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RESEARCH ARTICLE

Phytoplankton dominance structure and abundance as indicators of the trophic state and ecological status of Lake Kortowskie (northeast Poland) restored with selective hypolimnetic withdrawal

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Abstract. The objective of the study was to identify seasonal changes in phytoplankton taxonomic structure and development rates to characterize phytoplankton communities as determinants of the trophic and ecological conditions of Lake Kortowskie in northeast Poland which has been undergoing restoration with selective hypolimnetic withdrawal. The lake was designated as being of high trophic state and bad ecological status based on intense phytoplankton growth, the strong dominance and persistent occurrence of blue-green algae, and seasonal modifications in phytoplankton taxonomic structure and assemblage growth rates. The ecological status of the lake assessed in 2011 corresponds to that determined in 1987-1990 and 1999 and indicates that eutrophication in Lake Kortowskie is progressing.

Keywords: phytoplankton, lake, taxonomic structure, biomass, trophy, ecological status assessment

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Introduction

The trophic state of lakes is characterized by certain physicochemical and biological processes in their environments (Dillon and Rigler 1975, Vezjak et al. 1998). Conclusions concerning these processes, which reflect the trophic state of a given water body, can be drawn based on observations of the abiotic and biotic factors involved in aquatic ecosystem functioning (Zdanowski 1982, Kajak 1983, Mc Queen et al. 1986, Giorgio and Peters 1994). Phytoplankton is one of the biotic indicators of lake trophic state; its composition, dominance structure, and growth rate are responses to prevailing conditions, and changes in them are consequences of variable environmental conditions and biocenotic relationships within the aquatic ecosystem. Therefore, they are important elements in evaluations of lake trophic state (Hillbricht-Ilkowska and Kajak 1986, Burchardt 1993, Danilov and Ekelund 1999, Reynolds 2000) and the assessment of ecological status (Hutorowicz and Pasztaleniec 2009, Napiórkowska-Krzebietke et al. 2009, Hutorowicz et al. 2011).

Lake Kortowskie has been subject to restoration since 1956 by the selective removal of hypolimnion waters which is aimed at decelerating the progressive lake eutrophication (Olszewski 1959, Paschalski 1965, Tadajewski 1965, Bittel 1965, Bohr 1965, Sikorowa 1965). Restoration may have caused changes that affect different aspects of the lake's functioning, which explains the wide range and number of existing studies on the physicochemical (Olszewski 1971, Mientki 1975, 1986, Mientki and Teodorowicz 1996, Głażewski and Parszuto 2001, Mientki and Dunalska 2001, Dunalska 2002, Wiśniewski and Mientki 2002, Dunalska et al. 2001, 2007) and biological characteristics of Lake Kortowskie (Chudyba 1974, 1975, Niewolak 1974, Widuto 1976, 1977, Chudybowa 1977, Sikorowa 1977, Zmysłowska and Sobierajska 1977, Zmysłowska 1987). The phytoplankton of Lake Kortowskie was examined by Wysocka (1959) and Bohr (1965) in the 1950s. First Chudyba (1974, 1975) and then Chudybowa (1977) described seasonal changes in the lake's phytoplankton in the 1960s. Jaworska and Zdanowski (2011, 2012) studied the phytoplankton of Lake Kortowskie in the 1990s.

In the 1950s, the phytoplankton of Lake Kortowskie was mainly composed of species identified by Bohr (1965) as typical of eutrophic waters. In the 1960s, Chudyba (1974, 1975) described the phytoplankton community in the lake as a composition of diatoms, chlorophytes, and cyanoprokaryotes. Algal blooms at this time lasted for relatively short periods. During the 1970s, more intensive algal growth was recorded only in spring. Phytoplankton biomass then was estimated at less than 10 mg l^{-1} (Sikorowa et al. 1975, Chudybowa 1977). During the 1987-1991 period further shifts in phytoplankton taxonomic structure and development patterns were observed and manifested as gradual increases in the frequency and domination of blue-green algae (Jaworska and Zdanowski 2011), while the prevailing role of Bacillariophyceae and Chlorophyta in the biocenosis declined gradually. The development of a phytoplankton community dominated by Cyanoprokaryota more abundantly than previously was also documented in 1997-1998 (Chudyba 2001). In 1999-2000, more pronounced changes in phytoplankton taxonomic structure were recorded; at the time, the total phytoplankton biomass was very high at up to 35 mg l^{-1}. Blue-green algae occurred in large numbers, and they were recorded not only in summer, but also in spring and autumn. Multi-annual variations in the phytoplankton taxonomic structure and community development intensity in Lake Kortowskie indicated trophic change in the ecosystem that was identified as progressing eutrophication (Jaworska and Zdanowski 2012).

This study is yet another attempt made to characterize Lake Kortowskie phytoplankton, but for the first time as an element of ecological status assessment. The objective of the study was to determine seasonal changes in phytoplankton taxonomic structure and development intensity and, based on these findings, to characterize the phytoplankton community in Lake Kortowskie as an indicator for determining its trophic state and assessing its ecological status.

Material and methods

The research was conducted in Lake Kortowskie, which is one of the Mazurian Lakes and lies within the administrative borders of the city of Olsztyn in northeastern Poland. The lake has an elongated shape along its north-south axis. The basin comprises three distinct parts: the south basin has a maximum depth of 17.2 m, the north basin one of 15.7 m, and the middle part is relatively shallow with a maximum depth of 6 m (Fig. 1). The average depth is 5.9 m (Synowiec 1965). The surface area of the lake is 94 ha, and its volume is 5,323,000 m^3. The total drainage basin of the lake is 38.0 km^2, and the direct drainage basin is 102 ha. The lake is supplied by five inflows, and there is only one river outflow – the Kortówka River, a tributary of the Łyna River, that is located in the southeastern part of the reservoir. The amount of waters flowing out of the lake is regulated by a weir that permits draining hypolimnion water through a pipeline installed in the southern part of the lake. The lake has been and is subjected to restoration consisting of the selective removal of hypolimnion waters.

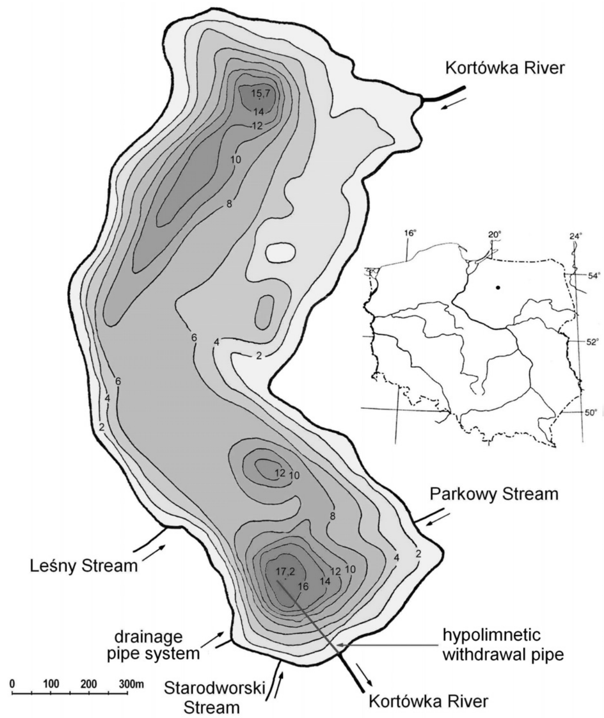

Figure 1. Location of sampling stations in Lake Kortowskie (map according Inland Fisheries Institute, Olsztyn, Poland).

The Lake Kortowskie phytoplankton was examined at two stations: station S was at the deepest site in the south, while station N was in the north (Fig. 1). Both sites were designated by Chudyba (1975) as representative ones. Our phytoplankton analyses were conducted in 2011. Samples were collected once a month from April to November from depths of 0-5 m in the water column at 1 m intervals, and averaged samples from the 0-5 m water column were finally obtained (Hutorowicz et al. 2011). Each averaged sample was used to obtain the final sub-samples consisting of 1 l of water each for quantitative phytoplankton analysis. The samples were collected with a 2 dm^{-3} Ruttner's sampler. Additional samples were collected with a 30 μm mesh plankton net. Preliminary qualitative analysis of the phytoplankton sampled was performed on live material collected with the plankton net; the final assays were performed on fixed material. Quantitative phytoplankton analysis was performed on preserved material collected from the water depths and concentrated by sedimentation. The samples were condensed to a volume which enabled determining at least 10 but no more than 25-50 phytoplankton algae in a single microscopic vision field at 400x magnification. The analyses were performed according to the methods described by Starmach (1989) using a Sedgwick-Rafter chamber (1 cm^3, 1000 mm^2) to calculate the number of individuals. A sample of a known volume of 1 cm^3 was placed under a cover glass and analyzed in three replications. The phytoplankton biomass was assessed with the cell volume measurement method (Heusden 1972, Luścińska and Oleksowicz 1984, Kawecka and Eloranta 1994, Hutorowicz 2005), and then it was computed from the product of abundance, mean cell volume of a given taxon, and mass density, which was assumed to be 1.0 g cm^{-3}. Qualitative and quantitative phytoplankton analyses were performed using the following microscope magnifications: 1.0x10x40 or 1.0x10x63 (Carl Zeiss-Axio Imager A1 microscope). The samples were analyzed according to phenological seasons: April and May were spring; June, July, and August were summer; September, October, and November were autumn.

The lake's ecological status was assessed using the method proposed by Hutorowicz and Pasztaleniec (2009) and by taking into consideration the abiotic typology of Polish lakes proposed by Kolada et al. (2005). The computed index values, or metrics, enabled classifying the lake to a certain ecological category proposed in the ecological class boundary method. Ecological status assessment was also calculated based on supplementary data from 1987-1990 and 1999 (Jaworska and Zdanowski 2011, 2012). The Phytoplankton Metric for Polish Lakes (PMPL) was computed for all of the data from 2011 and previous years, and the corresponding ecological status was determined with only two metrics – total biomass and blue-green algae biomass. The chlorophyll *a* metric was not included.

Results

Phytoplankton biomass in Lake Kortowskie ranged from 9.8 to 27.1 mg l^{-1} (mean 18.9 mg l^{-1}, standard

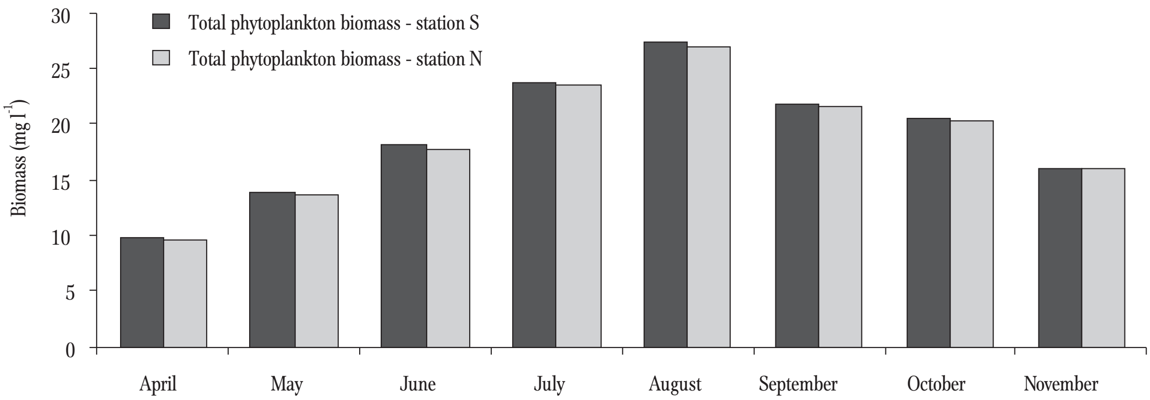

Figure 2. Total phytoplankton biomass (mg l^{-1}) at stations in Lake Kortowskie in 2011.

deviation (SD) = 6.1, n = 8), and exhibited similar seasonal dynamics of change at all the sites (Fig. 2). In the spring (April and May), the average phytoplankton biomass was 11.8 mg l^{-1} (SD=2.8), with 9.8 mg l^{-1} in April and the higher amount of 13.7 mg l^{-1} in May. In the early summer, biomass was even higher in June at 17.9 mg l^{-1}. Further increases occurred in July, when biomass was 23.7 mg l^{-1}. The highest value was recorded in August at 27.1 mg l^{-1}. The average summer phytoplankton biomass was 22.9 mg l^{-1} (SD=4.6). At the end of September, the phytoplankton biomass began to decline with values of 21.7 mg l^{-1} in September, and 20.3 mg l^{-1}in October. It was much lower in November at 15.9 mg l^{-1}. The average biomass in the autumn was 19.6 mg l^{-1} (SD=3.0).

The highest biomass was of Cyanoprokaryota followed by Dinophyceae and while Bacillariophyceae. Chrysophyceae, Chlorophyta, and Euglenophyta enhanced the taxonomic diversity of the phytoplankton, they did not contribute considerably to the biomass (Fig. 3). Bacillariophyceae dominated in spring comprising 60-70% of the total biomass. The diatom biomass was 7.6 mg l^{-1} in April, and it rose to 8.6 mg l^{-1} in May. The dominants were *Fragilaria crotonensis* Kitt. in April, and *Aulacoseira granulata* (Ehr.). Simonsen in May, while the sub-dominants were *Diatoma tenuis* Agardh,

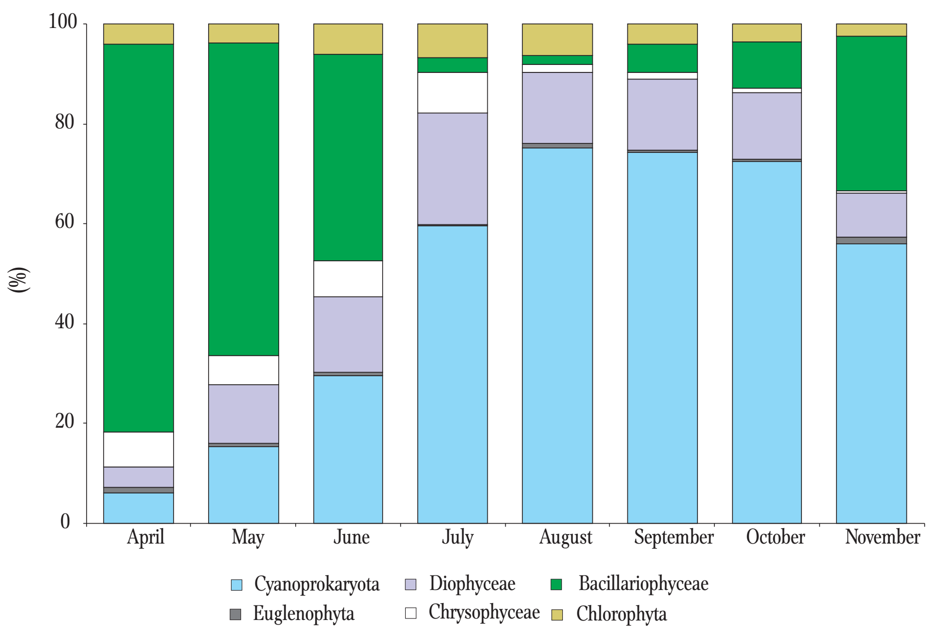

Figure 3. Share of particular systematic groups in the biomass of phytoplankton in Lake Kortowskie in 2011.

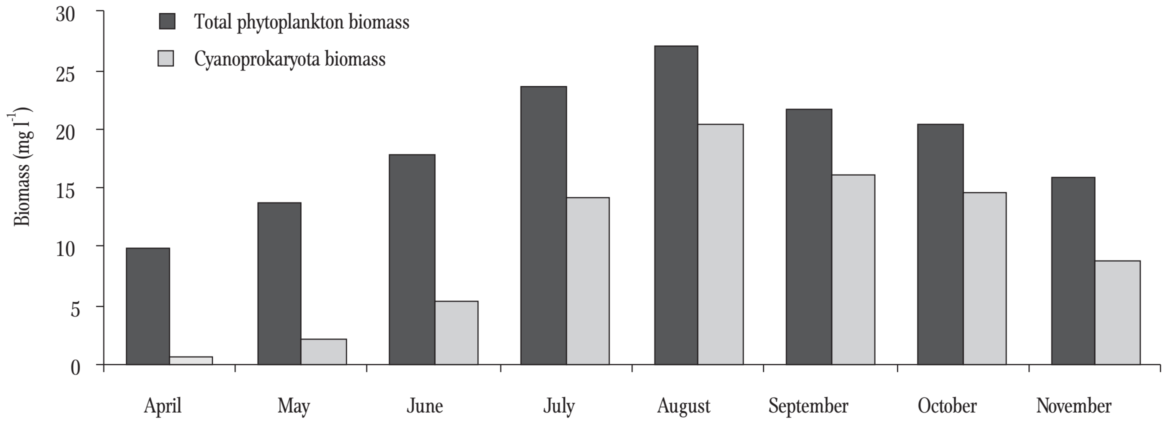

Figure 4. Total phytoplankton biomass (mg l^{-1}) and Cyanoprokaryota biomass (mg l^{-1}) in Lake Kortowskie in 2011.

Asterionella formosa Hass., and *Ulnaria acus* (Kütz.) M. Aboal. In the summer months of June, July, and August the phytoplankton was dominated by Cyanoprokaryota at 5.3 mg l^{-1} in June, which rose to 14.1 mg l^{-1} in July, and then exceeded 20 mg l^{-1} in August (Fig. 4). The average biomass of blue-green algae in summer was 13.3 mg l^{-1} (SD=7.6), which comprised 30% of the phytoplankton biomass in June, 60% in July, and 75% in August. The taxonomic diversity of blue-green algae was high, and included representatives of Nostocales, Chroococcales, and Oscillatoriales. Nostocales were most numerously represented by *Dolichospermum* and *Aphanizomenon*; the most abundant Chroococcales were *Microcystis* and *Woronichinia*, while *Pseudanabaena* and *Planktolyngbya* were the most numerous representatives of Oscillatoriales. However, the highest biomass was produced by the species *Dolichospermum circinalis* (Rabenh. ex Bornet et Flah.), *D. spiroides* Klebahn, *D. lemmermannii* P. Richter in Lemm., and *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah. The sub-dominant group of the summer phytoplankton was Dinophyceae, which occurred at a biomass of 2.7-5.3 mg l^{-1} and corresponded to 15-25% of the total phytoplankton biomass. In the autumn months of September, October, and November, Cyanoprokaryota continued to be the dominant group. They represented 73-74% of the total biomass in late September and October, and 57% in November. The autumn blue-green algae biomass decreased to 16.1, 14.7, and 8.9 mg l^{-1} in the consecutive months of autumn. Initially, in September and October, the dominant autumn species was *Aphanizomenon flos-aquae*, and the abundance and species diversity of blue-green algae were high. Later, in November, it was only *Pseudanabaena limnetica* (Lemm.) Kom., which had previously been a sub-dominant species, that contributed to the blue-green algae biomass in amounts characteristic of dominants. The diatom biomass increased to 5 mg l^{-1} at this time, and their contribution to phytoplankton biomass reached 30%. The most abundant were *Aulacoseira granulata* and *Ulnaria acus*.

The value of the metric used in ecological status evaluation determined in 2011 was 4.03 (PMPL=4.03). Lake Kortowskie was classified among lakes with bad ecological statuses based on this value and in accordance with ranges that designate particular ecological classes of lakes (Table 1). The values of this metric varied in previous years, and that determined using data from 1999 also classified this lake as having a bad ecological status. Poor ecological status was designated based on the data from 1987-1990 (Table 1).

Discussion

Each trophic type of the lakes is characterized by a certain qualitative and quantitative structure of phytoplankton, which reoccurs in a given lake's life shaped by its trophy (Sommer et al. 1986, Gawler et al. 1988, Lair and Ayadi 1989). Thus, in addition to other ecosystem components, phytoplankton

Table 1
Results of ecological status assessment based on total phytoplankton biomass and blue-green algae biomass

Year	Total phytoplankton biomass (mg l^{-1})		Blue-green algae biomass (mg l^{-1})	Metric total phytoplankton biomass	Metric blue-green algae biomass	PMPL	Ecological status
	Min-max (mean)	Min-max (mean) summer	Min-max (mean) summer				
2011	9.8-27.1 (18.9)	23.7-27.1 (25.3)	14.1-20.4 (17.3)	3.85	4.21	4.03	bad
1999	4.1-33.1 (20.3)*	27.3-33.1 (30.2)*	20.2-26.3 (23.3)*	3.90	4.58	4.24	bad
1990	1.4-14.2 (9.3)*	13.1-14.2 (13.4)*	6.3-7.9 (7.1)*	3.11	3.13	3.12	poor
1989	2.1-17.0 (8.9)*	11.3-17.0 (13.9)*	6.1-8.6 (7.3)*	3.07	3.15	3.11	poor
1988	1.5-15.9 (8.9)*	10.7-15.9 (13.3)*	6.5-7.3 (6.9)*	3.07	3.09	3.08	poor
1987	1.7-15.2 (8.6)*	10.3-15.2 (12.6)*	5.9-6.8 (6.3)*	3.04	2.98	3.02	poor

*data from Jaworska and Zdanowski (2011, 2012)

taxonomic composition, dominance structure, growth rate, and dynamics of seasonal change serve as indicators of lake trophic state (Spodniewska 1978, 1979, Burchardt 1993, Hutorowicz 1999, Reynolds et al. 2002).

The phytoplankton in Lake Kortowskie was characterized by intense growth, seasonal variability in taxonomic composition and dominance structure which directly affected biomass. The biomass values in Lake Kortowskie are indicative of a high degree of eutrophication. According to Hillbricht-Ilkowska and Kajak (1986), Lake Kortowskie is classified as eutrophic. According to the lake trophic classes proposed by Heinonen (1980) for Finnish lakes, eutrophic lakes are those in which phytoplankton biomass ranges between 3.5 and 10.0 mg l^{-1}. Spodniewska (1983) suggested that a phytoplankton biomass above 8 mg l^{-1} is characteristic of eutrophic lakes in the Mazurian Lake District.

Phytoplankton biomass values are most often a direct effect of dominant taxonomic group development. The trophic state of a lake not only affects the growth of phytoplankton but also shapes its taxonomic structure (Burchardt et al. 1994, Hutorowicz 1999, Snit'ko and Rogozin 2002). The rate of phytoplankton growth in Lake Kortowskie was controlled predominantly by Cyanoprokaryota growth. Blue-green algae were present in the phytoplankton from the early spring until late autumn. Their development gradually became more and more intense until they began to dominate the phytoplankton in summer, which was a position they maintained in the autumn. Periodically, they competed with Dinophyceae for dominance in the phytoplankton communities; however, despite intense growth, Dinophyceae did not assume the dominant position in the phytoplankton communities inhabiting Lake Kortowskie. The strong dominance of blue-green algae and dinoflagellates is typical of highly eutrophic water bodies (Burchardt and Łastowski 1999, Reynolds 2000), because both Dinophyceae and Cyanoprokaryota find advantageous conditions in eutrophic lakes. Nonetheless, blue-green algae often have a better chance of maintaining their dominance because they are equipped with a number of species-specific, physiological adaptation mechanisms that enable them to compete successfully and predominate over other algae (Shapiro 1990). The environmental adaptations of blue-green algae and their rapid response rate enable them, under favorable conditions, to develop intensively, which often leads to their occurrence in quantities so large that algal blooms happen (Lafforgue et al. 1995). According to Palmer (1962), phytoplankton blooms are defined as each instance of mass algal development in water. Nebaeus (1984) suggested certain threshold values for defining algal blooms; namely, chlorophyll *a* concentrations > 20 mg m^{-3} or total phytoplankton biomass > 3 g m^{-3}. Chlorophyll concentrations and phytoplankton biomass exceeded these values in Lake Kortowskie, which could imply that the mass occurrences of planktonic algae and the formation of algal blooms are possible. The high biomass values produced by blue-green algae possibly indicate that these could be blue-green algal blooms, and, potentially, the dominant blue-green algae taxa can help to identify which species could create blooms. The mass occurrence of blue-green algae is a determinant of the advanced trophic state of lakes (Spodniewska 1986). The intensive growth of blue-green algae observed in Lake Kortowskie, the highest biomass of which was 20 mg l^{-1}, exhibited a tendency towards algal blooms, and, thus, permits classifying this lake as eutrophic (Hillbricht-Ilkowska and Kajak 1986).

According to the Hutorowicz and Pasztaleniec (2009) classification of lake ecological status, the multi-metric based only on two partial metrics – total phytoplankton biomass and blue-green algae biomass, indicated that Lake Kortowskie was of a bad ecological status in 2011. The status determined from the 1999 data was the same, while the data from 1987-1990 indicated the ecological status in Lake Kortowskie was poor. The parameter that significantly influenced changes in ecological status was the successively increasing blue-green algae biomass (Jaworska and Zdanowski 2011), which is an important indicator in ecological status assessment (Hutorowicz and Pasztaleniec 2009). Based on the value of the blue-green algae biomass metric determined, Lake Kortowskie was classified as belonging to the bad ecological status group. Another regularity was reported by Hutorowicz et al. (2011) with regard to five stratified lakes located in the Wel River basin; the blue-green algae biomass metric of three lakes was distinctly lower than the total phytoplankton biomass and the chlorophyll *a* metrics, which reduced the PMPL multi-metric, and this led two of these lakes being classified as a better ecological status.

Conclusions

The phytoplankton dominance structure and abundances analyzed in Lake Kortowskie permitted determining the lake's trophic state and to assess its ecological status. Phytoplankton communities characterized by such high biomass and specific dominance structure are typical of eutrophic lakes, to which Lake Kortowskie belongs despite its continuous restoration by the selective removal of hypolimnion waters. The intense growth of phytoplankton, with its high share of persistently present blue-green algae combined with seasonal changes in phytoplankton communities effected by blue-green algae dominance indicated the high trophic state and bad ecological status of Lake Kortowskie in 2011. A bad ecological status was also determined from the data from 1999, while the ecological status assessed from the 1987-1990 data was poor. The overall assessment of the ecological status of Lake Kortowskie was influenced primarily by the blue-green algae biomass metric, particularly in 1999 and 2011, when it contributed to Lake Kortowskie being classified in the bad ecological status category.

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Author contributions. B.J. designed the study; B.J., J.D., and D.G. performed the study; B.J. analyzed the phytoplankton; B.J. and M.B. wrote the paper. All of the authors read and approved the final manuscript.

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