

Long-term trends in changes of the chemical composition of waters in lakes heated by electric power plants

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Abstract. The aim of the study was to identify trends in changes of the chemical composition of the waters of a heated lake ecosystem. Lakes Licheńskie, Ślesieńskie, Gośławskie, and the water uptake and discharge canals of electrical power plants were the subjects of the study. The waters studied were characterized by hydrocarbonate and lime salinity. Calcium and hydrocarbonate accounted for approximately 60-70% of the total concentration of dissolved ions in the waters. Changes in the overall salinity of the waters were characterized by a progressive increase of water electrolytic conductivity and increases in calcium, hydrocarbonate, and sulfate. The organic fraction was the dominant form of nutrient in the epilimnion of these lakes. The near-bottom layers were dominated by phosphate and ammonium nitrogen. Concentrations of these increased in the spring-summer period as oxygen deficits increased at the bottom. Lake eutrophication limited the availability of nitrogen and carbon to the phytoplankton. The low retention times of the water in the lakes limited phytoplankton blooms.

Keywords: lakes, heated waters, eutrophication, water chemistry, salinity, nutrients

Introduction

Aquatic environment thermal pollution, the effects of which are linked directly to elevated temperatures and

changes in water retention, is a specific type of anthropogenic stress. Increased water temperature stimulates eutrophication (Zdanowski 1976, Regier et al. 1990, Fee et al. 1992, Flanagan et al. 2003). Warming lake waters can disrupt water circulation, reduce oxygen content, accelerate nutrient release from sediments, and cause intense phytoplankton blooms (Mooij et al. 2005, Blenckner et al. 2006, Jeppesen et al. 2009). The accumulation of nutrients, which, when they undergo physical changes, shape the chemical composition of waters. Discharges of heated waters alter thermal regimes, ecological structure, and the functioning of aquatic ecosystems (Patalas 1970, Hillbricht-Ilkowska and Zdanowski 1988a, Zdanowski 1994a, Socha and Zdanowski 2001). These phenomena, along with morphometric, meteorological, and hydrological aspects, can intensify the decomposition of organic matter, the exchange of mineral substances between the water and bottom sediments, but they can also cause changes in water salinity (Scheren et al. 2000, Carpenter 2005, Sand-Jensen et al. 2007). The aim of this study was to identify long-term changes of water salinity which are decisive in determining the structure and functioning of the aquatic ecosystems of lakes that are effected by the discharge of heated waters from electric power plants.

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Materials and methods

The Konin lakes in the Wielkopolsko-Kujawskie Lake District in central Poland, which were included in the cooling systems of the Konin Electric Power Plant in 1958 and the Pątnów Electric Power Plant in 1970, are an example of an ecosystem subjected to thermal pollution, open pit mining, and urbanization. This system comprises the lakes Gosławskie, Pątnowskie, Licheńskie, Mikorzyńskie, and Ślesieńskie (Fig. 1), which are connected to the Warta River and Lake Gopło by the navigable Warta-Gopło Canal (34 km long), and are located in a catchment with a surface area of 418 km² (Zdanowski 1994a, Socha and Zdanowski 2001). The surface waters of this area mainly flow through the Struga Biskupia and Kleczewska to Lake Gosławskie, into which flow over 80% of all the waters discharged from the open pit lignite mines. A small portion of these waters were directed through the Rów Główny to Lake Mikorzyńskie. The phosphorus load released into Lake Gosławskie by the Struga Biskupia, in quantities of 3.02 g m⁻² year⁻¹, exceeded by 75-times the allowable load according to the criteria by Vollenweider (1968). The quantity of phosphorus precipitated was higher, which allowed a low trophic status to be maintained and not only in Lake Gosławskie, but also throughout the entire ecosystem (Hillbricht-Ilkowska and Zdanowski 1988b, Zdanowski 1994a). Since 2001, the water flowing out of the catchment has been collected in a post-mining pit forming a retention basin with a surface area of 346 ha and a maximum depth of 48 m. The phosphorus load currently delivered to Lake Gosławskie through the Struga Biskupia has decreased threefold to 1.01 g m⁻² year⁻¹. A significant source of phosphorus in this lake is the water pumped from the Warta-Gopło Canal to Lake Pątnowskie. The phosphorus load flowing into this lake in 1995-2010 was 5.9 g m⁻² year⁻¹, which exceeded the permissible load 147-fold.

Three of the five heated Konin lakes – Gosławskie, Licheńskie and Ślesieńskie, which along with the canals comprise a cohesive hydrological

system, were selected for the analyses of water chemical composition. Lake Gosławskie is a shallow pond-type basin with a surface area of 454.5 ha, a maximum depth of 5.3 m, a mean depth of 3.0 m, and it is heated throughout the year. It has a regular, poorly developed shore line. The Struga Biskupia receives runoff from an extensive agricultural catchment and the lignite pit mines. Water exchange occurred every two days in this lake in the 1995-2010 period. Lake Licheńskie has a surface area of 153.6 ha, a maximum depth of 13.0 m, and a mean depth of 4.9 m. Since 1958, this lake has been heated year round and receives approximately half of the post-cooling waters discharged by both power plants (Socha and Zdanowski 2001, Pyka et al. 2007, Stawecki et al. 2007). Water exchange in this lake in the 1995-2010 period was from two to nine days, with retention usually longer in summer (May, June) and shorter in fall and winter. Of all the lakes in the system, this one is most susceptible to eutrophication. Lake Ślesieńskie, with a surface area of 148.1 ha, a maximum depth of 25.7 m, and a mean depth of 7.5 m, is a typical ribbon lake that receives heated waters from Lake Licheńskie only in summer. In summers during the 1995-2010 period, the maximum water exchange time was 36 days. During summer when the lake is included in the cooling system, the water exchange time is shortened to an average of 11 days.

Water samples for physicochemical tests were collected monthly in the 1995-2010 period from centrally-located stations in the lakes from the surface water (0.5 m) and near-bottom (0.5 m above the bottom) layers, and in the canals from the surface water layer (0.5 m). The physicochemical water analyses were performed according to standard methods (Standard Methods 1980, Hermanowicz et al. 1999). Water temperature measurements and oxygen contents were taken with a YSI 58 oxygen meter every meter from the surface to the bottom. The pH was measured with a HI 22 pH meter (Hanna Instruments), and electrical conductivity was measured with a DIGI 610 conductivity meter. Titration was used to determine the contents of carbonate and hydrocarbonate ions. The concentrations of calcium,

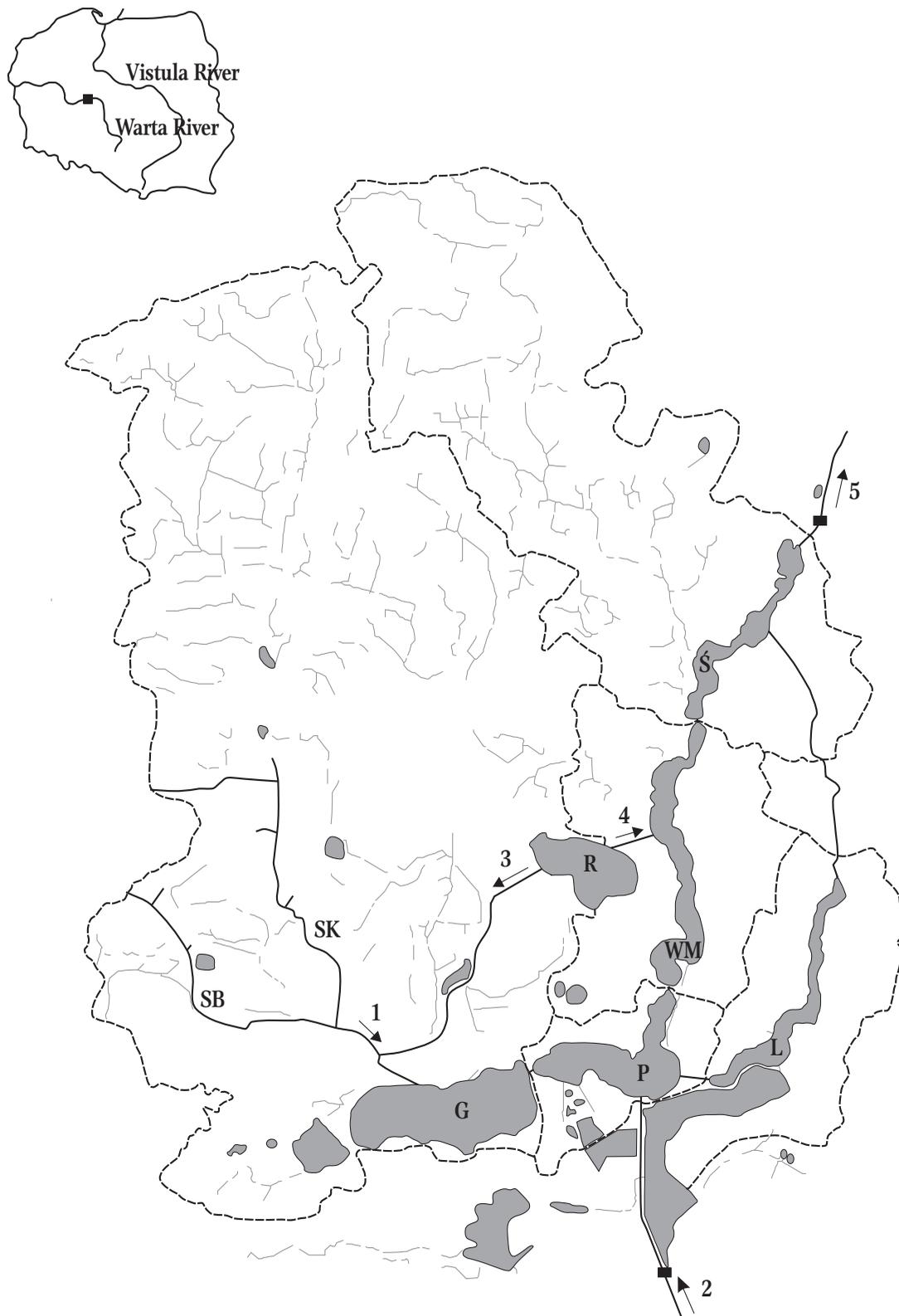


Figure 1. Konin lakes catchment. Lakes: L – Licheńskie, Ś – Ślesieńskie, WM – Mikorzyńskie, P – Pałnowskie, G – Gosławskie; R – post-mining water basin; 1 – Struga Biskupia (SB) and Struga Kleczewska (SK), constant supply from the catchment; 2 – supply from the Warta River during periods of negative water balance at the peak station; 3 – water outflow from the open pit lignite mine (until 2001); 4 – water outflow from the lignite mine through the Rów Główny (until 2001); 5 – supply to Lake Gopło.

magnesium, sodium, potassium, chloride, sulfate, and nitrate were determined with high-performance liquid ion chromatography in an HPLC device by Shimadzu. A UV-1601 spectrophotometer (Shimadzu) was used to determine the concentrations of phosphorus, total phosphorus (after mineralization), silica, and total iron, while total nitrogen was determined with an Epoll ECO 20 spectrophotometer.

The results of the chemical composition of waters from the lakes, recirculating canals, and from external sources supplying the system were compared with those from the 1965-1992 period (Korycka and Zdanowski 1976, Zdanowski 1976, Zdanowski 1988, Zdanowski et al. 1988, Zdanowski 1994a, 1994b, Zdanowski and Prusik 1994). Results of studies on changes in nitrogen and phosphorus (Pyka et al. 2007) and oxygen concentration and water temperatures (Stawecki et al. 2007, 2013) were also used in the present study.

Results

In the 1995-2010 period, the mean surface water temperature in the canals and the external sources supplying the system fluctuated from 12.7 (Struga Biskupia) to 21.3°C (Pałnów Power Plant warm discharge canal, Table 1), and the maximum did not exceed 33.0°C. The oxygen content in this period was within the range of 8-10 mg l⁻¹ and did not decrease below 4.0 mg l⁻¹ (50% oxygen saturation, Table 1). During the same period, the mean temperature of the surface water layer of the polymictic Lake Gośląskie, which is strongly mixed to the bottom, was 15.4°C (Table 1) and it did not exceed 27.2°C. The oxygen content was a mean of 10.4 mg l⁻¹ (102% oxygen saturation, Table 1). In summer, the quantity of oxygen dissolved in the water was lower (9.1 mg l⁻¹, 102% oxygen saturation, Table 2) and it did not exceed 11.7 mg l⁻¹ (146% oxygen saturation). The mean water temperature in the surface water layer of the monomictic Lake Licheńskie, which is mixed from September to May, was 17.4°C

(Table 1) at a maximum of 31.0°C during the study period. The range of the epilimnion did not exceed 10 m, and an unstable thermocline covered just 10% of the active bottom. The oxygen content in this layer was a mean of 9.3 mg l⁻¹ (92% oxygen saturation, Table 1), while in summer it was 8.7 mg l⁻¹ (98% oxygen saturation, Table 2) and did not exceed 11.2 mg l⁻¹ (143% oxygen saturation). The near-bottom layer oxygen content in summer decreased to less than 1 mg l⁻¹ (Table 2). The vertical oxygen content of the lake waters described by the clinograde oxygen profile was typical of eutrophic lakes. It was confirmed that the surface water layer temperature in Lake Licheńskie in the summer period of recent years had decreased by about 3.5°C; however, this was still an average of 3°C higher in comparison to that in Lake Ślesieńskie and 2°C in comparison to that in Lake Gośląskie. The heating of the waters by the power plants did not cause significant changes in the content of dissolved oxygen. The thickness of the epilimnion in the stratified, dimictic Lake Ślesieńskie in the summer period was an average of 6 m. Changes in oxygen content in the vertical profile was described generally by the clinograde oxygen profile, and sometimes by a negative heterograde with a clearly delineated hypolimnion. The mean oxygen content in the surface water layer of Lake Ślesieńskie was 10.4 mg l⁻¹ (Table 1) and did not exceed 19.9 mg l⁻¹. The mean water temperature during the study period increased to 13.4°C (Table 1) and did not exceed 26.4°C. At the peak of the summer stagnation period, the average temperature of the surface water layer was 21.4°C, while in the near-bottom layer it was 5.0°C (Table 2). The oxygen content in the surface water layer did not exceed 9.0 mg l⁻¹ (100.8% oxygen saturation), while in the near-bottom layer it decreased to trace amounts (Table 2).

Throughout the hydrological system, the surface water layer pH was alkaline, and relatively stable. The highest value was noted in Lake Gośląskie (8.5) and the lowest (8.1) in the Struga Biskupia and Warta-Gopło Canal (Table 1). The highest pH values, simultaneously with trace amounts of carbon dioxide, occurred in the surface water layers during the spring-summer period when phytoplankton

Table 1
 Variability (mean \pm SD) of basic physicochemical parameters in the surface water layers in lakes Licheńskie, Ślesieńskie, and Gosławskie and the water uptake and discharge canals in 1995-2010. KPP – Konin Power Plant, PPP – Pątnów Power Plant

Parameter	Lake									
	Water recirculation canal system					External supply				
	Gosławskie	Licheńskie	Ślesieńskie	KPP inlet cold canal	KPP warm discharge canal	PPP warm discharge canal	Licheński Canal	Struga Biskupia	Warta-Gopło Canal	
T (°C)	15.4 \pm 6.8	17.4 \pm 7.4	13.4 \pm 7.6	14.8 \pm 7.1	20.8 \pm 6.6	21.3 \pm 6.1	20.2 \pm 6.5	12.7 \pm 6.8	14.9 \pm 6.9	
O ₂ (mg l ⁻¹)	10.4 \pm 2.2	9.3 \pm 2.1	10.4 \pm 2.6	10.3 \pm 2.4	9.0 \pm 1.8	8.9 \pm 1.6	8.3 \pm 1.8	10.2 \pm 2.1	8.8 \pm 2.8	
O ₂ (%)	102.0 \pm 16.2	92.0 \pm 19.8	97.7 \pm 22.7	99.3 \pm 16.3	98.2 \pm 11.9	98.4 \pm 11.3	88.6 \pm 14.2	93.7 \pm 11.7	85.4 \pm 23.3	
CO ₂ (mg l ⁻¹)	0.6 \pm 0.2	1.5 \pm 1.8	1.9 \pm 1.4	1.2 \pm 0.9	1.4 \pm 1.0	1.4 \pm 1.0	1.9 \pm 1.5	5.5 \pm 3.6	4.5 \pm 3.7	
pH	8.5 \pm 0.2	8.4 \pm 0.2	8.4 \pm 0.3	8.4 \pm 0.2	8.3 \pm 0.2	8.4 \pm 0.2	8.3 \pm 0.2	8.1 \pm 0.2	8.1 \pm 0.3	
Ca ²⁺ (mg l ⁻¹)	75.2 \pm 10.3	72.6 \pm 9.8	68.1 \pm 8.1	71.1 \pm 8.0	72.9 \pm 9.7	74.2 \pm 10.0	73.0 \pm 8.6	108.5 \pm 16.6	74.9 \pm 8.3	
Mg ²⁺ (mg l ⁻¹)	27.3 \pm 2.8	27.8 \pm 2.8	27.8 \pm 3.0	27.6 \pm 2.8	27.5 \pm 2.7	27.5 \pm 3.0	27.5 \pm 2.9	23.9 \pm 5.3	27.0 \pm 4.1	
K ⁺ (mg l ⁻¹)	6.9 \pm 1.7	6.4 \pm 1.3	6.3 \pm 1.4	6.4 \pm 1.4	6.3 \pm 1.2	6.3 \pm 1.3	6.3 \pm 1.3	4.7 \pm 1.0	7.8 \pm 2.0	
Na ⁺ (mg l ⁻¹)	22.8 \pm 4.3	22.3 \pm 3.5	22.0 \pm 3.4	22.0 \pm 3.2	22.0 \pm 3.6	21.9 \pm 3.4	21.6 \pm 3.1	13.7 \pm 1.8	29.0 \pm 6.3	
CO ₃ ²⁻ (mg l ⁻¹)	0.6 \pm 0.3	3.8 \pm 2.9	4.5 \pm 4.4	3.6 \pm 2.0	3.3 \pm 2.6	3.5 \pm 2.7	3.1 \pm 2.0	0.9 \pm 0.7	4.5 \pm 3.7	
HCO ₃ ⁻ (mg l ⁻¹)	297.7 \pm 30.1	281.3 \pm 27.4	263.1 \pm 29.0	280.0 \pm 25.5	282.7 \pm 25.2	286.6 \pm 30.3	289.2 \pm 27.5	348.1 \pm 41.9	303.2 \pm 34.0	
Cl ⁻ (mg l ⁻¹)	18.4 \pm 3.3	17.7 \pm 3.6	18.1 \pm 3.8	17.6 \pm 3.6	17.2 \pm 2.9	17.3 \pm 3.1	17.6 \pm 3.9	11.1 \pm 3.4	23.8 \pm 6.2	
SO ₄ ²⁻ (mg l ⁻¹)	83.0 \pm 17.3	75.3 \pm 14.0	73.5 \pm 12.4	74.6 \pm 13.2	74.1 \pm 12.1	76.1 \pm 13.2	75.0 \pm 13.4	99.7 \pm 35.3	86.1 \pm 15.9	
Fe _{tot} (mg l ⁻¹)	0.035 \pm 0.030	0.026 \pm 0.017	0.016 \pm 0.011	0.025 \pm 0.016	0.030 \pm 0.024	0.028 \pm 0.015	0.035 \pm 0.022	0.125 \pm 0.120	0.185 \pm 0.084	
SiO ₂ (mg l ⁻¹)	10.3 \pm 3.6	8.6 \pm 3.4	6.1 \pm 3.4	7.8 \pm 3.5	8.4 \pm 3.6	9.1 \pm 4.0	8.8 \pm 3.5	17.2 \pm 3.6	8.8 \pm 3.2	
Conductivity (µS cm ⁻¹)	552 \pm 58	577 \pm 65	552 \pm 58	566 \pm 63	571 \pm 61	576 \pm 64	573 \pm 64	650 \pm 93	648 \pm 70	

Table 2

Variability (mean \pm SD) basic physicochemical parameters in the surface and near bottom water layers in 1995-2010 in the summer period (May-September) in lakes Licheńskie, Ślesieńskie, and Goślawskie

Parametr	Lake Goślawskie	Lake Licheńskie		Lake Ślesieńskie	
	surface	surface	bottom	surface	bottom
T (°C)	21.4 \pm 3.6	23.8 \pm 3.1	14.9 \pm 3.3	21.4 \pm 3.1	5.0 \pm 0.6
O ₂ (mg l ⁻¹)	9.1 \pm 1.5	8.7 \pm 1.4	1.1 \pm 0.6	9.0 \pm 1.3	0.6 \pm 0.3
O ₂ (%)	101.5 \pm 17.4	98.2 \pm 22.5	10.9 \pm 7.9	100.8 \pm 16.3	4.5 \pm 2.8
CO ₂ (mg l ⁻¹)	0.4 \pm 0.1	1.3 \pm 0.8	10.8 \pm 6.2	1.2 \pm 0.7	15.8 \pm 8.6
pH	8.5 \pm 0.2	8.4 \pm 0.3	7.8 \pm 0.3	8.5 \pm 0.3	7.6 \pm 0.2
Ca ²⁺ (mg l ⁻¹)	69.1 \pm 8.4	66.4 \pm 7.6	74.8 \pm 10.6	65.2 \pm 6.2	74.5 \pm 7.9
Mg ²⁺ (mg l ⁻¹)	27.2 \pm 3.1	27.8 \pm 2.7	27.7 \pm 2.0	27.5 \pm 2.1	27.7 \pm 3.5
K ⁺ (mg l ⁻¹)	6.7 \pm 1.5	6.5 \pm 1.4	6.5 \pm 1.3	6.2 \pm 1.2	6.5 \pm 1.2
Na ⁺ (mg l ⁻¹)	22.5 \pm 4.2	22.5 \pm 4.0	21.8 \pm 4.0	22.1 \pm 3.7	22.1 \pm 4.3
CO ₃ ²⁻ (mg l ⁻¹)	0.4 \pm 0.1	4.2 \pm 2.5	0.8 \pm 0.4	6.1 \pm 4.6	0.3 \pm 0.1
HCO ₃ ³⁻ (mg l ⁻¹)	277.9 \pm 24.8	263.9 \pm 23.7	325.1 \pm 41.0	251.5 \pm 22.4	312.0 \pm 28.9
Cl ⁻ (mg l ⁻¹)	18.7 \pm 3.3	19.0 \pm 4.3	17.5 \pm 3.7	18.9 \pm 5.0	18.8 \pm 3.9
SO ₄ ²⁻ (mg l ⁻¹)	81.0 \pm 16.9	77.1 \pm 15.8	67.5 \pm 19.4	77.6 \pm 14.8	73.3 \pm 15.7
Fe _{tot} (mg l ⁻¹)	0.031 \pm 0.027	0.025 \pm 0.016	0.059 \pm 0.051	0.016 \pm 0.010	0.047 \pm 0.028
SiO ₂ (mg l ⁻¹)	9.1 \pm 2.9	8.4 \pm 1.9	14.6 \pm 4.0	5.9 \pm 2.5	11.4 \pm 3.2
Conductivity (μ S cm ⁻¹)	623 \pm 51	574 \pm 67	604 \pm 78	553 \pm 56	603 \pm 59

production increased. However, the highest concentrations of carbon dioxide (up to 50.0 mg l⁻¹) occurred in summer in the near-bottom water layer when the water pH decreased to less than 8.0 (Table 2).

The mean annual content of calcium ions in the 1995-2010 period in the studied lakes was similar (Fig. 2a). In the surface water layers it fluctuated between 68.1 and 75.2 mg l⁻¹ (maximum 117.0 mg l⁻¹), and in the system canals between 71.1 and 74.2 mg l⁻¹. Higher calcium ion values were noted only in the Struga Biskupia (mean 108.5 mg l⁻¹; Table 1) at a maximum of 149.0 mg l⁻¹. During the summer, the mean calcium concentration did not differ substantially from the annual mean, but the maximum calcium concentration increased in the surface (to 97.8 mg l⁻¹) and near-bottom (to 117.4 mg l⁻¹) layers.

The mean concentration of magnesium in the surface water layer throughout the system was at a similar level of approximately 28 mg l⁻¹ (Fig. 2b), and it comprised about 40% of the ion concentration in the water. Smaller values of approximately 24 mg

l⁻¹ were only noted in the Struga Biskupia (Table 1). During the summer, no significant differences were noted in magnesium concentrations between the surface and near-bottom water layers in the studied lakes (Table 2). The mean concentrations of sodium and potassium in the surface water layers of the system were similar and were stable at levels of 22.0 mg l⁻¹ and 6.0 mg l⁻¹ (Tables 1, 2). Higher concentrations of these ions were confirmed consistently in the waters of the Warta-Gopło Canal (7.8 mg l⁻¹ and 29.0 mg l⁻¹), while lower values were noted in the Struga Biskupia (4.7 mg l⁻¹ and 13.7 mg l⁻¹, Table 1).

The mean concentration of hydrocarbonate in the surface water layers of the system fluctuated from 263.1 (Lake Ślesieńskie, Fig. 2c) to 348.1 mg l⁻¹ (Struga Biskupia), while carbonate did not exceed 4.5 mg l⁻¹ (Table 1). The content of hydrocarbonate comprised about 70% of the dissolved ion concentration in the water. Hydrocarbonate concentrations in the near-bottom layers of lakes Licheńskie and Ślesieńskie in the summer period increased to 416.0 mg l⁻¹, while those of carbonate did not exceed 11.4

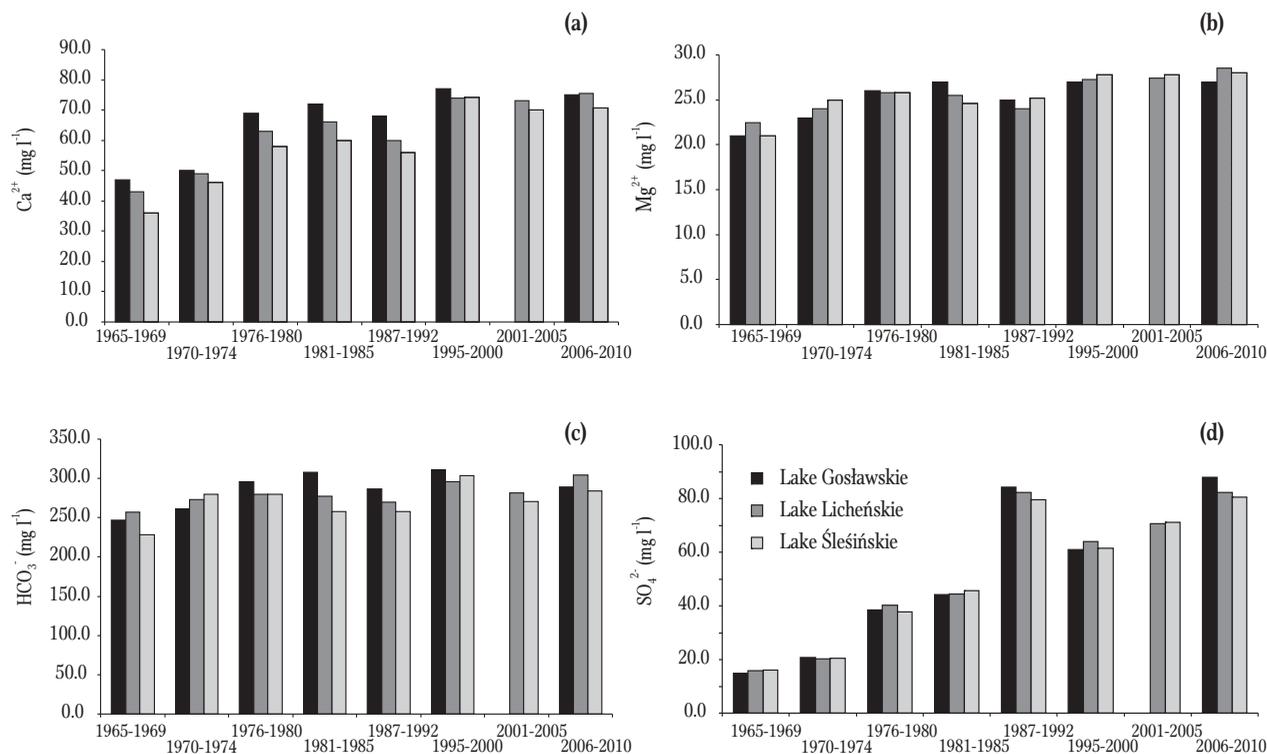


Figure 2. Changes in mean contents of calcium (A), magnesium (B), hydrocarbonate (C), and sulfate (D) in lakes Gosławskie, Licheńskie, and Ślesieńskie in 1965–2010. Data according to Patalas 1970, Zdanowski 1976, 1988, 1994a, Hillbricht-Ilkowska and Zdanowski 1988a, 1988b, Zdanowski et al. 1988, Zdanowski and Prusik 1994.

mg l⁻¹. The mean concentration of sulfide ions in the surface water layers of the system fluctuated from 73.5 mg l⁻¹ (Lake Ślesieńskie, Fig. 2c) to 99.7 mg l⁻¹ (Struga Biskupia, Table 1), and did not exceed 172.0 mg l⁻¹. During the summer, the mean content of sulfate was lower in Lake Licheńskie at 77.1 mg l⁻¹ in the surface water and 67.5 mg l⁻¹ in the near-bottom water layers (Table 2). The content of sulfate comprised about 25% of the dissolved ion concentration in the water. The overall quantity of sulfate in the surface waters of lakes Licheńskie and Ślesieńskie was higher than that in the near-bottom water layer.

The mean concentrations of chloride in the surface water layers of the system during the study period remained at comparable levels of approximately 17–18 mg l⁻¹ (Table 1). Higher concentrations were noted in the waters of the Warta-Gopło Canal (23.8 mg l⁻¹), but those in the Struga Biskupia were two times lower (11.1 mg l⁻¹, Table 1). The mean concentration of chloride ions in the surface and

near-bottom water layers in the lakes in summer were also similar (17–19 mg l⁻¹, Table 2).

Iron was not generally noted in the surface water layers of the system in quantities of more than 0.185 mg l⁻¹ (Table 1), and in the near-bottom water layers in summer it did not exceed 0.859 mg l⁻¹. The concentration of iron ions confirmed in the Warta-Gopło Canal and the Struga Biskupia were several times higher (Table 1). In summer, the surface water layers in lakes Licheńskie and Ślesieńskie were noted to have two- to threefold lower iron concentrations than did the near-bottom layers (Table 2). The contents of silica in the surface layers of the waters studied fluctuated from a mean of 6.1 mg l⁻¹ (Lake Ślesieńskie) to 17.2 mg l⁻¹ (Struga Biskupia, Table 1), and they did not exceed 26.9 mg l⁻¹. Twofold higher concentrations of silica were noted in the near-bottom water layers at a maximum of 22.9 mg l⁻¹ in summer in the waters of the lakes studied (Table 2).

Table 3
 Variability (mean \pm SD) of nitrogen and phosphorus in the surface water layers in lakes Licheńskie, Ślesieńskie, and Gosławskie and the water uptake and discharge canals in 1995-2010. KPP – Konin Power Plant, PPP – Pątnów Power Plant

Parameter	Lake					Water recirculation canal system				External supply	
	Gosławskie	Licheńskie	Ślesieńskie	KPP inlet cold canal	KPP warm discharge canal	PPP warm discharge canal	Licheński Canal	Struga Biskupia	Warta-Gopło Canal		
N _{tot} (mg l ⁻¹)	1.35 \pm 0.85	1.12 \pm 0.65	1.16 \pm 0.68	1.23 \pm 0.68	1.21 \pm 0.62	1.19 \pm 0.62	1.22 \pm 0.55	1.27 \pm 0.74	1.60 \pm 0.36		
NH ₄ -N (mg l ⁻¹)	0.08 \pm 0.05	0.07 \pm 0.04	0.08 \pm 0.05	0.08 \pm 0.06	0.08 \pm 0.05	0.08 \pm 0.04	0.09 \pm 0.08	0.14 \pm 0.07	0.38 \pm 0.24		
NO ₃ -N (mg l ⁻¹)	0.24 \pm 0.15	0.20 \pm 0.12	0.19 \pm 0.14	0.18 \pm 0.11	0.24 \pm 0.16	0.24 \pm 0.16	0.23 \pm 0.15	0.29 \pm 0.28	0.27 \pm 0.24		
NO ₂ -N (mg l ⁻¹)	0.010 \pm 0.006	0.013 \pm 0.012	0.009 \pm 0.005	0.011 \pm 0.005	0.015 \pm 0.007	0.013 \pm 0.012	0.015 \pm 0.007	0.207 \pm 0.016	0.032 \pm 0.020		
P _{tot} (mg l ⁻¹)	0.155 \pm 0.091	0.132 \pm 0.075	0.139 \pm 0.071	0.122 \pm 0.033	0.139 \pm 0.082	0.134 \pm 0.075	0.135 \pm 0.075	0.136 \pm 0.061	0.212 \pm 0.204		
PO ₄ -P (mg l ⁻¹)	0.063 \pm 0.034	0.062 \pm 0.031	0.070 \pm 0.041	0.051 \pm 0.032	0.066 \pm 0.034	0.063 \pm 0.034	0.063 \pm 0.030	0.068 \pm 0.029	0.096 \pm 0.037		

The electrical conductivity of the surface water layers of the system ranged from a mean of 552.0 (lakes Gosławskie and Ślesieńskie, Fig. 3) to 650.0 $\mu\text{S cm}^{-1}$ (Struga Biskupia, Table 1), and did not exceed 1007.0 $\mu\text{S cm}^{-1}$. Higher electrical conductivity values (by approximately 100 $\mu\text{S cm}^{-1}$) than those noted in the lakes and the system canals were characteristic of the waters of the Warta-Gopło Canal and the Struga Biskupia (Table 1). During the summer, higher values of this parameter were noted in the waters of Lake Gosławskie than those in lakes Licheńskie or Ślesieńskie (Table 2). As a rule, electrical conductivity in the near-bottom water layers of the lakes was higher in summer at about 600 $\mu\text{S cm}^{-1}$ (Table 2), and it did not exceed 726 $\mu\text{S cm}^{-1}$.

Nitrogen, total phosphorus, and the dissolved mineral fractions thereof were characterized by similar variability in the surface water layers of the lakes in the system and in the power plant uptake and discharge canals in 1995-2010 (Table 3). During the study period, the mean concentration of ammonia nitrogen in the lake surface water layers did not exceed

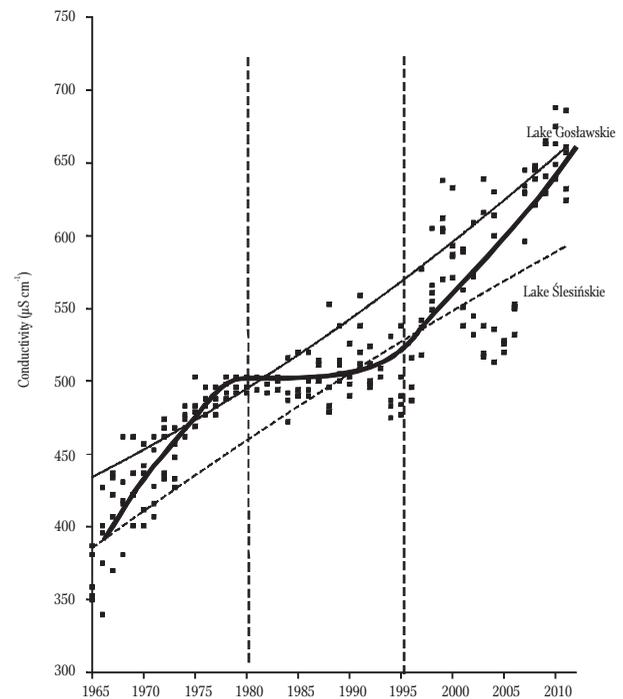


Figure 3. Trends in water salinity changes EC ($\mu\text{S cm}^{-1}$) in the Konin lakes in 1965-2010. Data according to Patalas 1970, Zdanowski 1976, 1988, 1994a, Hillbricht-Ilkowska and Zdanowski 1988a, 1988b, Zdanowski et al. 1988, and data from IFI (unpublished).

Table 4

 Variability (mean \pm SD) of nitrogen and phosphorus in the surface and near bottom water layers in 1995-2010 in the summer period (May-September) in lakes Licheńskie, Ślesieńskie, and Gosławskie

Parameter	Lake Gosławskie	Lake Licheńskie	bottom	Lake Ślesieńskie	surface
	surface	surface		surface	
N_{tot} (mg l ⁻¹)	1.10 \pm 0.49	0.98 \pm 0.43	2.40 \pm 1.51	0.94 \pm 0.35	2.45 \pm 0.69
NH ₄ -N (mg l ⁻¹)	0.08 \pm 0.05	0.07 \pm 0.04	1.32 \pm 1.18	0.08 \pm 0.05	1.48 \pm 0.49
NO ₃ -N (mg l ⁻¹)	0.14 \pm 0.07	0.10 \pm 0.04	0.10 \pm 0.03	0.05 \pm 0.03	0.08 \pm 0.03
NO ₂ -N (mg l ⁻¹)	0.006 \pm 0.004	0.013 \pm 0.007	0.049 \pm 0.017	0.006 \pm 0.003	0.016 \pm 0.005
P _{tot} (mg l ⁻¹)	0.162 \pm 0.128	0.142 \pm 0.115	0.571 \pm 0.294	0.133 \pm 0.105	0.510 \pm 0.467
PO ₄ -P (mg l ⁻¹)	0.050 \pm 0.023	0.055 \pm 0.022	0.481 \pm 0.272	0.049 \pm 0.024	0.379 \pm 0.081

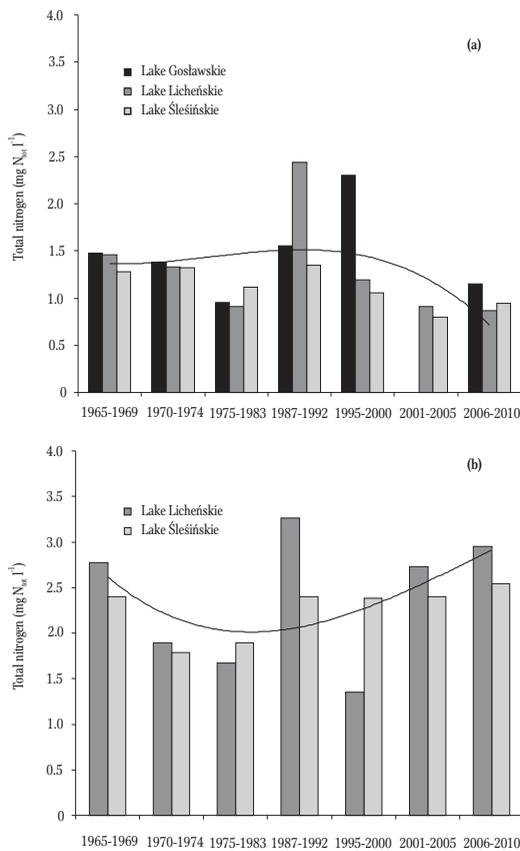


Figure 4. Mean contents of total nitrogen in surface (A) and near-bottom (B) water layers in lakes Gosławskie, Licheńskie, and Ślesieńskie in summer (May-September) in 1966-2010. Data according to Patalas 1970, Zdanowski 1976, 1988, 1994a, Hillbricht-Ilkowska and Zdanowski 1988a, 1988b, Zdanowski et al. 1988, Pyka et al. 2007.

0.08 mg l⁻¹, while the content of nitrate did not exceed 0.24 mg l⁻¹ (Table 3). In the last decade of the study period, a decrease in the concentration of total nitrogen was noted in the surface water layers to a mean of 1.00 mg l⁻¹, while a twofold increase in total

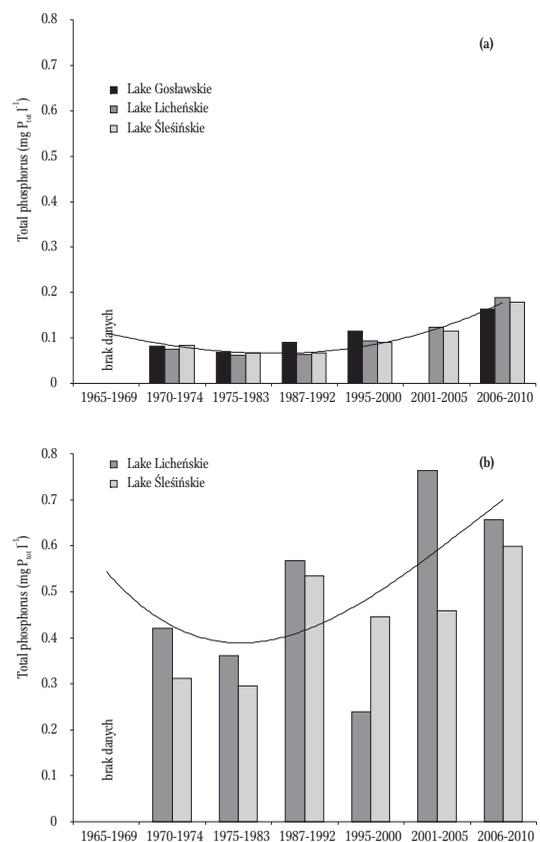


Figure 5. Mean contents of total phosphorus in surface (A) and near-bottom (B) water layers in lakes Gosławskie, Licheńskie, and Ślesieńskie in summer (May-September) in 1970-2010. Data according to Patalas 1970, Zdanowski 1976, 1988, 1994a, Hillbricht-Ilkowska and Zdanowski 1988a, 1988b, Zdanowski et al. 1988, Pyka et al. 2007.

phosphorus to a mean of 0.200 mg l⁻¹ was noted (Fig. 4 and 5). Higher values of nitrogen and phosphorus were always noted in the Warta-Gopło Canal and in the Struga Biskupia (Table 3). The dominant form of these nutrients during the summer was organic

nitrogen (about 80-90%) and organic phosphorus (about 60%).

During the summer, higher mean concentrations of nitrogen and total phosphorus were noted in the near-bottom water layers of the lakes at maximums of 2.45 mg l^{-1} and 0.571 mg l^{-1} , respectively (Table 4). The dominant forms of nitrogen at the peak of the stagnation period were organic nitrogen (50%) and ammonia (30-50%), and of phosphorus – phosphate (80%). The contents of ammonia nitrogen and phosphate increased during the spring-summer period with increasing oxygen deficits at the bottom at maximums of 4.00 mg l^{-1} and 0.90 mg l^{-1} .

Discussion

The heating of waters by electric power plants did not result in significant changes in the content of dissolved oxygen in the discharge canals in the last period of the study. Variations in thermal conditions and oxygen content mainly occurred in summer in the lakes in layers beneath the epilimnion. Summer water temperature stratification persisted in Lake Licheńskie mainly during the warmest period (Stawecki et al. 2007, 2013). This lake is mixed intensively as a result of its morphometric characteristics and the high water temperatures, which reduce water density and increase the depth of the mixed layer. Despite the more intense movement of water masses, oxygen deficits in the water below 10 m were more pronounced, which indicates a high degree of eutrophication of this lake. Lake Ślesieńskie was partially or totally covered by ice in the winter. Reduced oxygen concentrations in the peak summer stagnation in the deeper layers (below 6 m) could have indicated eutrophication in this lake (Stawecki et al. 2007, 2013).

The salinity of the heated Konin lakes was relatively stable. The basic chemical components of the water varied slightly among the individual lakes and in the power plant uptake and discharge canals. Differences in individual parameters among the lakes were small. The system, which is similar to that of rivers with regard

to the surface water layers, meant that the chemical composition of the studied waters was homogeneous. The contents of calcium and hydrocarbonate comprised about 60-70% of the dissolved ion concentration in the water; thus the waters of the studied lakes were of the hydrocarbonate-calcium type, which is characteristic of the harmonic lakes of the European lowlands (Zdanowski 1982, Korycka 1991, Marszelewski 2005). According to Stangenberg's (1936) assessment criteria of disharmonic and harmonic lake development, the waters of the Konin lakes system are well buffered thanks to the considerable contents of calcium, carbonate, and hydrocarbonate ions.

The greatest increase in electrical conductivity and accompanying increases in the concentrations of calcium, magnesium, hydrocarbonate, and sulfate were noted in the waters after 1970 when all of the lakes were included in the cooling system for the two power plants. This was primarily a consequence of dusts generated by fossil fuel combustion (Korycka and Zdanowski 1976, Zdanowski and Korycka 1976, Zdanowski et al. 1988, Zdanowski and Prusik 1994). Changes in calcium concentrations increased systematically in the 1965-2010 period, and still comprised approximately 50% of the dissolved ion concentration in the water, and in the last decade it was even as much as twice as high (Fig. 2a). No long-term trend of changes were noted in the quantities of magnesium and hydrocarbonate in the Konin lakes (Fig. 2b and 2c). Long-term analyses of changes in sulfate contents in the waters of the system indicate a clear increasing trend. Concentrations of this ion in the last period of the study were fivefold higher than those in the 1965-1969 period (Fig. 2d).

In the 1980-1995 period, following the installation of electrofilters in the power plants, salinity values in the Konin system stabilized. The electrical conductivity of the waters began to increase again by about $150 \mu\text{S cm}^{-1}$ (Fig. 3), the primary reason for this was directing post-mining waters through the Struga Biskupia to Lake Gosławskie, and also from the Warta River waters supplied to the peak station of Lake Pątnowskie (Fig. 1) when water levels were inadequate in the lake system. The quantity of mineral compounds transported with these waters,

mainly of iron, calcium, magnesium, sulfate, and chloride, but also nitrogen and phosphorus, was high and along with dust precipitation these were a significant source of continual increases in mineral salt concentrations and the maintenance of an alkaline water pH throughout the system.

Lake Gosławskie, which receives the largest load of pollution from the catchment mainly from the waters that flow through the Struga Biskupia, has always had the highest electrical conductivity, while Lake Ślesieńskie, which is located the farthest from dust emission and receives the smallest load of post-cooling waters, has always had the lowest. Changes in the chemical composition of Lake Gosławskie waters, as well as those of the rest of the lakes in the system because they are connected and water is exchanged, still depended on the inflow of mineral salts from the catchment. Despite the significant inflow of sulfate, the qualitative characters of the water were still determined by the high contents of calcium and hydrocarbonate in comparison to other ions.

Increased temperature, intense mixing, and high rates of exchange in the waters in and among the lakes in the first years that the cooling system was in operation supported eutrophication, which was noted primarily in summer plankton blooms. Decreases in trophic status in subsequent years (1970-1985), which were manifested as decreasing quantities of nutrients, was linked with sedimentation and processes that bind phosphorus to calcite, apatite, and fluoroapatite. Increasing water salinity and constantly high pH > 8.30 balanced the loads of phosphorus introduced into the lakes, thereby reducing its availability to algae (Zdanowski 1988, Zdanowski et al. 1988, Hillbricht-Ilkowska and Zdanowski 1988a). The analyses of long-term changes in the mean total nitrogen content of the surface water layers in the lakes studied confirmed progressive decreases in concentrations of it in recent years (mean to 1.2 mg l^{-1}). The mean content of total phosphorus in this same period, however, increased systematically to a mean of 0.142 mg l^{-1} (Fig. 4 and 5). In the 1965-1983 period, the mean concentrations of total nitrogen and phosphorus in the

near-bottom water layers decreased to 1.70 mg l^{-1} and 0.30 mg l^{-1} , respectively, while from 1987, they increased twofold to 3.00 mg l^{-1} and 0.65 mg l^{-1} , respectively (Fig. 4 and 5). Currently, the quantities of nitrogen and phosphorus in the lakes studied are characteristic of moderately eutrophic basins (Zdanowski 1982, Kufel 2000, 2001). The low ratio values of N:P (8-9) indicate that the waters are richer in phosphorus and that nitrogen plays a limiting role in the development of phytoplankton. Increased phosphorus resources in the waters indicated the decreased effectiveness of phosphorus precipitation to the sediments in the form of sparingly soluble calcium-related compounds. Consequently, under conditions of increased water retention in the lakes and decreased water exchange among the lakes, primary production in these lakes will increase, and phenomena associated with strong eutrophication will intensify.

Water circulation in the system, which includes water exchange and short retention times in the lakes, also had a decisive impact on the sedimentation of organic matter mainly in the profundal zones of the lakes. Preliminary tests of the chemical composition of the sediments from the lakes indicated that the dominant quantitative components were calcium and carbonate (up to 70% dry weight) that were deposited as calcium carbonate, and also silica, and the majority of sedimented phosphorus was bound permanently in virtually insoluble fractions. The organic matter content did not exceed 15% dry matter (Brzozowska et al. 2007, Hutorowicz et al. 2007).

Increased temperatures and frequent changes in hydrological conditions from, among other factors, increased flow and changes in water retention times in the lakes, could support continued rapid metabolic rates of organic matter in the studied lakes, which would limit mass phytoplankton blooms. As a result of microbiological decomposition and biotransformation of organic matter, the lakes examined in this study, analogously to other aquatic ecosystems (Cole et al. 1994, 2000, Duarte and Prairie 2005, Kosten et al. 2010), could become sources of free carbon dioxide and nitrogen compound

atmospheric emissions, and, thus, contribute to the greenhouse effect.

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