatom indices reveal significant improvement at several littoral sites compared to previous years, supporting the conclusion that ecological conditions are gradually improving, especially in nearshore zones. However, low Jaccard similarity values demonstrate substantial community restructuring rather than recovery toward historical assemblages.

The Nygaard trophic index confirms that Lake Durowskie remains in an eutrophic to hypertrophic state. Taken together, the results indicate a transitional ecological phase characterized by persistent eutrophication accompanied by increasing biodiversity and partial biological recovery. Continued long-term monitoring and nutrient load reduction remain essential to consolidate ecological improvements and prevent future degradation.

These findings highlight the importance of long-term biological monitoring for evaluating the effectiveness of lake restoration strategies.

6. Supplementary Materials: not supplementary materials.

7. Author Contributions

Conceptualization – B.M., B.L.; methodology – B.M., B.L.; formal analysis – B.M.; Investigation – B.M.; data curation – B.M.; writing – original draft preparation – B.M.; writing – review and editing – B.L.; visualization – B.M.; supervision – B.L. All authors have read and agreed to the published version of the manuscript.

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11. Conflicts of Interest: the authors declare no conflicts of interest.

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Гипертрофты көлдің экологиялық қалпына келуінің индикаторлары ретінде фитопланктон мен перифитонның ұзақ мерзімді динамикасы: Дуровское көлі, Польша

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Аңдатпа. Ұзақ мерзімді эвтрофикация Еуропадағы тұщы су көлдері экожүйелеріне әсер ететін негізгі экологиялық қысымдардың бірі болып табылады. Солтүстік-батыс Польшада орналасқан Дуровское көлі ауылшаруашылық ағындыларының, қалалық қызметтің және жоғары ағыста орналасқан көлдермен гидрологиялық байланысының әсерінен қоректік заттардың тұрақты түсуіне ұшырап, гипертрофты күйге жеткен. 2009 жылдан бастап көлдің экологиялық жағдайын жақсартуға бағытталған қалпына келтіру шаралары жүйелі экологиялық мониторингпен қатар жүргізілуде. Бұл зерттеу 2008–2025 жылдар аралығында Дуровское көліндегі фитопланктон мен перифитон қауымдастықтарының ұзақ мерзімді динамикасын экожүйенің экологиялық қалпына келуінің индикаторлары ретінде бағалауға бағытталған. Үлгілер көлдің әртүрлі учаскелерінен және құятын ағындардан жиналып, таксономиялық құрамы, молшылығы, биомассасы және экологиялық сипаттамалары бойынша талданды. Экологиялық жағдай Шеннон–Уивер әртүрлілік индексі (H′), Пиелу теңестірілу индексі (E), Жаккар ұқсастық индексі, Нюгардтың аралас трофикалық индексі және диатомдық индекс (DI) сияқты биологиялық индекстерді қолдану арқылы бағаланды. Нәтижелер көл бойынша фитопланктонның салыстырмалы түрде жоғары түрлік әртүрлілігі мен теңестірілуін көрсетті. Түрлік байлықта *Chlorophyta* мен *Bacillariophyceae* басым болды, ал жалпы биомассаның қалыптасуына негізінен динофлагеллаттар, әсіресе *Ceratium* hirundinella және Peridiniopsis berolinense түрлері әсер етті. Ұзақ мерзімді бақылаулар 2022 жылдан бастап балдырлардың түрлік байлығының артқанын және Жаккар ұқсастық индексінің төмен мәндерін (17–25%) көрсетті, бұл қауымдастық құрылымының елеулі қайта қалыптасуын білдіреді. Нюгард индексі көлді тұрақты түрде гипертрофты деп сипаттағанымен, перифитонның диатомдық индексінің кейбір учаскелерде жақсаруы экологиялық жағдайдың біртіндеп жақсаруын көрсетеді. Жалпы алғанда, алынған нәтижелер эвтрофтық қысым сақталған жағдайда көл экожүйесінің өтпелі қалпына келу кезеңінде екенін көрсетеді және фитопланктон мен перифитонның гипертрофты көлдерді ұзақ мерзімді мониторингте бағалау үшін маңызды индикаторлар екенін дәлелдейді.

Түйін сөздер: фитопланктон; перифитон; эвтрофикация; экологиялық қалпына келу; ұзақ мерзімді мониторинг; биоиндикаторлар; диатомдық индекс; гипертрофты көл; Дуровское көлі.

Долгосрочная динамика фитопланктона и перифитона как индикаторов экологического восстановления гипертрофного озера: озеро Дуровское, Польша

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Аннотация. Длительная эвтрофикация остается одним из наиболее значимых факторов экологического давления на экосистемы пресноводных озер Европы. Озеро Дуровское, расположенное в северо-западной части Польши, на протяжении длительного времени подвергалось поступлению избыточных биогенных веществ вследствие сельскохозяйственного стока, урбанизированной деятельности и гидрологической связанности с вышерасположенными озерами, что привело к формированию гипертрофного состояния. С 2009 года на озере реализуются мероприятия по восстановлению, сопровождаемые систематическим экологическим мониторингом, направленные на улучшение его экологического состояния. Настоящее исследование посвящено оценке долгосрочной динамики фитопланктона и перифитона в качестве биологических индикаторов экологического восстановления озера Дуровского за период 2008–2025 гг. Отбор проб фитопланктона и перифитона осуществлялся на различных участках озера и в притоках, после чего проводился анализ их таксономического состава, численности, биомассы и экологических характеристик. Для оценки пространственно-временных изменений экологического состояния применялся комплекс биологических индексов, включая индекс разнообразия Шеннона–Уивера (H′), индекс выравненности Пиелу (E), индекс сходства Жаккара, смешанный трофический индекс Нюгарда и диатомовый индекс (DI). Результаты показали высокое видовое разнообразие и выравненность фитопланктона. По видовому богатству доминировали *Chlorophyta* и *Bacillariophyceae*, тогда как формирование общей биомассы в значительной степени определялось динофлагеллятами, прежде всего *Ceratium hirundinella* и *Peridiniopsis berolinense*. С 2022 года отмечено увеличение общего числа видов водорослей и низкие значения индекса Жаккара (17–25%), что свидетельствует о значительной перестройке сообществ. Несмотря на сохранение гипертрофной классификации по индексу Нюгарда, диатомовый индекс перифитона на ряде участков указывает на постепенное улучшение экологических условий. В целом полученные результаты свидетельствуют о переходной стадии экологического восстановления озера при сохраняющемся эвтрофном давлении и подтверждают высокую информативность фитопланктона и перифитона как биоиндикаторов для долгосрочного мониторинга и устойчивого управления гипертрофными озерными экосистемами.

Ключевые слова: фитопланктон; перифитон; эвтрофикация; экологическое восстановление; долгосрочный мониторинг; биоиндикаторы; диатомовый индекс; гипертрофное озеро; озеро Дуровское.