

Long-term changes of phytoplankton in Lake Niegocin, in the Masurian Lake Region, Poland

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Abstract

The objective of this study was to determine the change in phytoplankton biomass in Lake Niegocin following modernization of the sewage treatment plant in Gیزیcko, Poland in 1994. Phytoplankton samples were taken from March to November 1991 – 2001, and chlorophyll levels were determined from 1986 through 2001.

High levels of total phytoplankton biomass (max. 8.2 mg l⁻¹) and chlorophyll concentrations (max. 93.9 µg l⁻¹) were recorded in Lake Niegocin up to 1994. Filamentous cyanoprokaryotes (90%), mainly *Planktothrix agardhii* and *Aphanizomenon flos-aquae*, were the most abundant taxa in summer. After modernization of the wastewater treatment plant (1995 to 1999), there was a change in the composition of the phytoplankton, biomass decreased threefold and chlorophyll concentrations fourfold, with dinoflagellates (*Peridinium* sp. div., *Ceratium hirundinella*) becoming dominant in the summer. However, increased biomass (max. 6.3 mg l⁻¹) and concentrations of photosynthetic pigments (max. 46.5 µg l⁻¹) occurred in 2000 and 2001, with the summer phytoplankton dominated by cyanoprokaryotes (e.g. *Microcystis aeruginosa*, *Leptolyngbya thermalis*).

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INTRODUCTION

Lake Niegocin, situated in north-eastern Poland, is one of the largest natural water bodies (area 2600 ha) in the Great Masurian Lakes region. This lake has a previous history of receiving insufficiently treated municipal sewage from the city of Giżycko and wastewater from the surrounding agricultural catchment that has accelerated its eutrophication. Previous records from 1971 to 1989 indicate that the phytoplankton biomass was greater than 8.0 mg l^{-1} , which is characteristic of the eutrophic lakes in the Masurian Lakeland (Spodniewska 1978, 1979; Krzywosz 1993). This level is also considered a threshold limit for algal blooms (Pavoni 1963, Heinonen 1980, Nebaeus 1984). The summer phytoplankton at this time was dominated by filamentous cyanoprokaryotes, mostly *Planktothrix agardhii* and *Aphanizomenon flos-aquae*, which may produce toxins (Reynolds 1991, Rapala et al. 1993, Kabziński et al. 2000, Mankiewicz et al. 2003). The growing pollution of Lake Niegocin has also been confirmed by numerous water quality, microbiological, and zooplankton studies (Bernatowicz et al. 1974; Gliwicz and Kowalczewski 1981; Zdanowski 1982; Kajak 1983; Karabin 1985; Niewolak 1989; Zdanowski et al. 1993; Zdanowski and Hutorowicz 1994; Kufel 1998, 2001; Kufel and Kufel 1999).

The sewage treatment plant in Giżycko was recently modernized by addition of a biological treatment stage with chemical phosphorus precipitation. Agricultural management of the Lake Niegocin catchment region has also been improved due to policies established in Poland. The present study was conducted to determine what changes in the phytoplankton assemblages of Lake Niegocin have occurred since these events took place and the sewage input into the lake was reduced.

STUDY AREA

Lake Niegocin receives water from two neighboring lakes, Grajewko and Wojnowo, as well as the Staświnka River. The maximum depth of Lake Niegocin is 39.7 m, with a mean depth of 9.9 m. From the 1980s to the early 1990s, the main source of lake pollution came from domestic sewage, industrial and municipal effluents, plus the inflow of slurry-polluted water from Lake Grajewko and Lake Wojnowo (Cyzdik et al. 1995). Prior to the modernization of the mechanical sewage treatment plant in Giżycko, only 7591 m^3 of wastewater was treated at the plant monthly. Since November 1994, this monthly treatment capacity has increased to about $200,000 \text{ m}^3$ of wastewater being treated prior to discharge into the lake.

The surrounding region of Lake Niegocin is primarily arable land, which in the 1980s accounted for 74.0% of land use, with forests 17.0%, and only 6.6%

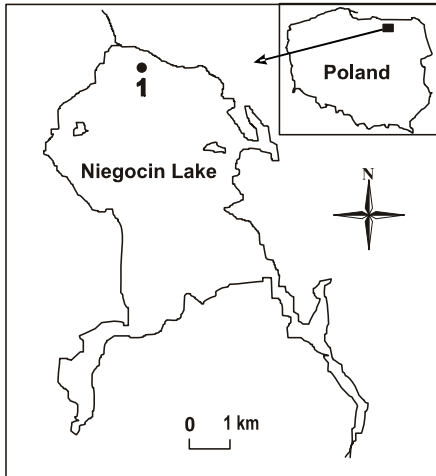


Fig. 1. Location of the sampling site in Lake Niegocin.

developed (Giercuskiewicz-Bajtlik 1990). These proportions were generally similar in 2000. However, strong recreational and tourist pressure have always constituted a serious threat to Lake Niegocin.

MATERIAL AND METHODS

Lake phytoplankton samples were taken monthly between March and November in 1991 – 2001. The material was collected according to Pliński et al. (1984) from depths of 0 – 10 m during spring and autumn at the deepest place in the lake (39.7 m), which is near the town of Giżycko

(Fig. 1). During summer, the samples were collected from the epilimnion, metalimnion and hipolimnion, as determined from water temperature measurements. The epilimnion occurred most frequently between the depths of 0 to 10 m, metalimnion – from 11 to 13 m and hipolimnion – from 14 m to the bottom. Samples were taken at one-meter intervals and then integrated and fixed with Lugol solution: 70 samples were collected in total. Additional samples were collected for taxonomic analysis with a 25 µm pore net, and were analyzed both live and after preservation. Phytoplankton were enumerated on an inverted plankton microscope “Nikon”, according to Utermöhl (1958). Individuals were counted in a sedimentation chamber (10 ml) at different magnifications: large taxa in the whole chamber at 100x, medium-sized taxa in 2-4 strips at 200x and nanoplankton in 100 fields at 400x. Biomass was calculated from cell volume measurements (Pliński et al. 1984, Kawecka and Eloranta 1994). Phytoplankton composition was determined using a Carl Zeiss Jena “Jenamed” light microscope at 200x, 400x and 1000x magnifications with oil immersion. The samples for diatom analyses were burnt with 30% H₂O₂ to remove organic matter and to make permanent slides. Identifications followed e.g. Huber-Pestalozzi (1961, 1983), Komárek, Anagnostidis (1986, 1989, 1999), Krammer, Lange-Bertalot (1986, 1988, 1991a, 1991b), and Anagnostidis, Komárek (1988).

Water samples (5 dm³) for chlorophyll determination (given as a sum of chlorophyll *a* and phaeophytins) were collected at the same time as phytoplankton samples. Photosynthetic pigment concentrations were determined spectrophotometrically by the alcohol method (ethanol extraction),

as described by Nusch (1980). Data on chlorophyll concentrations from 1986 to 1989 by Zdanowski and Hutorowicz (1994) were also used in this study.

Models of phytoplankton abundance changes were determined from transformed data on algal biomass and chlorophyll concentrations from 1986 to 2001. In order to calculate relative phytoplankton biomass, each result was divided by the maximum biomass over the entire examined period. Data on relative chlorophyll concentrations were transformed in the same way. Models of annual changes were obtained from the optimal trendline by the polynomial method.

RESULTS

Phytoplankton biomass and composition

A total of 342 taxa, representing 44 families, 108 genera and 6 phyla (Chlorophyta, Cyanoprokaryota, Cryptophyta, Dinophyta, Euglenophyta and Heterokontophyta, Table 1), were identified. The highest species richness was observed in the Bacillariophyceae (176), especially in the order Pennales (46% of the total number of taxa), and the Chlorophyta, mainly in the order Chlorococcales (19%), whereas the lowest species richness occurred in the Euglenophyta and Chrysophyceae.

Over the growth seasons (March to November) of 1991 through 1994 the total phytoplankton biomass in Lake Niegocin ranged between 0.6 and 8.2 mg l⁻¹ (Fig. 2). Following modernization of the wastewater treatment plant from 1995 to 1999, the biomass of planktonic algae never exceeded 2.86 mg l⁻¹, whereas in 2000 and 2001 the phytoplankton biomass reached 6.3 mg l⁻¹ (Fig. 2).

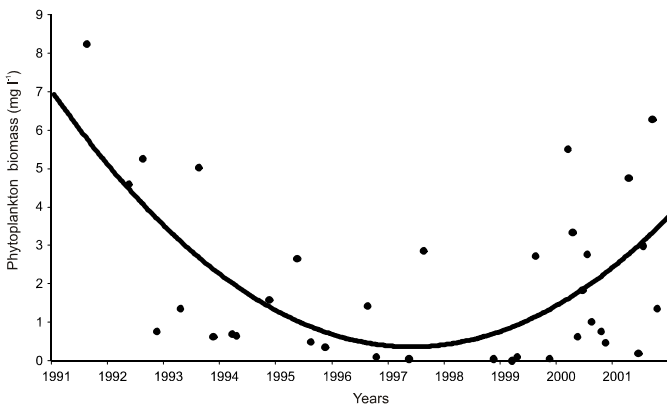


Fig. 2. Phytoplankton biomass (mg l⁻¹) during the growth season (from March to November) in Lake Niegocin between 1991 and 2001.

Table 1

Number and percentage of species, varieties or forms of phytoplankton in Lake Niegocin in years 1991-2001

Phytoplankton group	Family	Genus	Species, variety, form	
			Number	%
Cyanoprokaryota	9	18	37	10.8
Cyanophyceae				
Chroococcales	4	7	18	5.3
Oscillatoriales	3	8	8	2.3
Nostocales	2	3	11	3.2
Chlorophyta	20	47	106	31.0
Chlorophyceae				
Chlorococcales	10	30	65	19.0
Chlamydomphyceae				
Chlamydomonadales	3	5	6	1.7
Volvocales	1	2	2	0.6
Zygnemaphyceae				
Desmidiiales	3	6	29	8.5
Zygnemales	1	2	2	0.6
Codiolophyceae				
Ulotrichales	2	2	2	0.6
Euglenophyta	1	3	4	1.2
Euglenophyceae				
Euglenales	1	3	4	1.2
Heterokontophyta	10	34	179	52.4
Bacillariophyceae				
Centrales	2	6	19	5.6
Pennales	7	27	157	45.9
Chrysophyceae				
Ochromonadales	1	1	3	0.9
Cryptophyta	1	3	6	1.7
Cryptophyceae				
Cryptomonadales	1	3	6	1.7
Dinophyta	3	3	10	2.9
Dinophyceae				
Peridinales	3	3	10	2.9
Total	44	108	342	100

Composition of the spring phytoplankton

During spring of 1993 – 1995, the phytoplankton assemblages were dominated by diatoms (Fig. 3), which represented up to 91% of the total biomass. The species were

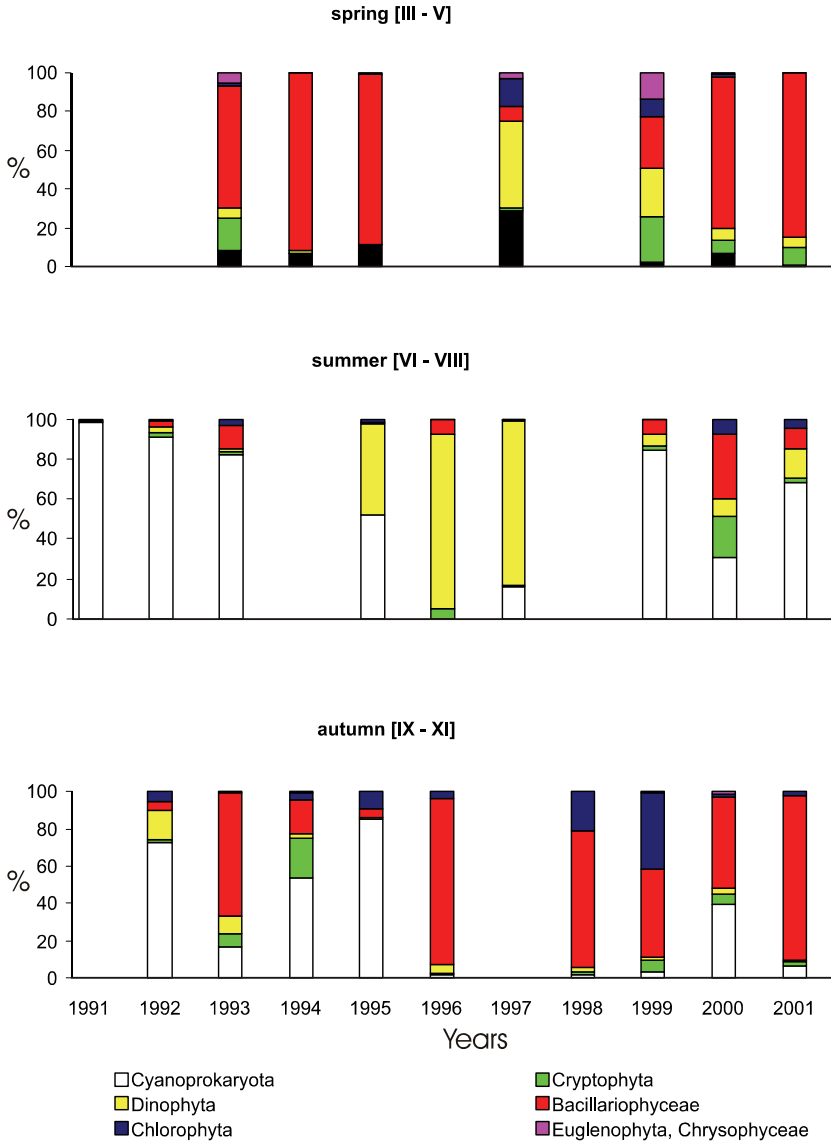


Fig. 3. Percentage contribution of particular groups of phytoplankton to the total biomass in Lake Niegocin in years 1991 - 2001.

mostly *Aulacoseira granulata* (Ehr.) Sim., *A. islandica* (O. Müll.) Sim., *Stephanodiscus neoastrea* Håk. et Hick., and *Asterionella formosa* Hass. (Table 2). In the spring of 1997, the algal biomass was lower and was dominated

Table 2

Dominant species (≥10% total biomass) of phytoplankton in Lake Niegocin during the growth season in years 1991-2001

	spring (March – May)	summer (June – August)	autumn (September – November)
1991		<i>Planktothrix agardhii</i> (Gom.) Anagn. et Kom. (96%)	
1992		<i>Planktothrix agardhii</i> (Gom.) Anagn. et Kom. (56%) <i>Aphanizomenon flos-aquae</i> (Lemm.) Lemm. (29%)	<i>Planktothrix agardhii</i> (Gom.) Anagn. et Kom. (42%) <i>Leptolyngbya thermalis</i> Anagn. (28%)
1993	<i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (28%) <i>Asterionella formosa</i> Hass. (22%) <i>Cryptomonas</i> sp. div. (15%)	<i>Planktothrix agardhii</i> (Gom.) Anagn. et Kom. (78%)	<i>Planktothrix agardhii</i> (Gom.) Anagn. et Kom. (16%) <i>Gymnodinium</i> sp. (10%)
1994	<i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (45%) <i>Stephanodiscus neoaestrea</i> Håk. et Hick. (45%)		<i>Leptolyngbya thermalis</i> Anagn. (36%) <i>Cryptomonas</i> sp. div. (21%)
1995	<i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (86%)	<i>Anabaena flos-aquae</i> (Lyngb.) Bréb. ex Born. et Flah. (45%) <i>Peridinium</i> sp. div. (45%)	<i>Aphanizomenon flos-aquae</i> (Lemm.) Lemm. (15%) <i>Stephanodiscus neoaestrea</i> Håk. et Hick. (10%)
1996	<i>Aphanizomenon flos-aquae</i> (Lemm.) Lemm. (11%)	<i>Peridinium</i> sp. div. (87%)	<i>Planktothrix agardhii</i> (Gom.) Anagn. et Kom. (82%) <i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (82%)
1997	<i>Gymnodinium</i> sp. (42%) <i>Leptolyngbya thermalis</i> Anagn. (18%) <i>Pediastrum boryanum</i> (Turp.) Menegh. (10%)	<i>Ceratium hirundinella</i> (O. F. Müll.) Bergh (62%) <i>Peridinium</i> sp. div. (21%)	
1998			<i>Stephanodiscus neoaestrea</i> Håk. et Hick. (34%) <i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (24%) <i>Pediastrum boryanum</i> (Turp.) Menegh. (17%) <i>Cyclotella</i> sp. (13%)
1999	<i>Gymnodinium</i> sp. (25%) <i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (24%) <i>Cryptomonas</i> sp. div. (24%) <i>Dinobryon divergens</i> Imb. (14%)	<i>Aphanizomenon flos-aquae</i> (Lemm.) Lemm. (30%) <i>Leptolyngbya thermalis</i> Anagn. (17%) <i>Anabaena flos-aquae</i> (Lyngb.) Bréb. ex Born. et Flah. (15%)	<i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (31%) <i>Pediastrum boryanum</i> (Turp.) Menegh. (22%) <i>Staurastrum</i> sp. (15%)
2000	<i>Stephanodiscus neoaestrea</i> Håk. et Hick. (31%) <i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (23%) <i>Stephanodiscus</i> sp. (12%)	<i>Microcystis aeruginosa</i> (Kütz.) Kütz. (26%) <i>Chroomonas acuta</i> Uterm.+ <i>Rhodomonas</i> sp. (16%) <i>Asterionella formosa</i> (15%)	<i>Stephanodiscus neoaestrea</i> Håk. et Hick. (26%) <i>Microcystis aeruginosa</i> (Kütz.) Kütz. (22%) <i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (17%) <i>Aphanizomenon flos-aquae</i> (13%)
2001	<i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (69%) <i>Stephanodiscus neoaestrea</i> Håk. et Hick. (11%)	<i>Leptolyngbya thermalis</i> Anagn. (28%) <i>Microcystis aeruginosa</i> (Kütz.) Kütz. (24%)	<i>Aulacoseira granulata</i> (Ehr.) Sim.+A. <i>islandica</i> (O. Müll.) Sim. (82%)

by the dinoflagellate *Gymnodinium* sp. (42%) and the cyanoprokaryote *Leptolyngbya thermalis* Anagn. (18%). Chlorophytes were less common, with *Pediastrum boryanum* (Turp.) Menegh. representing ca. 10% of the total biomass. At this time, diatoms represented 8% of the total biomass. In 1999, the diatoms, dinoflagellates, and cryptophytes each accounted for ca. 25% of the total planktonic algal biomass. Representatives of the genera *Gymnodinium*, *Aulacoseira* and *Cryptomonas* were the dominant taxa, and the chrysophyte *Dinobryon divergens* Imh was a major biomass contributor (14%). In the spring of 2000 and 2001, the phytoplankton biomass structure was similar to the years 1993 – 1995 when diatoms were the dominant group. During 2000 and 2001, diatoms represented ca. 78% and 85% of the total biomass for these years, respectively (Fig. 3).

Composition of the summer phytoplankton

In the years 1991 – 1993 cyanoprokaryotes dominated the total biomass (Fig. 3). In 1991, the greatest biomass (96%) was contributed by *Planktothrix agardhii* (Gom.) Anagn. et Kom. (8.0 mg l^{-1}) (Table 2). *P. agardhii* and *Aphanizomenon flos-aquae* (L.) Ralfs ex Born. et Flah. dominated in the next two years. A different structure of phytoplankton assemblages was present in the summer of 1995, which consisted of two major algal groups, the cyanoprokaryotes (e.g. *Anabaena flos-aquae* (Lyngb.) Bréb. ex Born. et Flah.) and dinoflagellates (e.g. *Peridinium* sp. div.) A distinct predominance of dinoflagellates (above 80%) occurred in the next two years. These included *Peridinium* sp. div. in 1996, and *Ceratium hirundinella* (O. F. Müll.) Bergh. in 1997. In the summer of 1999, the greatest biomass was due to the cyanoprokaryotes, mostly from the genera *Aphanizomenon*, *Anabaena*, and *Leptolyngbya*. A similar phytoplankton structure was present in the summer of 2001 (Fig. 3), but the total biomass was approximately threefold higher (Fig. 2). In 2000, the three co-dominant groups were cyanoprokaryotes (*Microcystis aeruginosa* (Kütz.) Kütz.), dinoflagellates and cryptophytes.

Composition of the autumn phytoplankton

In the autumn of 1992, the phytoplankton assemblages were dominated by filamentous cyanoprokaryotes (72%) (Fig. 3), e.g. *Planktothrix agardhii* and *Leptolyngbya thermalis* (Table 2). Relatively high biomass was also contributed by the dinoflagellates, including *Gymnodinium* and *Peridinium*. A different phytoplankton structure was present in the autumn of 1993. The major taxa were diatoms, which accounted for 66% of the total biomass, whereas the cyanoprokaryotes represented 17%. The next year, the phytoplankton was again dominated by filamentous algae (54%), whereas diatoms and cryptophytes each

represented by approximately 20%. In 1995, the algal representation was similar to the autumn of 1992, whereas in the years 1996 – 1998 the diatoms (with 74 – 89% of the total biomass) were the dominant group. At that time another large contributor to algal biomass were the chlorophytes (max. 21%). In the autumn of 1999, diatoms were co-dominant with the chlorophytes (e.g. *Pediastrum boryanum*, *Staurastrum* sp.), and in 2000 with the cyanoprokaryotes (e.g. *Microcystis aeruginosa*). In 2001, as in 1996 and 1998, the diatoms formed about 80% of the total biomass.

Chlorophyll content

In the period preceding the modernization of the sewage treatment plant in Giżycko (1986 – 1994), the chlorophyll concentration in Lake Niegocin ranged between 0.6 (March 1987) and 93.9 $\mu\text{g l}^{-1}$ (August 1994), with a mean concentration from March to November of 16.1 $\mu\text{g l}^{-1}$ (Fig. 4).

After modernization of the sewage treatment plant in 1994, the chlorophyll concentration in Lake Niegocin decreased considerably. Until the end of the 1990s the chlorophyll concentration ranged between 0.8 and 36.2 $\mu\text{g l}^{-1}$ from February to November, with an average of 11.6 $\mu\text{g l}^{-1}$ (Fig. 4). However, in 2000 there was an increase in the chlorophyll concentrations, which continued in 2001 with highest levels of ca. 50.0 $\mu\text{g l}^{-1}$. The mean concentration was almost as high as the average recorded from 1986 to 1994.

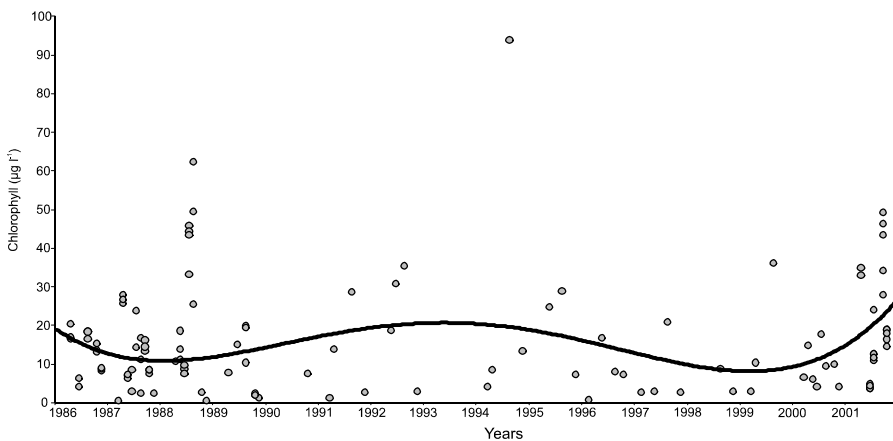


Fig. 4. Chlorophyll concentration ($\mu\text{g l}^{-1}$) in Lake Niegocin in years 1986 – 2001.

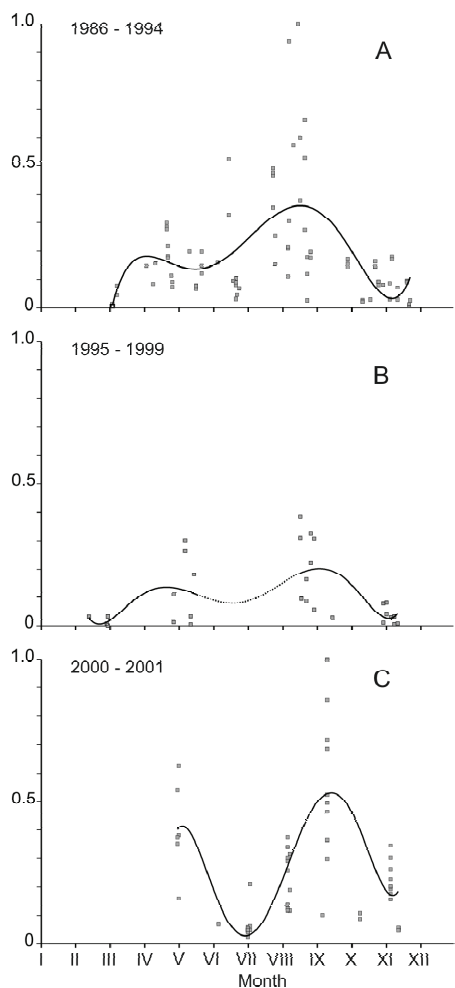


Fig. 5. Models of seasonal dynamics of phytoplankton in years 1986 - 1994 (A), 1995 - 1999 (B) and 2000 - 2001 (C) in Lake Niegocin.

Models of seasonal phytoplankton development

Before the wastewater treatment plant was modernized the pelagial phytoplankton development consisted of two peaks that occurred during spring (late April to early May) and summer (late July to early August) (Fig. 5A). The summer development was almost twofold higher than in spring and consisted primarily of cyanoprokaryotes (Fig. 6). In the years 1995 - 1999, when dinoflagellates dominated in the summer, the phytoplankton abundance was low during both the spring and summer peaks (Fig. 5B). The phytoplankton development in 2000 and 2001 resembled the patterns observed preceding the sewage treatment plant modernization. There were two algal abundance peaks in 2000 - 2001 that occurred over the growth season, and the summer peak occurred in early September and was higher, compared to spring (Fig. 5C), and the presence of the cyanoprokaryotes had increased (Fig. 6).

DISCUSSION

Until 1995 Lake Niegocin was seriously threatened with increased eutrophication, primarily due to point source pollution by municipal wastes from Giżycko. These wastes contained excessive phosphorus loads ($1.66 \text{ g P m}^{-2} \text{ year}^{-1}$) that were above Vollenweider's criterion of $0.20 \text{ g P m}^{-2} \text{ year}^{-1}$

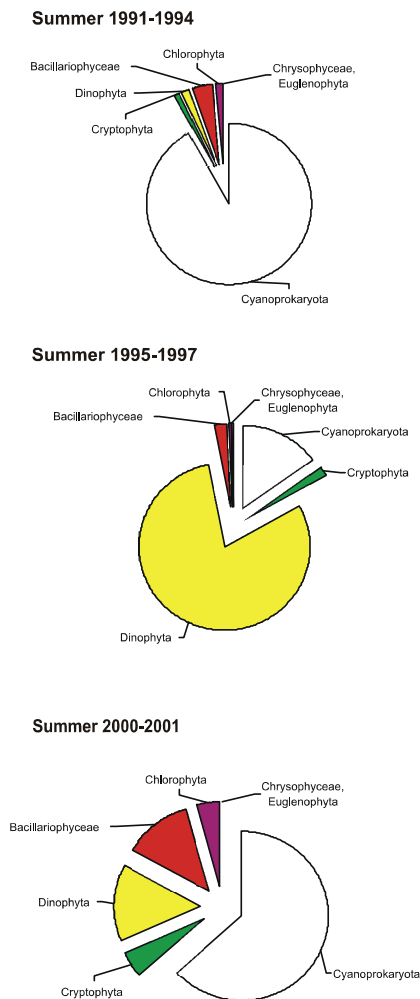


Fig. 6. Structure of phytoplankton biomass in summer (from June to August) during years 1991 - 2001 in Lake Niegocin.

(Giercuskiewicz-Bajtlik and Głabński 1981, Giercuskiewicz-Bajtlik 1990). Spodniewska (1979, 1986) and Zdanowski and Hutorowicz (1994) indicate that the increase in the lake's productivity could be due to water inflow from both Lake Wojnowo and Lake Grajewko, which are heavily polluted by effluents from animal farms located in their catchments. In addition, the catchment area of Lake Niegocin contains 74% arable land, which is subject to considerable seasonal water level fluctuations and significant agricultural runoff (Dąbrowski 2002a, 2002b). The relatively low degradation susceptibility attributed to Lake Niegocin (category II) (Dorochowicz 1994, Cydzik et al. 1995) and its high level of stability (IV) (Zdanowski 1982) could not counter the excessive pollution inflow to the lake. In the years 1991 – 1994, high phytoplankton biomass (above 8.0 mg l⁻¹) was recorded in Lake Niegocin (Spodniewska 1978, 1979). At the beginning of the 1990s, during summer, the most abundant phytoplankton groups

were filamentous cyanoprokaryotes possessing heterocysts (e.g. *Planktothrix agardhii*, *Aphanizomenon flos-aquae*), which are unattractive food items to filter-feeding animals. The domination by *P. agardhii* in the majority of large Masurian lakes already had occurred by the 1970s (Spodniewska 1983, 1986). In addition, the algal blooms of these taxa could result in toxin production, constituting a potential threat to the lake ecosystem and its constituents, as well as humans. *P. agardhii* strains are known to produce microcystine, a potent

hepatotoxin, and *Aphanizomenon flos-aquae* has been reported to produce aphanotoxin, which negatively affects the central and peripheral nervous system (Reynolds 1991, Rapala et al. 1993, Kabziński et al. 2000, Mankiewicz et al. 2003).

The phytoplankton structure and biomass, plus the chlorophyll concentrations in successive growing seasons between 1991 and 1994 suggest relatively high stability of this ecosystem (Romo and Miracle 1995, Stefaniak et al. 2003), which was maintained due to the constant inflow of untreated wastewater (Anderson et al. 2002). This is confirmed by the results of previous investigations conducted on Lake Niegocin in 1971 – 1989 (Bernatowicz et al. 1974, Spodniewska 1978, 1979, Krzywosz 1993). During this period the increased phytoplankton biomass also produced frequent algal blooms (Pavoni 1963; Spodniewska 1978, 1979; Heinonen 1980; Nebaeus 1984).

The relatively small total phytoplankton biomass of April 1993 and 1994 was similar to the results reported by Krzywosz (1993) in the spring of 1986 and 1987, but differed from 1978, 1988 and 1989 when algal biomass was greater, reaching 15.5 mg l^{-1} (Krzywosz 1993). The dominant algae were pollution-tolerant diatoms of the genera *Aulacoseira*, *Stephanodiscus* and *Asterionella* (Rakowska 2001). The autumn algal biomass from 1992 to 1994 was similar to that reported by Krzywosz (1993) in the autumn of 1978 and 1986 – 1989. However, in contrast to previous years, the common phytoplankton components in autumn were filamentous cyanoprokaryotes, and centric diatoms, which dominated in spring or summer of 1992 – 1994.

Historically, there were very low Secchi disk values in summer in the consecutive years before the wastewater treatment plant was modernized (Zdanowski et al. 1984, 1993; Zdanowski and Hutorowicz 1994; Kufel 1998; Kufel and Kufel 1999). In addition, there were reports of unacceptable water conditions in Lake Niegocin, according to the Lake Quality Assessment System (Cydzik et al. 1995, Wróblewska 2002). The number of harvested fish (e.g. tench, pike, cisco) decreased over this period, and mass fish deaths were recorded (Zachwieja 1966, Wołos 1988, Wołos and Szlażyńska 1988, Pyka et al. 1989, Zakęś and Pyka 1990, Krzywosz 1991).

The improvements made at the Giżycko sewage treatment plant was followed by a decrease in the total biomass of planktonic algae in Lake Niegocin as well as by changes in the algal composition. The greatest changes occurred during summer, when the dominant cyanoprokaryotes were replaced by dinoflagellates (*Peridinium* sp. div. and *Ceratium hirundinella*). Although dinoflagellates are common in oligo-, meso- and eutrophic waters (Krupa 1981a, 1981b; Reynolds 1984; Bucka 1989; Burchardt 1993; Hutorowicz 2000), according to Bucka and Wilk-Woźniak (2002) their high abundance indicated lower pollution levels in the lake. However, the first indication of a negative

response to improvement of the water quality was the change in the phytoplankton assemblages in the summer of 1999, with increasing phytoplankton biomass that continued into 2001 (Fig. 2).

The *Aulacoseira* and *Stephanodiscus* species that dominated in spring represented the assemblage structure from 1993 to 1995, and 2000 – 2001, although their earlier abundance levels were much higher. During the clean water stage (1999), and representing a lower total biomass were the nanoplankton cryptophytes *Chroomonas acuta* and *Rhodomonas* sp. These are fast-reproducing pioneer algae, adaptable to the existing environmental conditions with a type *r* survival strategy, and usually appearing in great numbers after the collapse of algal bloom. According to Szyszka (1990), they are a “link” in the succession of summer phytoplankton assemblages. In the summer of 2000, the cyanoprokaryote *Microcystis aeruginosa* dominated the algal assemblages, and due to its positive buoyancy formed surface blooms. Strains of this species produce hepatotoxins of the microcystine group, which may inhibit the development of other phytoplankton and reduce photosynthesis rates and chlorophyll concentration (Watanabe 1997, Casanova 1999, Singh 2001, Romanowska-Duda 2002, Mankiewicz et al. 2003). The other co-dominants at this time were *Asterionella formosa* and *Ceratium hirundinella*, which occur frequently in eutrophic lakes (Wojciechowski 1972). An explanation for the increased development of planktonic algae in 2001 might be the failure of the sewage treatment plant in Giżycko, which was flooded after heavy rainfalls in July 2001. Subsequently, untreated wastewater entered Lake Niegocin for a two week period. This condition was followed in early September by increased abundance and biomass of algae, similar to that observed before modernization of the sewage treatment plant.

In autumn (2000 – 2001), the biomass and structure of the algal assemblages were comparable to those observed before the wastewater treatment plant was modernized in November 1994. In 2000 – 2001 the dominant taxa were *Microcystis aeruginosa* and *Stephanodiscus neoastrea*, whereas *Planktothrix agardhii*, *Leptolyngbya thermalis*, *S. neoastrea* and *Aulacoseira granulata* were the dominant species in the 1990s. These are pollution-tolerant and cosmopolitan species, commonly found in eutrophic waters bodies in the autumn (Rakowska 2001, Bucka and Wilk-Woźniak 2002).

The seasonal patterns correspond to mathematical models that illustrate significant long-term seasonal changes have occurred in the phytoplankton assemblages of Lake Niegocin (Fig. 5). A comparison between these results and the models developed by Oleksowicz (1988) shows that the phytoplankton assemblages in Lake Niegocin 1986 – 1994 were characteristic of biogenetically enriched waters, and according to the PEG model (Plankton Ecology Group), typical of temperate zone eutrophic lakes (Sommer et al. 1986, Kawecka and

Eloranta 1994). The seasonal variability during 1995 – 1999 was typical of lakes with a medium-sized biogenic pool (Oleksowicz 1988), whereas the 2000 – 2001 phytoplankton pattern resembled that described for 1986 – 1994. These relatively fast changes in the algal summer abundance and structure indicate low stability of the ecosystem and the ability of the lake to respond over short time periods to a changing nutrient balance within its waters. This may be due to the great abundance of biogenic compounds in the whole ecosystem, especially in bottom deposits (internal supply), and constant strong tourist and recreation pressure.

CONCLUSIONS

Until 1995 the phytoplankton assemblages in Lake Niegocin developed under conditions of heavy pollution loads. Relatively high total biomass of planktonic algae (about 8.0 mg l^{-1}), was systematically recorded in Lake Niegocin, with concentrations of chlorophyll *a* and phaeophytins reaching $93.9 \text{ } \mu\text{g l}^{-1}$. Mass development of filamentous cyanoprokaryotes, primarily hepatotoxin- and neurotoxin-producing species (e.g. *Planktothrix agardhii* and *Aphanizomenon flos-aquae*), was observed in summer.

The modernization of the wastewater treatment plant in Giżycko was followed by changes in the abundance and structure of planktonic algae in Lake Niegocin, which indicated their response to reduced sewage inflow. The decrease in the total phytoplankton biomass and chlorophyll concentrations, as well as radical changes in the dominant summer species (e.g. *Peridinium* sp. div. and *Ceratium hirundinella*), indicated the algal assemblages response to new environmental conditions.

However, the increase in abundance of planktonic algae in Lake Niegocin in 2000 and 2001, and the domination by cyanoprokaryotes *Aphanizomenon flos-aquae*, *Leptolyngbya thermalis* and *Microcystis aeruginosa* in the summer since 1999, showed that the above changes were short-lived. One reason for the relatively low stability of this ecosystem may be the intermittent availability and introduction of additional nutrients to these waters, which influenced algal development and the lake's trophic status.

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