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Functioning of the Lake Rusałka ecosystem in Poznań (western Poland)

Ryszard Gołdyn[1*], Stanisław Podsiadłowski[2], Katarzyna Kowalczewska-Madura[1], Renata Dondajewska[1], Elżbieta Szeląg-Wasielewska[1], Agnieszka Budzyńska[1], Piotr Domek[1], Wanda Romanowicz-Brzozowska[1]

[1]Department of Water Protection, Faculty of Biology
Adam Mickiewicz University
ul. Umultowska 89, 61-614 Poznań, Poland
[2]Institute of Agriculture Engineering, Poznań University of Life Sciences
ul. Wojska Polskiego 50, 60-629 Poznań, Poland

Key words: shallow lake, water bloom, cyanobacteria, phytoplankton, zooplankton, macroinvertebrates

Abstract

Lake Rusałka is a shallow, artificial, strongly eutrophic reservoir. Thermal stratification is weak and comprises only about 8% of the bottom surface. In summer, the epilimnion is oversaturated with oxygen due to intensive phytoplankton growth (chlorophyll *a* up to 80.2 µg l^{-1}), while conditions in the hypolimnion are anaerobic. The high concentration of ammonium nitrogen and low N:P ratio stimulated intense growth of cyanobacteria in the period from June to November. The domination of rotifers in the metazooplankton and low diversity and biomass of benthic macroinvertebrates was the cause of low top-down pressure of these

[*]Corresponding author: *rgold@amu.edu.pl*

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organisms on the phytoplankton. The most advantageous restoration measures were identified to improve water quality and make the recreational use of the lake possible.

INTRODUCTION

The detailed study of the functioning of a lake ecosystem is the foundation of a properly prepared restoration program. In shallow water bodies, of which Lake Rusałka is one, the ecosystem's reaction to internal nutrient loading from the bottom sediments is very important (Ryding and Rast 1989, Gołdyn et al. 2010, Kowalczewska-Madura et al. 2010). The presence of toxic cyanobacteria blooms prohibits possible water usage, especially for recreational purposes. They affect negatively other organisms in the food-web (Koski et al. 1999, Tokoyama and Park 2002), and pose a threat to people swimming in the lake (Chorus and Bertram 1999, Falconer 1999, Kobos et al. 2005). Interactions between organisms in the food-web can significantly modify processes within the ecosystem, simultaneously exerting an influence on water quality variables. The presence of large filter-feeding organisms is particularly important, as they have a biomanipulation effect (Shapiro and Wright 1984). The presence of submerged vegetation is also paramount to maintaining clear water.

The aim of the studies conducted in Lake Rusałka was to investigate the seasonal variation of water quality and to identify the factors responsible for persistent cyanobacteria water blooms, which limit the recreational use of the lake. The expected results of the research were planned to be used as the basis for determining the optimal restoration method for this lake. Part of the data, which concerned the experimental estimation of internal phosphorus loading from bottom sediments, was published in a separate paper (Gołdyn et al. 2010).

MATERIALS AND METHODS

Lake Rusałka is an artificial reservoir, situated in the northwestern part of the city of Poznań. It was created in 1943 when a valley of the Bogdanka River and the clay mining pits located there were flooded. Morphometric data on the reservoir and its basin are presented in Table 1. The immediate catchment area is comprised of 90% forests and 10% meadows. Despite this fact, Lake Rusałka is highly vulnerable to degradation. The reasons are almost all found in the morphometric and hydrographic features of the lake, especially in its shallow average depth. Because of its location close to the center of Poznań and the attractive grasslands around its shores, Lake Rusałka is used for recreation and is a popular relaxation site among the citizens of Poznań in summer. It is also used for swimming and angling (Pułyk and Tybiszewska 1995, Gołdyn et al. 1996). The Bogdanka River is the lake's most important tributary. Five smaller

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Table 1

Morphometric data of Lake Rusałka (according to Pułyk and Tybiszewska 1995, Gołdyn et al. 1996).

Variables	Unit	Value
Surface of the lake	ha	36.7
Mean depth	m	1.9
Maximal depth	m	9.0
Length of shore line	m	3300
Surface of total catchment area	km^2	25.1
Surface of immediate catchment area	km^2	0.839

streams also supply the lake: Golęciński Stream and 4 temporary, nameless inflows that drain the immediate catchment area (Fig. 1).

The study of Lake Rusałka was conducted monthly from April to November 2005. Water samples were taken in the vertical profile every meter (from the surface to a depth of 7 m) in the deepest part of the lake (station 1 – Fig. 1) and, in the case of benthic macroinvertebrates, at a second station in the shallow part of the lake at a depth of 2 m. The concentration of ammonium nitrogen, nitrite, nitrate, organic and total nitrogen, soluble reactive phosphorus (SRP), total phosphorus, BOD_5, suspended solids (seston dry mass) and chlorophyll *a* were analyzed for each water sample. Samples for phyto- and zooplankton analysis (species composition and quantitative analysis) were collected from the same points in the vertical profile of station 1. Water temperature, pH, conductivity, and oxygen content were measured directly in the lake with YSI 610-DM-meter. Water transparency was measured with a Secchi disc. The physicochemical analyses were conducted according to Polish standards (Dojlido 1995, Elbanowska et al. 1999). Suspended solids were analyzed by weight after filtration through a Whatmann's glass fiber filter GF/C and desiccation at 105°C. Chlorophyll *a* was assessed with the Lorenzen method (spectrometric, monochromatic method) after extraction in acetone with correction for pheopigments (PN-86, C-05560-02). Quantitative analyses of phytoplankton were performed on uncondensed samples fixed in Lugol's solution with the Utermöhl modification, using an inverted microscope and 9 ml-volume sedimentation chambers (Wetzel and Likens 2000). Zooplankton analysis were made using 10-liter samples, filtered through plankton net with 40 μm mesh diameter and preserved in Lugol's solution. Sedgwick-Rafter plankton chambers with a volume of 0.5 ml were used for quantitative analysis. Benthic macroinvertebrates were taken using a Kajak core sampler with 10 replicates per sample. They were flushed on a sieve with a 0.4 mm mesh

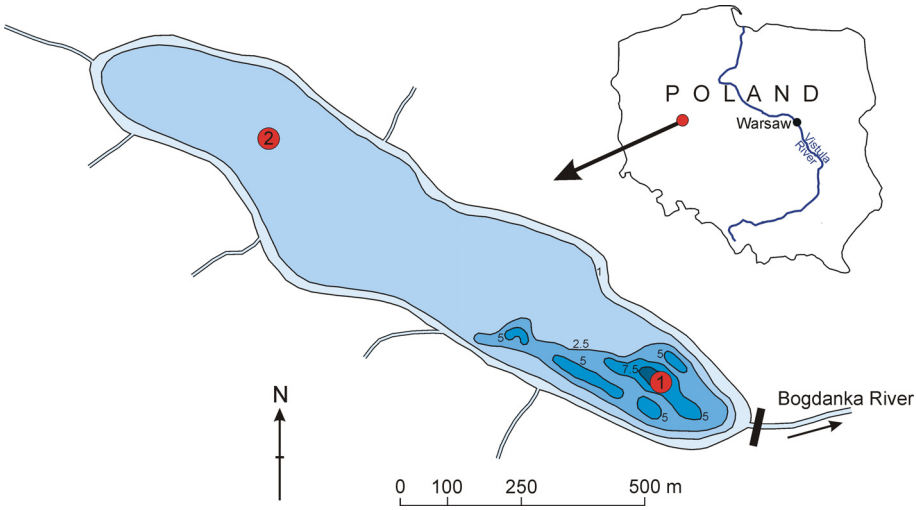


Fig. 1. Location of sampling stations in Lake Rusałka (bathymetry according to Pułyk and Trybiszewska 1995, modified).

diameter and preserved with formaldehyde solution. The number and biomass of organisms were recalculated to 1 m^2.

RESULTS

Seasonal thermal stratification was noted in the deepest part of Lake Rusałka; however, most of the bottom was in contact with epilimnetic water (92%). At the beginning of summer the epilimnion extended to 3 m. During the following months it deepened to 4 and 5 m. Strong winds probably mixed the lake at the beginning of August and windless weather renewed stratification. In the fall period full water mixing began at the end of September, when mixing reached the bottom of the reservoir (Fig. 2a).

As a result of the short spring mixing period and fast stratification in Lake Rusałka, by April oxygen depletion in the near-bottom water was already noted, and this persisted until the fall circulation in September (Fig. 2b). A sharp oxycline was noted usually at 3-5 m in summer. The epilimnion was always well oxygenated and in July and September showed high oversaturation with oxygen (up to 198.6%).

Lake Rusałka is a highly eutrophic water body, which is evident in the low water transparency that decreased to 60 cm in the summer period. Intense phytoplankton growth in the lake led to soluble carbon dioxide depletion from the water and caused a strong increase in pH in the surface water layer, which

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reached values as high as 9.19 at the end of summer, but in the near-bottom layer it was close to neutral.

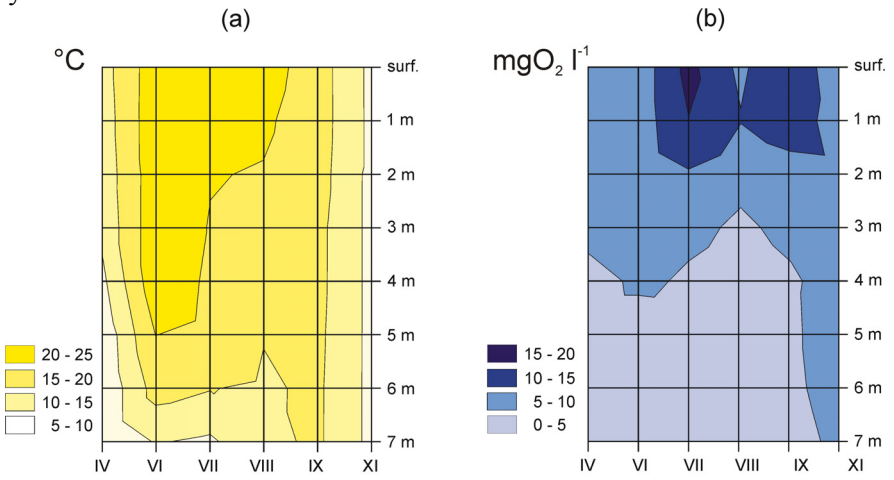


Fig. 2. Seasonal and vertical changes of temperature (a) and oxygen content (b) in Lake Rusałka at station 1.

The most important mineral form of nitrogen was ammonium nitrogen, which was present in the waters of the lake throughout the investigation (Fig. 3a). The highest concentration occurred in July just above the bottom sediments and reached 8.9 mg l^{-1} N. Near the surface, concentrations ranged from 0.46 mg l^{-1} N to 1.76 mg l^{-1} N. Nitrites (not shown) were present in Lake Rusałka only in small quantities during fall (0.01 mg l^{-1} N), while nitrates were noted in spring and fall (not exceeding 0.6 mg l^{-1} N). Concentrations of organic nitrogen in the trophogenic layer were the highest in summer when they reached up to 2.14 mg l^{-1} N. Total nitrogen concentrations ranged from 2.0 mg l^{-1} N to 2.4 mg l^{-1} N in the surface layer, and from 2.6 mg l^{-1} N to 13.2 mg l^{-1} N in the near-bottom layer (Fig. 3b).

Soluble reactive phosphorus was not detected in the trophogenic layer of Lake Rusałka in summer, but near the bottom concentrations reached 0.45 mg l^{-1} P. The total phosphorus content reached values from 0.02 mg l^{-1} P at the surface to 0.51 mg l^{-1} P near the bottom (Fig. 4).

The ratio of nitrogen and phosphorus was clearly higher in spring and fall than in summer. Maximal values in fall were 33.7, while in summer they decreased to 2.8. Electrolytic conductivity in Lake Rusałka was much higher in spring and at the beginning of summer than in subsequent months. Clear

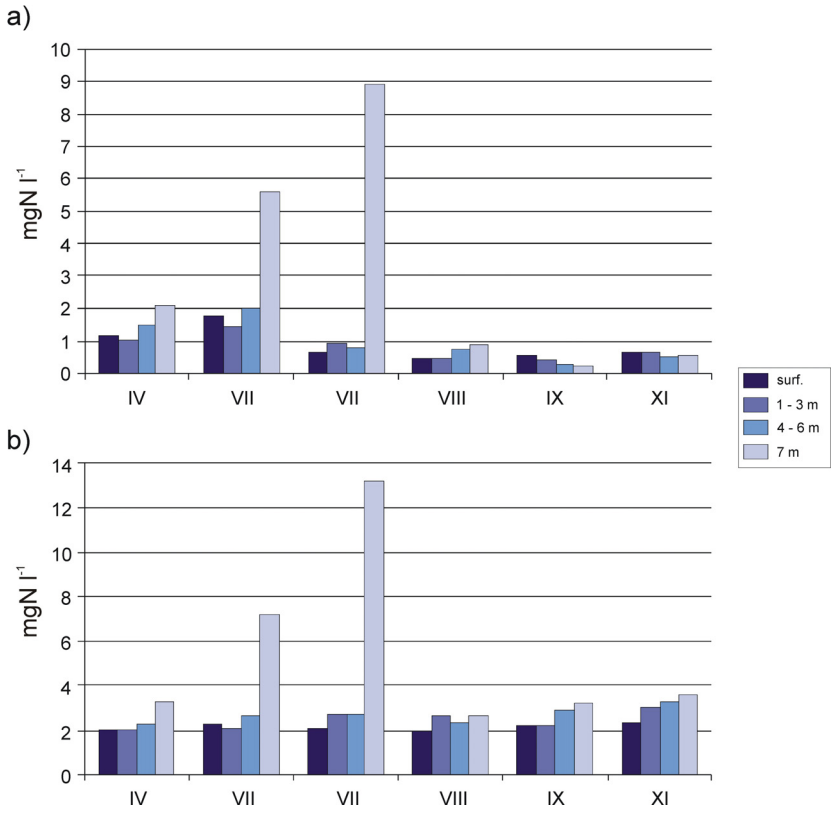


Fig. 3. Changes of ammonium (a) and total (b) nitrogen concentrations in Lake Rusałka.

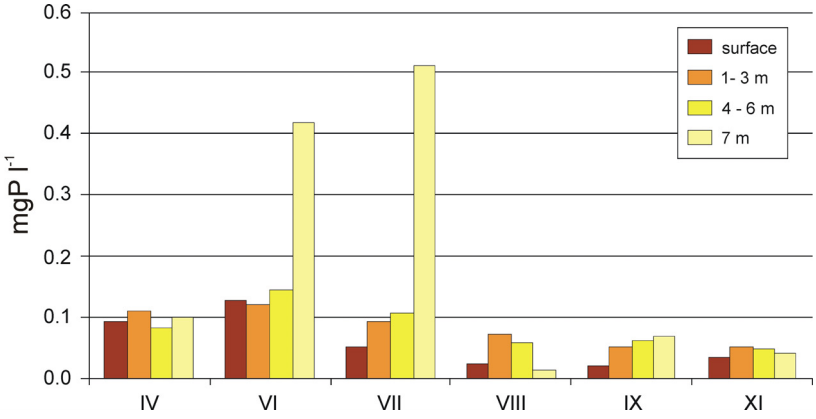


Fig. 4. Total phosphorus concentration in a vertical section of Lake Rusałka.

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stratification of values was visible in the vertical section. They ranged from 657 μS cm^{-1} at the surface to 1059 μS cm^{-1} near the bottom in fall. Chlorophyll *a* concentration in Lake Rusałka increased from spring to summer, attaining maximal values at the beginning of the fall circulation period in the lake in September. These values reached 80.2 μg l^{-1} at a depth of 1 m. Clear vertical stratification of chlorophyll *a* concentration, which was caused by the thermal stratification of the lake water, was observed until July (Fig. 5). Due to increasing water mixing, chlorophyll *a* concentrations in the vertical profile equalized from August until November.

Changes of seston content in the water were very similar to those of chlorophyll *a* with a range of 5.5 mg l^{-1} (at 5 m in November) to 24.6 mg l^{-1} (at 2 m in July). BOD_5 values varied from 3.5 to 11.3 mg l^{-1} O_2 and increased with water depth.

The quantity of phytoplankton in Lake Rusałka in the near-surface water layer varied from 16.4 thousand cells ml^{-1} in April to 587.1 thousand cells ml^{-1} in September. Cyanobacteria dominated the abundance of phytoplankton from early summer until the beginning of November (Fig. 6). Usually 2-3 species of filamentous cyanobacteria dominated, e.g. *Planktolyngbya subtilis* (W. West) Anagnostidis et Komàrek, *Anabaena flos-aque* fo. *lemmermanii* (P. Richter) Canabaeus, *Aphanizomenon flos-aque* (L.) Ralfs, *Pseudanabaena galeata* Böcher. During spring, chrysophytes (*Ochromonas* sp.) and green algae of the genus *Desmodesmus* were the most numerous.

The highest biomass of cyanobacteria species was noted in samples taken in June until August, but this is also when the biomass of chrysophytes (*Dinobryon* spp.) and/or dinoflagellates (*Peridinium* spp.) was the highest as well. Intense growth of *Pseudanabaena galeata* in September influenced the clear domination of cyanobacteria in the phytoplankton biomass. The diatom *Asterionella formosa* Hassal and chrysophytes from the genus *Dinobryon* (mainly *D. sociale* Ehrenberg) attained the highest biomass in November.

The total number of zooplankton in the surface water layer of the lake ranged from 630 to 7585 specimens l^{-1}. The maximal number was observed in late September and early October. A second, smaller peak of abundance was noted in spring (Fig. 7). The rotifers dominated both the quantitative and qualitative composition of zooplankton. The percentage of crustaceans was small, and only in spring did it reach 45%. During summer and fall it ranged from 2.3% to 9.4%. Copepods were much more common than cladocerans.

The share of *Keratella cochlearis* fo. *tecta* (Gosse) in the total number of rotifers was high. Other dominating species included *Polyarthra vulgaris* Carlin, *Anureopsis fissa* (Gosse), and *Synchaeta* sp. The most common copepods were *Thermocyclops oithonoides* (Sars) and youth stages (nauplii and copepodites). The most common cladocerans were *Bosmina coregoni* Baird and

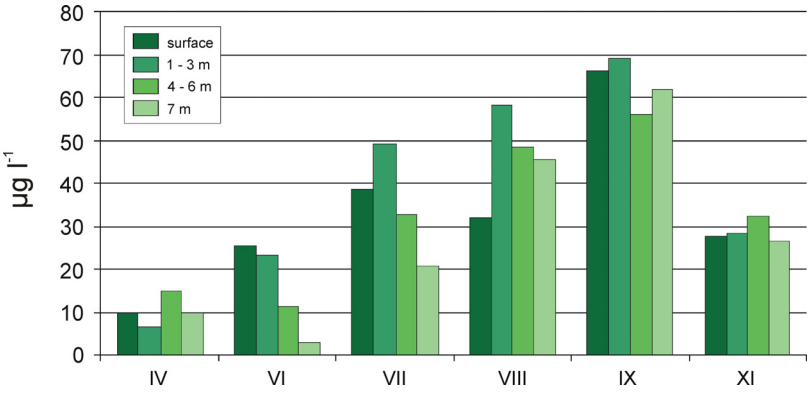


Fig. 5. Changes of chlorophyll *a* concentrations in Lake Rusałka.

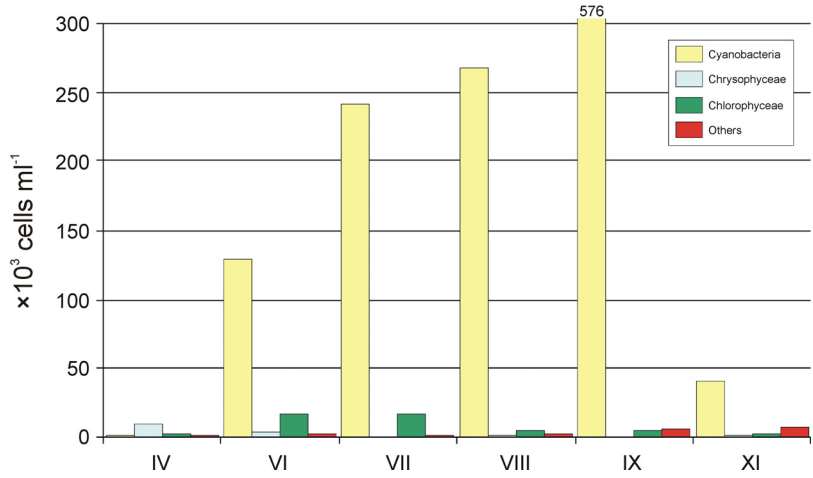


Fig. 6. Phytoplankton abundance in the surface water layer of Lake Rusałka during subsequent months in 2005.

B. longirostris (Mueller) during spring and *Daphnia cucullata* Sars in summer and fall.

Distinct differences were noted in the taxonomic composition and biomass (Fig. 8) of benthic macroinvertebrates in the shallow part of the lake (2 m water depth – station 2) and in the deepest part of the lake (profundal – station 1). Larvae of phantom midges (*Chaoboridae*) occurred in the profundal zone. They were also noted in water samples taken from the hypolimnion. During spring

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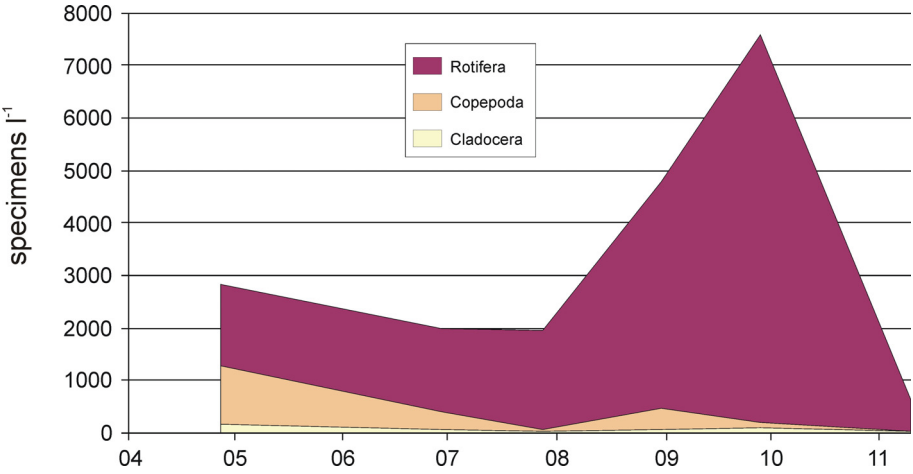


Fig. 7. Changes of the zooplankton abundance in the near-surface water layer in Lake Rusałka.

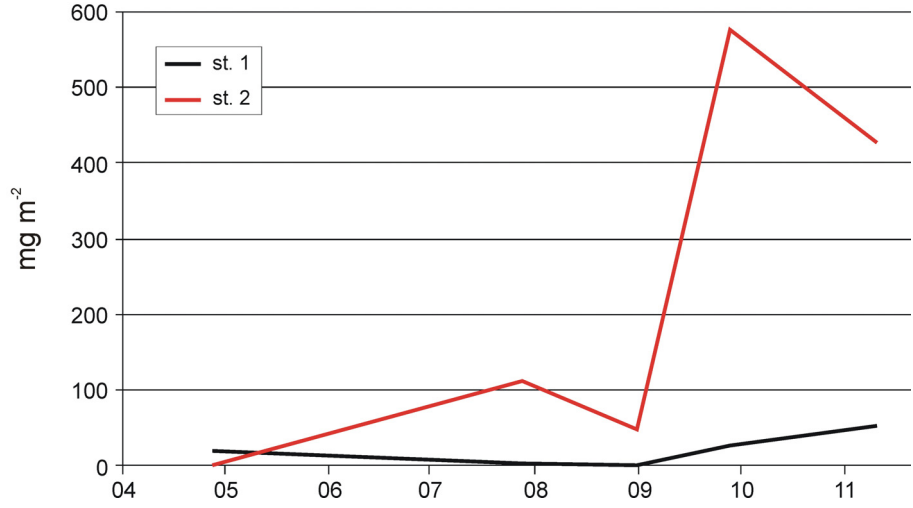


Fig. 8. Biomass of benthic macroinvertebrates in Lake Rusałka.

and fall the occasional occurrence of chironomids (*Chironomidae*) and snails (*Gastropoda*) was noted. Chironomids were the most numerous in a shallow part of the lake, where they were noted in small quantities throughout the period of investigation. Their number increased at the end of September, after new instars of the summer generation appeared. The number and biomass of the remaining taxonomic groups of macroinvertebrates was small (Table 2).

DISCUSSION

The extensive area of active bottom observed in Lake Rusałka is the reason it can be consider polymictic. Water mixing is favored by the location of the lake with its long axis in line with the dominant westerly winds. Despite very good water circulation in this lake, oxygen depletion in deeper layers (below 4 m) was observed in the small deep area, especially during the summer period. In turn, oxygen oversaturation, which was noted in the surface water layer, was connected with intense phytoplankton growth, creating water blooms in this lake. The diffusion of oxygen from the epilimnion to deeper layers was strongly limited, and oxygen consumption was intensified due to the decomposition of fresh organic matter in the bottom sediments and suspended solids in the water. This was accompanied by the distinct smell of hydrogen sulfide. Oxygen consumption in the particular layers of water in the lake during the vegetation period indicates the trophic level of the lake (Lampert and Sommer 2001, Tórz et al. 2004). According to this indicator, Lake Rusałka can be classified as a lake with a high trophic state.

The classification of the trophic state of Lake Rusałka based on the Carlson index (1977) (Table 3) and the range of variables proposed by OECD (1982) (Table 4) indicated that the state of the lake is highly eutrophic.

The excessive growth of phytoplankton leading to water blooms is an important symptom of eutrophication (Kajak 1998). Evidence of such water blooms in Lake Rusałka was confirmed by the number as well as biomass of phytoplankton, which reached very high values. As a result of their intense growth, water transparency decreased markedly and chlorophyll *a* concentrations increased in the epilimnion. The chlorophyll *a* concentrations noted significantly exceeded 25 $\mu g\, l^{-1}$, the maximal value considered for eutrophic waters by the OECD (1982). Thus, the studied lake is ranked as hypertrophic. The lack of the stratification of chlorophyll *a* concentrations at the end of summer and in fall, despite low water transparency, indicates that wind-driven water mixing in this lake was good.

The occurrence of cyanobacteria blooms is characteristic for lakes with a high trophic state. There are many hypotheses that explain the domination of cyanobacteria in lakes (Shapiro 1990, Blomqvist et al. 1994). Factors that are advantageous for the occurrence of cyanobacteria blooms include high water temperature, low light intensity, low N:P ratio, high P and low CO_2 availability, the buoyancy of cyanobacteria, and selective grazing of herbivorous zooplankton. Increased cyanobacteria biomass might also be caused by the assimilation of ammonium nitrogen and molecular nitrogen (Blomqvist et al. 1994). The assimilation of molecular nitrogen was significant in Lake Rusałka in summer, when species from the order *Nostocales* grew more intensely than

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Table 2

Density of macroinvertebrates (specimens per m^2) in the shallow (A) and deep parts (B) of Lake Rusałka.

Taxa	IV.2005		VII.2005		VIII.2005		IX.2005		XI.2005	
	A	B	A	B	A	B	A	B	A	B
GASTROPODA	-	-	-	-	-	-	46	23	-	-
DIPTERA: *Chaoboridae*	29	116	-	-	23	-	-	115	23	184
Chironomidae	116	29	230	23	46	-	1104	-	276	23
Ceratopogonidae	29	-	46	-	92	-	69	-	184	-
HYDRACARINA	-	-	-	-	23	-	-	-	-	-

Table 3

Classification of the trophic state of Lake Rusałka based on the Carlson index (1977).

	Value	Boundary values for eutrophy	Trophic state
TSI (TP)	74.37	<70	Hypertrophy
TSI (ChL)	71.71	53-70	Hypertrophy
TSI (SD)	67.37	53-70	Eutrophy

Table 4

Classification of the trophic state of Lake Rusałka based on variables proposed by OECD (1982).

Variable	Value	Boundary values for eutrophy	Trophic state
Mean TP (µg/l)	96	<100	Eutrophy
Mean chlorophyll-a (µg/l)	34.7	<25	Hypertrophy
Max chlorophyll-a (µg/l)	80.2	<75	Hypertrophy
Mean Secchi disc (m)	0.8	>1.5	Hypertrophy
Min Secchi disc (m)	0.6	>0.7	Hypertrophy

other species of algae and cyanobacteria. On the other hand, ammonium nitrogen was advantageous to cyanobacteria domination throughout the studied period. The domination of cyanobacteria and the intense growth of phytoplankton species belonging to other taxonomic groups is evidence of the advanced eutrophication of the studied lake. Similarly intense growth of phytoplankton was observed in other eutrophic reservoirs in Poland (Pająk 2003, Grabowska 2005, Rakowska et al. 2005).

According to the theory of alternative stable lake states (Scheffer et al. 1993), Lake Rusałka is currently in a turbid state (with the domination of phytoplankton), which is more stable than the clear-water state (with the domination of macrophytes). The lack of submerged macrophytes in lakes favors phytoplankton expansion, which limits light penetration into the water,

thus, preventing the recolonization of reservoirs by macrophytes (Scheffer and Jeppesen 1998, Gołdyn 2000).

Intensive phytoplankton development caused the depletion of nitrate nitrogen in the lake during the summer. The denitrification process occurring under anaerobic conditions in the deepest part of the lake could have had some significance as well. The high concentration of ammonium nitrogen in Lake Rusałka in the deepest water layer, especially during summer, indicated mineralization processes were active, but it also indicated a lack of nitrification due to anaerobic conditions. The content of organic nitrogen in Lake Rusałka varied depending on the intensity of the life processes of planktonic organisms. Higher concentrations were usually noted during the summer period when intense blooms occurred, indicating the autochtonous origin of this form of nitrogen in the lake.

The high concentration of SRP in the deepest part of the lake in summer was the result of intense internal loading from the bottom sediments. This process was stimulated by anaerobic conditions, increased temperature, and thermal stratification of the deepest water stratum, in which phosphorus originated from the bottom and was diluted and accumulated during the summer season. The low content of SRP and the high concentration of total phosphorus in the epilimnion indicate that this element circulates rapidly. SRP was intensively released from the so-called active bottom that was in contact with the warm epilimnetic waters (Gołdyn et al. 2010). Phosphorus release by metazooplankton, the fish inhabiting the water, and organisms from the microbial loop was also important (Szeląg-Wasielewska et al. 2006, Kowalczewska-Madura et al. 2010). The small concentration of this form of phosphorus or even its absence in the epilimnion during the summer months indicated that it is taken up by phytoplankton intensely. This means that SRP could be a limiting factor of primary production during the summer months.

The low N:P ratio during the summer months also indicated that nitrogen was a limiting element for growth in most planktonic algae species. This referred mainly to species adapted to nitrate nitrogen uptake, as it was not noted in the water during the summer months. This phenomenon, however, stimulated cyanobacteria growth, especially species adapted to N_2 fixation (Kawecka and Eloranta 1994). Together with other species adapted to assimilating ammonium nitrogen, they form water blooms that increase during the summer season.

Lakes situated on river courses in lowland landscapes, as Lake Rusałka, are supplied with a low content of suspended solids flowing in with tributary waters. The suspensions in the epilimnetic water (seston) are mostly of planktonic origin. This was confirmed by the statistically significant correlation of seston and chlorophyll values ($r = 0.447$ at $p = 0.002$, $n = 46$). However, BOD_5 values were not dependent on either seston or chlorophyll *a* values in

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Lake Rusałka. Soluble organic matter probably has a much greater influence on BOD_5 than do suspended solids. Unfortunately, dissolved organic carbon was not studied in this lake. There are probably many sources of dissolved organic matter, e.g., planktonic organisms, shallow bottom sediments, recreational use of the water, mainly by anglers, who throw bait into water before angling (Szyper et al. 1995).

The small number of crustaceans as well as the very small share of cladocerans indicated that the fish assemblage composition is disadvantageous to water quality in the lake (Perrow et al. 1997). The dominating cyprinids exerted strong food pressure on large zooplankton, rendering them unable to exert their top-down influence on the phytoplankton. Increasing the number of predatory fish is essential for increasing the food pressure of plankton crustaceans on phytoplankton (Gołdyn and Mastyński 1998).

The large share of rotifers and especially *Keratella cochlearis* fo. *tecta* in the metazooplankton proves that Lake Rusałka is in a very advanced trophic state (Karabin 1985).

Phantom midge (*Chaoboridae*) larvae are insensitive to oxygen deficits in water and sediments, and are present in the profundal zone of this lake despite the oxygen depletion in summer (DiGiovanni 1996, Jäger and Walz 2002). The sporadic presence of chironomid instars and snails during spring and fall was closely connected with water mixing in these seasons and well-oxygenated water and sediments in the lake including those in the deepest part. The small number and low biomass of all the taxonomic groups of macroinvertebrates at both stations was the result of the strong feeding pressure exerted by fish, mainly due to the domination of cyprinid species (Leppä et al. 2003). This phenomenon also has a strong impact on nutrient retention by the bottom sediments because of increased sediment resuspension caused by benthivorous fish (Svensson et al. 1999).

CONCLUSIONS

The current thorough study of the functioning of the Lake Rusałka ecosystem rendered it possible to identify the main causes of bad water quality and to propose restoration measures for its improvement. Cyanobacteria water blooms are linked with the presence of ammonium nitrogen and deficits of nitrate nitrogen, as well as with the low N:P ratio and internal loading of phosphorus from the bottom sediments. An easy way to immobilize phosphorus in the bottom sediments is to increase Fe^{+3} content and redox potential. This is possible for instance by dosing ferric sulfide or chloride (PIX reagent) and calcium nitrate directly to the sediments, when necessary (Søndergaard et al. 2002). Stocking the lake with piscivorous fish (especially pike fingerlings, Berg

et al. 1997), could facilitate increasing populations of zooplankton crustaceans and benthic invertebrates. They would help to decrease phytoplankton abundance and increase water transparency (top-down effect) making possible submerged macrophyte succession.

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