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Phytoplankton based assessment of the ecological status of four shallow lakes (Eastern Poland) according to Water Framework Directive – a comparison of approaches

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ABSTRACT

The EU Water Framework Directive includes phytoplankton as one of the four biological elements to be used in the assessment of the ecological status of surface waters. In this work we establish the ecological status of four shallow lakes in the Polesie Region of Eastern Poland on the basis of phytoplankton and physicochemical data from the lake water. A number of recently developed phytoplankton indices, including the Carlson Index, *Q* index and German PSI were compared. Cyanoprokaryota, chlorophytes and dinophytes dominated in Lakes Głębokie and Sumin, while in the Lakes Rotcze and Maśluchowskie the biggest share belonged to Chlorophyta. On the basis of the Carlson Index, Lake Głębokie had the highest trophic score, while the lowest score was for Lake Rotcze. A similar result was also found with the *Q* index which indicated a good ecological state for Lake Rotcze ($Q = 3.5$), a bad state for Lake Głębokie ($Q = 0.9$), a poor status for Lake Sumin ($Q = 1.2$) and a moderate status for Lake Maśluchowskie ($Q = 2.9$). Similar results were obtained with the use of the German PSI which classified Lake Głębokie as bad status (PSI = 4.7) and Lake Rotcze as good (PSI = 2), although differences between the 2 indices appeared between the moderate and poor status lakes (respectively in the case of Lake Sumin – PSI = 2.6 and Lake Maśluchowskie – PSI = 4.4).

Introduction

Phytoplankton plays a central role in the structure and functioning of freshwater ecosystems. In many waters algae and cyanobacteria contribute to a large proportion of the primary production and may exert a heavy influence on other ecosystem components (e.g. zooplankton, macrophytes and macroinvertebrates). The quality and quantity of the phytoplankton depends in part on the nutrient load. Therefore the use of phytoplankton for water quality assessment (especially assessing eutrophication impact) has a long history. Different methods have been developed; some of them use phytoplankton abundance (typically as chlorophyll *a*), whereas others examine the structure of the phytoplankton community (dominant and indicator species). Classification schemes based on phytoplankton biomass in terms of chlorophyll *a* or biovolume values were developed more than 20 years ago (Heinonen 1980; OECD 1982; Hillbricht-Ilkowska and Kajak 1986). The water quality assessment systems based on the taxonomic composition typically listed trophic indicator species (Thunmark 1945; Nygaard 1949; Järnefelt 1952; Heinonen 1980; Rosén 1981; Tremel 1996). The application of phytoplankton data for the assessment of water quality has also been developed using different numerical indices. Carlson's (1977) trophic state index (in which chlorophyll *a*, total phosphorus concentration and Secchi depth are included) is commonly used to measure eutrophication. Trophy quotients have also been based on the number of taxa from different algal groups (Thunmark 1945; Nygaard 1949; Barbé et al. 2003; Kangro et al. 2005) or diversity indices like the Simpson Index and the Shannon-Wiener Index (Shannon and Weaver 1949; Lloyd and Ghelardi 1964). Despite many advantages, none of these indices has become commonly and widely accepted. Therefore, the raw values of phytoplankton abundance and biomass (wet weight, chlorophyll *a* concentration) are generally used for water quality assessment and the phytoplankton species structure is often presented only in a descriptive way (its taxonomic structure).

In the EU Water Framework Directive (WFD) (2000/60/EC, EU, 2000), phytoplankton is one of the four biological quality elements (but five biological groups: phytoplankton, macrophytes and phytobenthos, macroinvertebrates and fish) required for the

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ecological status assessment of surface waters. According to the WFD, the phytoplankton based assessment should include: species composition, species abundance or biomass, and the frequency and intensity of phytoplankton blooms. The WFD prescribes the assessment of the ecological quality of surface waters using an Ecological Quality Ratio (EQR). The EQR is defined as the relationship between the current observed value and a reference condition for a given ecological element. The reference condition reflects a relatively undisturbed state, corresponding to very low pressure, with only minimal human impacts. The Directive gives descriptive ("normative") definitions of five classes of ecological status (High, Good, Moderate, Poor and Bad), leaving the numerical boundaries between the classes to be elaborated by each EU country.

Numerous attempts have recently been made to develop the phytoplankton parameters, indicator species and their values to fulfill the WFD requirements; however, available published documents are still limited. Two methods published so far include the Q and PSI indices described in detail by Padisák et al. (2006) and Mischke et al. (2008), respectively.

In this paper, using phytoplankton data obtained during a one-year study in four shallow lakes located in the Polesie Region, we attempt to evaluate the ecological status of four shallow Polish lakes, applying the methods mentioned above in order to examine their comparability despite their different methodological approaches.

Study area and methods

The studies were carried out in four lakes (Głębokie near Uścimów, Maśluchowskie, Rotcze and Sumin) situated in Eastern Poland within the Łęczna-Włodawa Lakeland (51°30′N, 23°20′E) (Fig. 1). The morphological parameters of the lakes as well as some physicochemical and biological data are presented in Table 1. These lakes are shallow, with the maximum depth ranging from 4.3 to 9.4 m and surface areas not exceeding 100 ha. Among the studied lakes, Rotcze and Sumin are unstratified water bodies, whereas the other two have stable thermal stratification for at least three months in the year. According to the Polish lake typology (Kolada et al. 2005), they represent types 7a and 7b (lowland unstratified and stratified lakes with high calcium content: $>25\,mg\,dm^3$).

Samples for phytoplankton analysis were collected monthly between May and September 2001. Water depth, Secchi disk visibility, conductivity and pH were measured in situ. In each lake, samples of water were taken with a Ruttner type sampler ($2\,dm^3$ capacity) from the deepest part of the lake at one meter interval and poured into one collective sample. In the case of the polymictic Lake Rotcze, the whole water column was sampled, whereas the other lakes were sampled within the epilimnion layer only (at one meter interval and then poured into the collective sample). The chemical analyses of soluble nutrients ($N\text{-}NH_4$, $N\text{-}NO_3$, $P\text{-}PO_4$) and total values (TN and TP) were measured in the

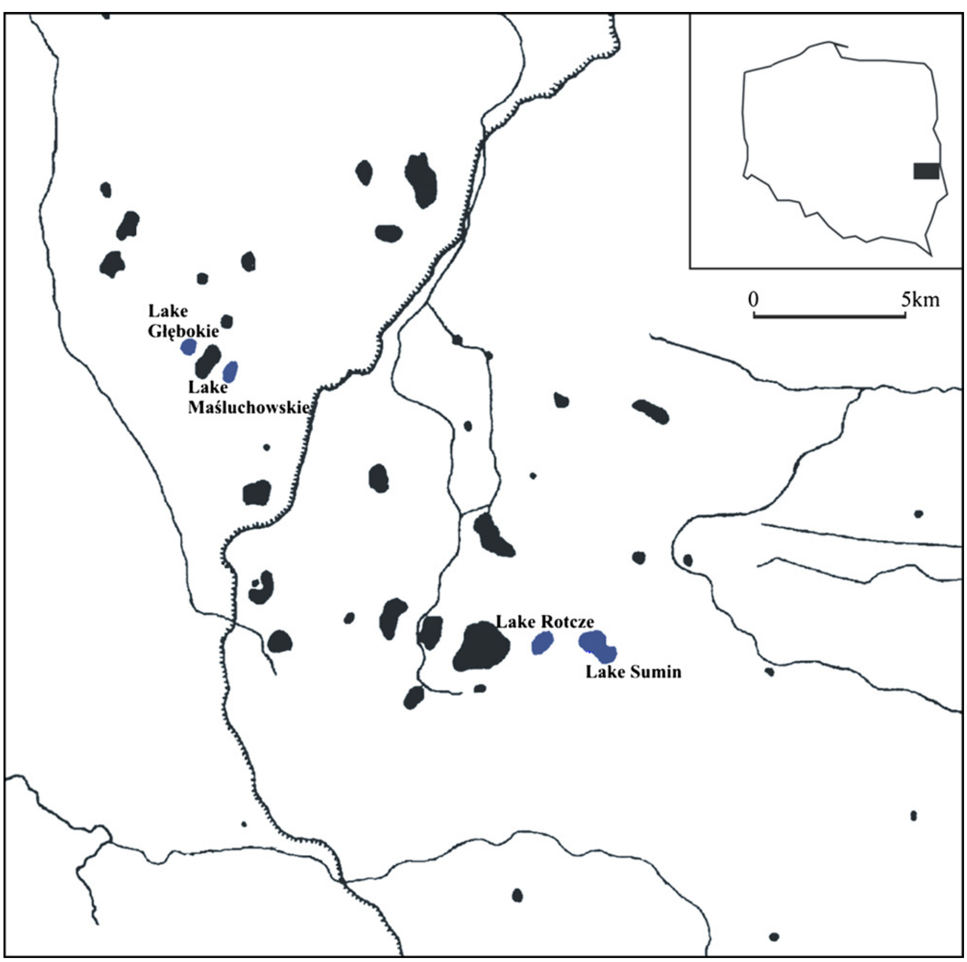

Fig. 1. Studied lakes within Łęczna-Włodawa Lakeland.

Table 1
Mean values (and minimum–maximum range) of morphometric (after Harasimiuk et al., 1998) and physicochemical and biological parameters of studied lakes.

	Głębokie	Maśluchowskie	Rotcze	Sumin
Area (ha)	20.3	27.0	45.8	84.5
Max. depth (m)	7.1	9.4	4.3	6.5
Mean depth (m)	3.4	4.6	1.9	1.6
VQ[a]	2.52	0.93	1.90	9.65
SD (m)	**0.7** (0.5–1.0)	**1.6** (0.9–2.0)	**2.0** (1.8–2.5)	**0.8** (0.8–1.0)
pH	**8.6** (7.7–9.6)	**8.3** (7.5–10.2)	**8.8** (8.3–9.3)	**8.6** (8.39–8.76)
Alkalinity (mVal dm^{-3})	**1.5** (1.1–1.9)	**0.8** (0.7–0.9)	**1.5** (1.1–2.2)	**3.2** (2.9–3.7)
Conductivity ($\mu S\,cm^{-1}$)	**296** (215–440)	**153** (135–171)	**243** (180–400)	**455** (376–660)
P-PO_4(mg dm^{-3})	**0.02** (0.005–0.031)	n.d. –0.011	**0.02** (0.008–0.029)	**0.01** (0.002–0.030)
P_{TOT} (mg dm^{-3})	**0.21** (0.151–0.288)	**0.07** (0.017–0.163)	**0.09** (0.035–0.120)	**0.09** (0.016–0.135)
N-NH_4 (mg dm^{-3})	**0.91** (0.6–1.31)	**0.78** (0.49–1.57)	**0.53** (0.47–0.63)	**0.72** (0.66–0.81)
N-NO_3(mg dm^{-3})	**0.29** (0.14–0.56)	**0.15** (0.11–0.21)	**0.23** (0.08–0.55)	**0.19** (0.11–0.24)
N_{TOT}(mg dm^{-3})	**1.29** (0.386–3.538)	**1.68** (0.45–3.38)	**0.97** (0.48–1.80)	**1.13** (0.521–2.239)
Chlorophyll *a* ($\mu g\,dm^{-3}$)	**84.9** (62.2–119.5)	**25.9** (14.5–49.8)	**13.1** (6.2–21.6)	**29.3** (22.4–37.3)
Total numbers of phytoplankton ($N\,10^3\,dm^{-3}$)	**2752.1** (1577.4–4418.0)	**4137.7** (3075.0–5212.9)	**1092.5** (627.2–1859.1)	**6267.5** (4230.9–10612.8)
Total biomass of phytoplankton (mg dm^{-3} fw)	**26.06** (6.76–56.37)	**16.75** (11.93–23.76)	**3.85** (0.98–9.09)	**8.05** (4.14–15.36)

[a] Ratio of the total catchment's area (m^2) to the volume of lake (m^3).

laboratory according to colorimetric methods (Hermanowicz et al. 1999). Phytoplankton samples for quantitative analyses were fixed in formalin. Algal counts (cells, colonies and filaments) were evaluated with a Zeiss Axiovert 135 inverted microscope, according to the Utermöhl method (Utermöhl 1958). For counting, samples were transferred to a settling chamber (2.5 or 5 ml capacities were used, depending on algal density), and at least 100 individuals of the most numerous algae were counted per sample. The counting unit of colonial species was a colony, for filamentous species it was 100 μm and for others it was a cell. Biovolumes were determined according to Hillebrand et al. (1999). For taxonomic analysis, additional samples were obtained with 20 μm plankton net, while the phytoplankton species composition was determined under a light microscope (Nikon ECLIPSE E600W) from living and formalin–glycerine mixture-fixed samples. Measurements of chlorophyll *a* concentrations involved filtering water through Whatman GF/C filters on the day of sampling, followed by extraction in ethanol and determination by the spectrophotometric method (Nusch 1980). The absorption of the extract was determined with a Beckman DU640B spectrophotometer, at wavelengths of 665 and 750 nm.

The evenness index was calculated according to the Shannon-Weaver Index (Shannon and Weaver 1949) and Lloyd-Ghelardi (1964). The trophy status was evaluated by the trophic state index (Carlson 1977). Statistical correlations (the Pearson coefficient) were calculated by means of StatSoft 6.0 Programme.

In order to assess the ecological status we adopted the methods published for Hungarian and German lowland lakes. It should be noted that both the methods were made for an assessment of natural lake with a lake area larger than 50 ha. In our work we test its suitability also for smaller lakes. One of the reasons for selecting these indices was the great similarity between geographical regions (especially in German and Poland) as well as the lakes having similar typology.

The assemblage index (Q index)

The phytoplankton composition may also be considered in terms of phytoplankton "functional" assemblages. Reynolds (1980) discerned patterns in a series of phytoplankton data from a group of lakes in Northwest England. He separated 14 species assemblages. They are loosely described as "functional groups" based on the physiological, morphological and ecological attributes of the species that may potentially dominate or co-dominate in a particular type of water body. Subsequently, the scheme has been expanded to assemblages representing a wider number of lakes and environmental conditions (Reynolds 1998; Reynolds et al. 2002; Kruk et al. 2002). At present, 33 functional groups are described (Reynolds et al. 2002; Padisák et al. 2003). Functional groups are potentially more predictable than individual species or genera in terms of their response to nutrient conditions under a broad set of physical conditions and, therefore, can potentially be developed to indicate the impacts of nutrient pressures more consistently. On the basis of the phytoplankton functional group concept outlined in Reynolds et al. (2002), Padisák et al. (2006) developed the *Q* index that classifies lakes into 5 classes of water quality. The *Q* index was developed to assess the ecological status of different lake types according to the requirements of the WFD. The index takes into account the relative shares of functional groups in the total biomass, as well as a factor number (*F*) determined for each functional group in each type of water body.

The *Q* index ranges between 0 and 5 and can be translated into a five grade classification system: 0–1: bad, 1–2: tolerable (poor), 2–3: medium (moderate), 3–4: good and 4–5: excellent (high). In our studies, species contributing >5% to the total biomass were classified into the functional types defined by Reynolds et al. (2002). Following the steps recommended by Padisák et al. (2006) for the *Q* index application, the *F* factor was adopted for each functional group occurring in the studied lakes. Among the Hungarian lakes described in Padisák et al. (2006), type 5 is closest to the studied lakes.

The German PSI (Phyto-See-Index)

The German multi-metric lake phytoplankton index (PSI) consists of three mandatory metrics: "biomass", "algal classes" and the "Phytoplankton-Taxa-Seen-Index" (PTSI) (Mischke et al. 2008). The metric "biomass" is calculated as the arithmetic average of the following three parameters: the total biovolume of phytoplankton, the chlorophyll *a* concentration and the maximum value of chlorophyll *a*. "Algal classes", depending on the lake type, is composed of two or three parameters, including the biomass of cyanobacteria, chlorophytes, dinophytes, cryptophytes and chrysophytes. PTSI is calculated on the basis of indicator taxa lists relevant for each lake type. Each indicator taxon has its own trophic value and a weighting factor which describes the degree of constancy with which a taxon can be detected within its trophic preference range. To calculate PTSI, all trophic values are multiplied by their weighting factor and their abundance class value in a sample. Initially, this index serves to classify the trophic status of lakes. The scale of values is congruent to those of the LAWA Trophic Index (1999). Secondly, as a component of the PSI index, PTSI is calculated by comparing its value with a preset reference value for the relevant lake type.

In the case of all parameters, the values used were the arithmetic mean from the 5 monthly samples, which is transformed according to a lake-type specific formula. The single metrics and PSI index values range from 0.5 to 5.5, where 0.5 indicates the best status and 5.5 the worst one. In the present PSI calculations, we used the software-PhytoSee Version 3.0-developed by Mischke and Böhmer (2008).

In our study, the lakes were assigned to the relevant German lake types: stratified Lake Głębokie-to type 10.1, Lake Maśluchowskie with a relatively small catchment area (VQ < 1.5) was assigned to type 13. The two very shallow lakes (mean depth < 3 m) with VQ > 1.5 – Lakes Rotcze and Sumin were assigned to type 11.2. It is worth stressing that Lake Rotcze is undoubtedly polymictic, while Lake Sumin was stratified in the deepest part but the stratification involved only a small part of the whole lake volume.

Results

Physicochemical characteristics and trophic variables

The mean values for most of the measured water properties varied widely among the studied lakes (Table 1). The lowest values of conductivity were always recorded in Lake Maśluchowskie (mean 153 $\mu S\,cm^{-1}$), whereas in the others values above 200 up to 600 $\mu S\,cm^{-1}$ were usually recorded. The lakes were all alkaline, pH values ranged from 7.5 to 10.2 and the mean value (about 8) was similar in all the lakes. Alkalinity varied between about 1 to 4 $mVal\,dm^{-3}$. The lakes differed with respect to their nutrient concentrations. The lowest values were noted in Lake Rotcze where TP concentrations never exceeded 120 $\mu g\,dm^{-3}$, whereas in Lake Głębokie it reached 288 $\mu g\,dm^{-3}$ in July. The TN concentrations varied greatly, from very low values in Lakes Rotcze and Maśluchowskie (0.048 and 0.045 $mg\,dm^{-3}$, respectively) up to 3.54 $mg\,dm^{-3}$ in Lake Głębokie.

Physicochemical and biological factors indicate that among all the studied lakes the lowest fertility was characterized for Lake Rotcze. The water transparency was always high during the studied period and it had low phytoplankton abundance ($1099.5 \times 10^3\,dm^{-3}$), low chlorophyll *a* concentrations in the epilimnion (mean 13.1 μg) and low phytoplankton biomass (2.87 mg in dm^3). The other lakes were characterized by at least double these values (Table 1).

Trophic characterization was initially estimated using the Carlson Trophic State Index regarding all the TSI elements: Secchi depth, chlorophyll *a* concentration and TP. In Lake Rotcze, the TSI index varied between the values of 54 and 59 in the summer period, i.e. above the limiting meso-eutrophic level (50) according to the Carlson model, which classifies this lake as slightly eutrophic.

TSI for Lake Głębokie reached a value of 78 in July indicating the lake was hypereutrophic. Lake Głębokie was characterized by the highest values of chemical parameters among all the studied water bodies, i.e. a high level of nitrogen compounds, total phosphorus as well as by very low Secchi disk visibility (Table 1). At the end of July the chlorophyll *a* concentration reached 119 $\mu g\,dm^3$ (Table 1) and exceeded the boundary value characteristic of lakes with advanced eutrophy in the other regions of Poland (Hillbricht-Ilkowska and Kajak 1986). Intermediate Carlson's trophic indices scores (about 62) were noted in Lakes Sumin and Maśluchowskie. TSI values classify these lakes as eutrophic.

Table 2
Correlation matrix of phytoplankton parameters and indices (*italic numerals* for $p<0.01$; ***bold numerals*** for $p<0.05$).

	Chl *a*	SD	Biomasa	Q index	Carlson index	Evenness
Chl *a*	1	*-0.57*	*0.78*	*−0.59*	*0.85*	−0.48
SD		1	**−0.51**	0.36	*−0.65*	0.22
Biomass			1	**−0.56**	0.53	*−0.64*
Q index				1	−0.43	0.27
Carlson index					1	−0.32
Evenness						1

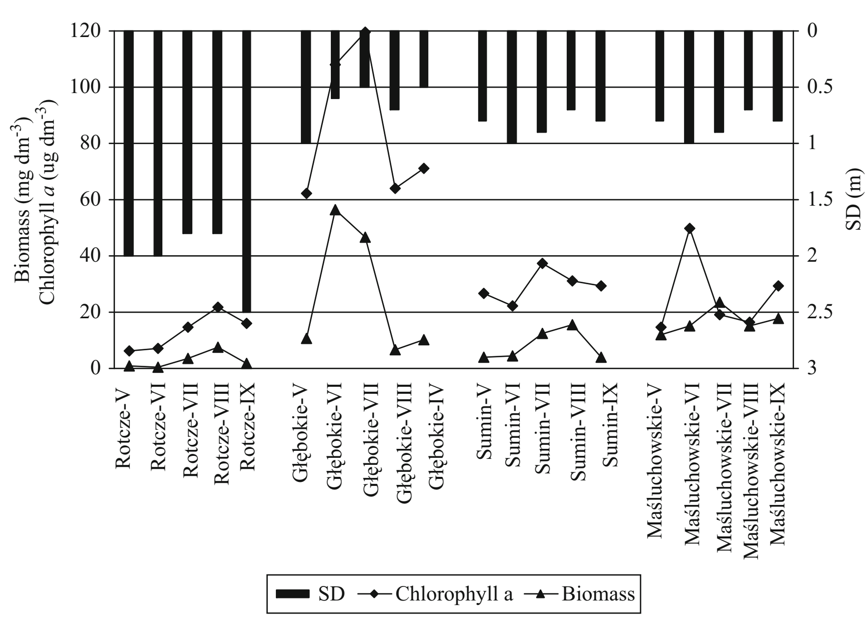

Fig. 2. Temporal variations of chlorophyll *a*, biomass and Secchi depth.

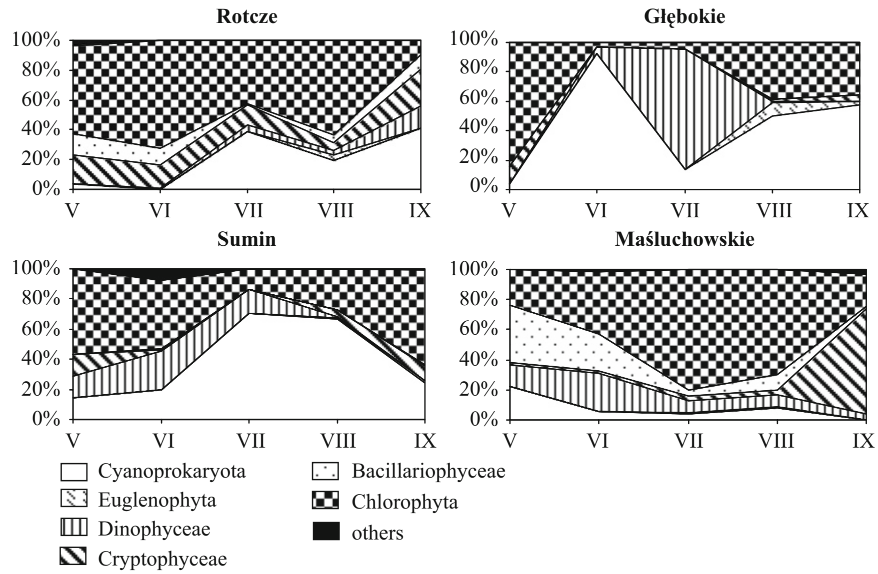

Fig. 3. Temporal variations of percentage shares of algal groups based on biomass.

All in all, the available data showed that the highest trophic level was characterized for Lake Głębokie, the lowest for Lake Rotcze and Lakes Sumin and Maśluchowskie were at an intermediate state.

A statistically significant linear correlation was recorded between chlorophyll *a* and total phytoplankton biomass values ($r = 0.78$; $p < 0.01$; $N = 20$) (Table 2, Fig. 2). The correlation between chlorophyll *a* concentration and Secchi depth ($r = -0.57$; $p < 0.01$; $N = 20$) was slightly stronger than that between the biomass and SD values ($r = -0.51$; $p < 0.05$; $N = 20$).

Species composition

During the study period a total of 180 algal species were recorded in the 4 study lakes. The number of taxa varied between Lakes Głębokie, Maśluchowskie, Rotcze and Sumin (97, 102, 69, 89). Biodiversity, expressed by the evenness index, ranged between 0.5 and 0.6 in all the lakes and was negatively correlated with biomass ($r = -0.64$, $p = ???$). The main phytoplankton taxonomic groups with a considerable share in biomass were: Cyanoprokaryota, Dinophyceae, Cryptophyceae and Chlorophyta (Fig. 3). In Lake Głębokie Cyanoprokaryota (*Microcystis* spp., *Woronichinia naegeliana*, *Aphanizomenon issatschenkoi*) had the largest share with an exception for May, when green algae predominated (*Pandorina morum*, *Staurastrum cuspidatum*, *Eutetramorus planctonicus*, *Coelastrum microporum*) and in July, when the dinophyte *Ceratium hirundinella* prevailed. Another water body with a high share of Cyanoprokaryota in biomass was Lake Sumin. This lake was dominated in summer by two Cyanoprokaryota species – *Microcystis aeruginosa* and *M. wesenbergii*; in the months of May, June and September Chlorophyta from the desmidiales and chlorococcales orders were the most abundant, while Dinophyceae and/or Cryptophyceae subdominated. The phytoplankton community in Lake Rotcze was composed mainly of green algae – among them Volvocales (*Pandorina morum* and *Volvox globator*) dominated in spring, whereas *Closterium dianae* and *Staurastrum gracile* dominated in summer. Cyanoprokaryota (*Coelomoron pusillum*, *Microcystis aeruginosa*) appeared in July and constituted about 20–30% of the total biomass until September. Just like Lake Rotcze, Lake Maśluchowskie was also characterized by a great number and biomass of Chlorophyta (many chlorococcales species, *Closterium acutum*, *Cosmarium bioculatum, Staurastrum* spp. and in July and August unidentified filamentous species from the Ulotrichales order) and Bacillariophyceae (*Fragilaria ulna*), Dinophyceae (*Peridinium bipes*) and Cryptophyceae (*Cryptomonas* spp.) in spring and autumn.

Ecological lake status

Assemblage approach

Several functional groups were identified during the entire study. Fig. 4 presents those of them which reached at least 10% of the total biomass, whereas the remaining ones were assigned to the "others" group. In Lake Głębokie, despite the contribution of many assemblages, group **Lm** was the most dominant. *Ceratium hirundinella*, *Woronichinia naegeliana* and *Microcystis* spp. were all constituents of this group. *Ceratium hirundinella* became the most important species in mid-summer (about 80% of the total biomass). In late summer the population of dinophytes collapsed and new assemblages appeared; first of all, group **P** – (*Closterium acutum*, *Staurastrum gracile*) and groups with lesser contributions to biomass (each below 10%), i.e. **H1** (*Anabaena* sp., *Aphanizomenon issatschenkoi*), **W2** (*Trachelomonas* spp.) and **F** (*Eutetramorus planctonicus* and other colonial, mucilage chlorophytes). Group **Lm,** dominated by the *Microcystis* species, increased its contribution in September. Another lake where the **Lm** association prevailed was Lake Sumin: during the whole summer, the phytoplankton of the lake was dominated by *Peridinum willei* together with *Microcystis aeruginosa*, *M. wesenbergii* and other *Microcystis* sp. Just as in Lake Głębokie, in Lake Sumin a more diverse composition of functional phytoplankton groups was recorded in spring and autumn. In these seasons, small chlorococcal algae from *Pediastrum*, *Scenedesmus*, *Coelastrum* genera formed group **J**, while desmids – *Closterium acutum*, *Cl. limneticum*, *Cosmarium depressum*, *C. humile* and *Staurastrum* spp. – were responsible for a great percentage share (between 10 and 60%) of group **P**.

In Lakes Rotcze and Maśluchowskie the functional group characterized by relatively high biomass was group **P**; it consisted of diatoms: *Aulacoseira* spp., *Fragilaria ulna*, desmids: *Closterium dianae*, *Staurastrum gracile* (in Lake Rotcze) and *Fragilaria ulna*,

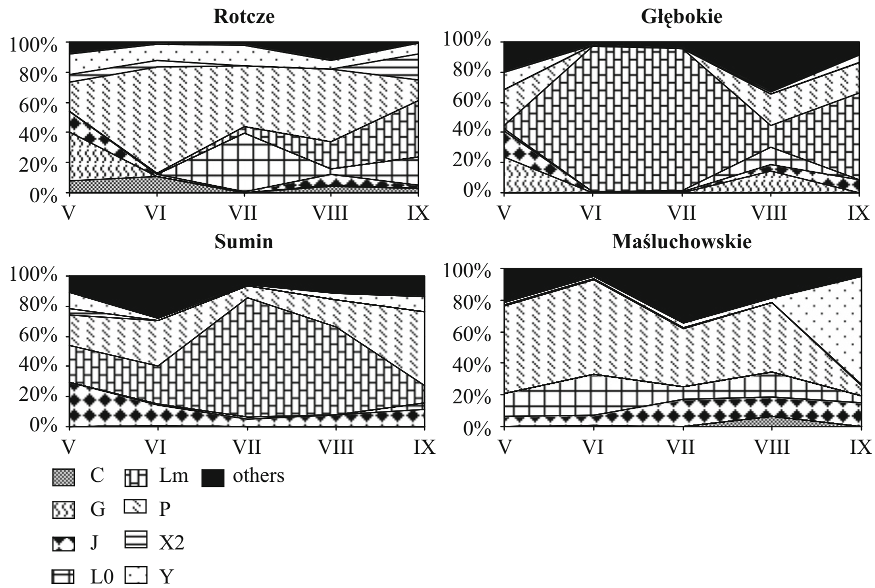

Fig. 4. Temporal variations of percentage shares of phytoplankton functional groups based on biomass.

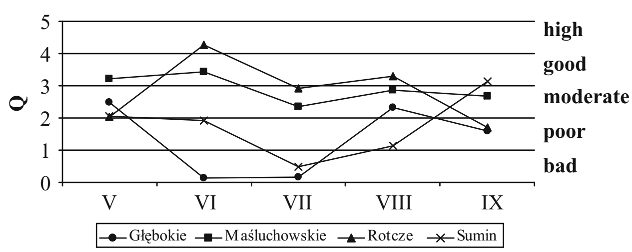

Fig. 5. Ecological status assessment by the *Q* index follows Padisák et al. (2006) recommendation for lake type 5 in the cited paper.

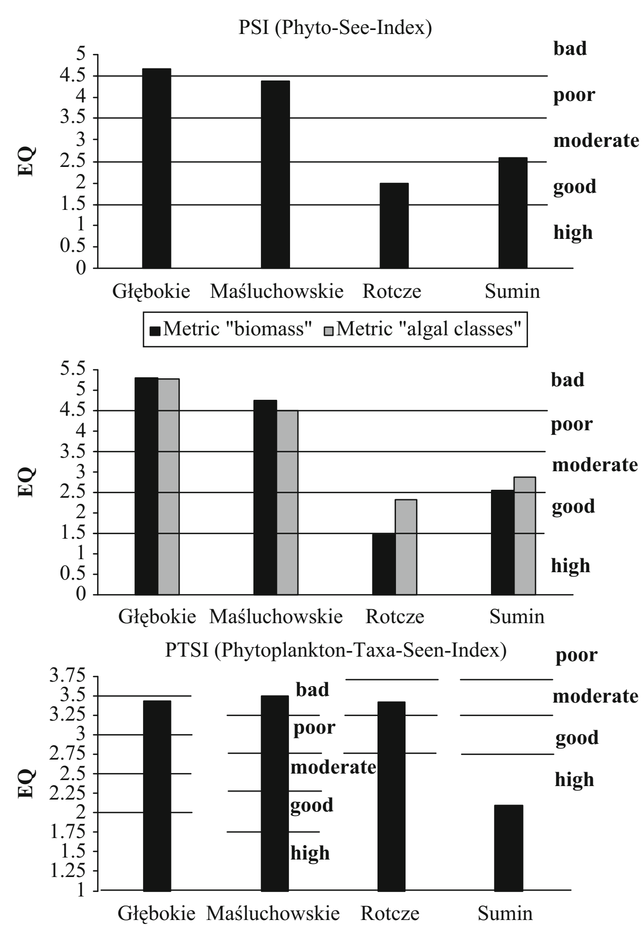

Fig. 6. Ecological Quality (EQ) values and status class assessment follows Mischke et al. (2008).

Closterium acutum, *Staurastrum pingue*, *Cosmarium bioculatum* in Lake Maśluchowskie. Group **L0** included *Peridinium bipes*, *Coelomoron pusillum*, *Merismopedia tennuissima*, whereas group **Y** consisted of unidentified *Cryptomonas* species.

The *Q* index showed differences among the studied lakes and within a lake over the vegetation season (Fig. 5). In general, the highest values of the *Q* index were recorded at the beginning of the study period (May–June) and at its end (September). In all the studied lakes the worst ecological status, according to the assemblage classification, occurred in mid-summer (at the end of July). Nevertheless, if we consider the summer period (June–July–August) as the most representative one, the mean *Q* index gives the following classification of the ecological status of the lakes: Lake Rotcze – good ($Q = 3.5$), Lake Maśluchowskie – moderate ($Q = 2.9$), Lake Sumin – poor ($Q = 1.2$) and Lake Głębokie – bad ($Q = 0.9$). The *Q* index had a significant negative correlation with trophic variables, such as chlorophyll *a* ($r = -0.60$; $p < 0.01$; $N = 20$) and total biomass concentrations ($r = -0.56$; $p < 0.05$; $N = 20$).

The German PSI (Phyto-See-Index)

A diverse range of values were recorded for individual PSI metrics (Fig. 6). The metric "biomass", based on chlorophyll *a* concentrations and the total biovolume of phytoplankton, and the metric "algal classes", based on the biomass of taxonomical groups, usually reached values one class higher or lower than PTSI – an index using indicator taxa. It was especially noticeable in Lake Głębokie, where the metrics "biomass" and "algal classes" classified the lake as bad status, whereas PTSI indicated it was poor status; and especially in the case of Lake Sumin where much better ecological status was estimated using PTSI (high) rather than with the other metrics (moderate) (Fig. 6). Because of the thermal stratification of the small, deepest part of Lake Sumin, we also calculated all metrics for Lake Sumin classifiying it as a thermally stratified lake (type 10.1). The change of the typology did not modify the general assessment and still classified the lake as moderate status, but considerably changed the value of the "biomass" and "algal classes" metrics which classified the lake as poor status. PTSI index also increased to 2.5, the boundary which represents good/moderate states.

The assessment of Lake Maśluchowskie by the German PSI classified it as poor or bad ecological status. Unlike the previous lakes, "biomass" classified Lake Rotcze results as high status, whereas the other metric "algal classes" and PTSI gave worse ecological status (good and moderate status, respectively). The great variability between the metrics for this lake was caused by the disproportion between the relatively low phytoplankton abundance (Fig. 2) and the presence of species recognized as indicators of high trophic conditions such as *Microcystis aeruginosa*, *Ceratium hirundinella* and *Staurastrum gracile*. Each of these taxa is characterized by a high trophic score and weighting factor which are the elements in the formula for PTSI calculation.

In cross-lake comparison, Lake Rotcze is the only lake of the 4 that was assessed as good status according to the classification based on the German index value (PSI = 2.0). Lake Sumin (PSI = 2.57) was moderate, Lake Maśluchowskie (PSI = 4.36) was classified as poor status, while Lake Głębokie (with PSI = 4.6) was classified as bad status.

Discussion

Studies conducted in 2001 indicate different trophic levels, based on raw physicochemical parameters (SD, nutrient concentrations) and the Carlson Trophic State Index. The highest fertility of Lake Głębokie and the lowest trophic level of Lake Rotcze were determined, whereas Lakes Sumin and Maśluchowskie can be placed at the medium level. All the trophic parameters were generally consistent in the assessment of the trophic status of the lakes. The divergence between chlorophyll *a* concentration and total phytoplankton biomass which appeared in some samples was probably mainly due to the high abundance of a large colonial alga in Lake Sumin in August when *Microcystis* spp. dominated as well as in Lake Maśluchowskie in July when filaments of unidentified Ulotrichales were counted in the sample. It could be the reason for an overestimation of the biovolumes in relation to the cellular chlorophyll *a* content. This may also explain why chlorophyll *a* was also linked much more strongly to TP ($r = 0.69$; $p < 0.01$; $N = 20$) than the total biomass was ($r = 0.36$; $p < 0.05$; $N = 20$). During the study period the highest amount of phytoplankton usually occurred in July and August, except for Lake Głębokie, where at the end of June the community of Cyanoprokaryota substantially developed (up to $52\,mg\,dm^{-3}$).

In the case of Lake Rotcze the single TSI_{TP} values (ranges from 55 to 72) placed the lake in a higher trophic class (advanced eutrophy) than TSI_{SD} (from 46 to 51) or TSI_{CHL} (48–60). It should be pointed out that the relation $TSI_{SD} \geq TSI_{CHL} < TSI_{TP}$ was present throughout the vegetation season, indicating that there were factors limiting algal growth. One key factor which influences phytoplankton is the abundance of macrophytes. Therefore, the mean TSI calculated for this lake can underestimate its trophic state. A similar lack of cohesion between trophic state indices was noted by Hillbricht-Ilkowska and Wiśniewski (1994) in the case of dimictic and deep lakes of the Suwalski Landscape Park. The data presented in this paper support this, particularly that TSI_{TP} can put shallow lakes in a higher trophic class than the other trophic indices, i.e. TSI_{SD} and TSI_{CHL}.

The catchments of the lakes differed markedly in terms of the type of soils, their distribution and use. In Lakes Rotcze and Sumin, about 50–60% of the area is covered by grasslands on hydrogenic soils and forests growing mostly on very poor rusty and brown soils, whereas two of the studied lakes (Lakes Głębokie and Maśluchowskie) typically have agriculturally used catchments (60–70%) (Harasimiuk et al. 1998). The considerable differences were found between the total nutrient loads from the terrestrial catchments between Lakes Rotcze and Głębokie; for example, the supply of Lake Rotcze with TP was far below the permissible one, according to the Vollenweider criteria (1976), whereas in the case of Lake Głębokie the permissible load was exceeded by a factor of 2 (Smal et al. 2005). A strong significant linear correlation ($r = 0.97$) was also found by Smal et al. (2005) between TN and TP loads to the lakes of the Polesie Region (Kleszczów, Rotcze, Sumin, Głębokie, Syczyńskie) and the nutrient concentrations in water. Moreover, it was found in the cited paper that water transparency decreased with the increasing contribution of the most fertile soils (rendzinas and black earths) in the catchments of the studied lakes. In the present work, SD reflected the fertility of lakes, while the mean Secchi depth decreased in the sequence of Lakes: Rotcze, Maśluchowskie, Sumin, Głębokie, as the total phytoplankton biovolume increased.

Comparing the assessments using the two approaches to ecological status assessment based on phytoplankton, i.e. the *Q* index with the German PSI, the same ecological status was identified in two of the studied lakes (Rotcze – good ecological status, Głębokie – bad ecological status). The other two lakes, Lake Maśluchowskie and Lake Sumin, were estimated as having moderate and poor status by the assemblage approach and, respectively, as having poor and moderate status by the PSI index (Figs. 5 and 6). Similar differences can be found when the ecological status of the studied lakes is assessed in accordance with the classification based on the chlorophyll *a* concentration, as developed for Polish lakes by Soszka et al. (2008). In accordance with this classification, the chlorophyll values in Lake Rotcze were good status as set out for polymictic lakes ($23.0\,\mu g\,dm^{-3}$) and chlorophyll concentration in Lake Sumin were typical of moderate ecological status ($23.0–38.6\,\mu g\,dm^{-3}$). The assessment of Lake Głębokie gave just as clear results, with chlorophyll values substantially exceeding the cut-off value between poor and bad status for stratified lakes ($28.2\,\mu g\,dm^{-3}$). In the case of Lake Maśluchowskie, it is more difficult to unambiguously assess the ecological status based on the chlorophyll concentration, since concentrations in the vegetation season varied from the boundary value between moderate status and poor status ($16.2\,\mu g\,dm^{-3}$) to the poor/bad status boundary ($28.2\,\mu g\,dm^{-3}$).

Based on the increasing fertility of lakes, measured as the Carlson Index in the summer period, the studied lakes may be ordered in the following way: Lake Rotcze < Lake Maśluchowskie < Lake Sumin < Lake Głębokie. This confirms the ecological status pattern measured as the *Q* index. Similar consistency between the assessment of water fertility variations based on the Carlson Index and the assessment of the ecological status based on the *Q* index was also found by other authors (Crossetti and de M. Bicudo 2008). Nevertheless, in our study the TSI calculated for Lakes Maśluchowskie and Sumin was almost equal; thus, only a weak correlation was noted between the *Q* and Carlson indices ($r = -0.43$; $p < 0.05$; $N = 20$).

The difference between the assessments under the methods was mainly due to the domination of desmids (*Closterium acutum*, *Staurastrum pingue*, *Cosmarium bioculatum*), along with the diatoms (*Fragilaria ulna* and *Fragilaria crotonensis*), in the biovolume of summer phytoplankton in the epilimnion of Lake

Maśluchowskie. These dominants were assigned to group **P**-typical of eutrophic epilimnia. According to Padisák et al. (2006), this functional group characterizes the maximum "*F* factor" used to calculate the *Q* index, which substantially increased the final assemblage index value. Similarly, the most numerous species of Lake Maśluchowskie were indicators of a higher trophy level, following the indicator list presented by Mischke et al. (2008) and indicating worse ecological status of the water body. In contrast, Lake Sumin was placed in the worse class based on the *Q* index. This was caused by the presence of the "highly eutrophic" group Lm (*Microcystis aeruginosa*, *Microcystis* sp. and *Microcystis wesenbergii*, *Peridinium willei*) with the minimum "*F* factor" value. The Cyanoprokaryota from the *Microcystis* genus are regarded as indicators of high trophic status, but only if they are determined at the species level; otherwise they are not considered as good indicator species.

It seems that both the methods are reliable for assessing the quality of shallow lakes. However, it should be borne in mind that the key element of the method developed by Padisák et al. (2006) is the determination of the *F* factor corresponding to a given lake type, based on the lake typology for a given country. Both methods are sensitive to taxonomic misidentifications of dominant species.

It should be pointed out, that in the case of shallow lakes, classification based on phytoplankton is crucial issue is to put the lake in the proper type. In some of these lakes stratification may be restricted to the deepest part of the waterbody, including only a small portion of the whole lake volume. Functioning of the lake in this situation (and phytoplankton characteristics) resembles more a polymictic lake. In addition the presence of a hypolimnion and its thickness can change from year to year because of weather conditions. As a consequence the wrong assignment of the lake can result in its misclassification.

There are several methods of ecological status assessment of waters threatened with advanced eutrophication, which are still being developed or have already been applied in EU countries. Nevertheless they are generally less appropriate for Polish lakes because of differences in typology and/or methodology of sampling e.g. Brettum index (Wolfram et al. 2008) designed for lakes of altitude higher than 200 m a.s.l. or Estonian method described by Kangro et al. (2005). We are not, however, ruling out the usefulness of these other methods for shallow lake assessment in Poland after they have been adapted and fully validated.

Conclusion

The data obtained during a one-year study in four shallow lakes demonstrated the variability of ecological status between the studied lakes. Although all the studied lakes are eutrophic, the assessment of their ecological status indicated a broader range of classes from good through to moderate and poor to bad. In the case of the two reservoirs with the best and the worst trophic parameters, the results of the two assessments agree. Both the *Q* index and the German PSI classified Lake Rotcze as having good ecological status and Lake Głębokie as having bad status. The distinction between moderate and poor status appeared to be more problematic.

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