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RESEARCH ARTICLE

Long-term changes in post-cooling water loads from power plants and thermal and oxygen conditions in stratified lakes

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Abstract. Trends in thermal and oxygen conditions were identified in three stratified lakes that are part of the cooling system of two Power Plants. The total water uptake and discharge by the power plants decreased from approximately 60.0 $m^{-3}s^{-1}$ in 1995-1999 to approximately 50.0 $m^{-3}s^{-1}$ in 2005-2010, while, simultaneously, the degree of water heating decreased. Changes in the hydrological conditions influenced an increase in the mean and maximum water retention times in the lakes. Decelerated water flow rates and lower inertia decreased the thickness of the epilimnion and water temperature and oxygen content in Lake Licheńskie, the shallowest of the lakes studied. Oxygen conditions deteriorated in the deeper, isolated waters of Lake Ślesińskie. The more advantageous morphometric conditions in Lake Mikorzyńskie contributed to improved oxygen conditions in the near-bottom water layer and decreased levels of oxygen deficits in the spring-summer period.

Keywords: lake, heated waters, temperature, oxygen, oxygen deficits

Introduction

Most lakes in the temperate zone are either dimictic or polymictic. Lake basin shape only determines the type, frequency, and effective range of mixing, which has a direct impact on oxygen resources in the metalimnion and hypolimnion (Olszewski et al. 1978). The type of mixing also impacts matter cycling and the functioning of individual elements of the biotic structure in lakes (Hillbricht-Ilkowska and Zdanowski 1988a, 1988b, Mitchell et al. 1996, Kentzer 2001, Zdanowski et al. 2002, Kubiak 2003, Marszelewski 2005). Discharges of heated waters into lakes disrupts the natural thermomictic conditions, increases evaporation, accelerates matter cycling rates, and alters environmental conditions (Dunstall et al. 1985, Socha and Zdanowski 2001).

Among the Konin lakes located in the Wielkopolsko-Kujawskie lake district, the primary recipient of post-cooling waters was Lake Licheńskie, which was connected to the cooling system in 1958. One third of the waters from the Pątnów Power Plant (PPP) are discharged into this lake and slightly more than half of those from the Konin Power Plant (KPP). Lake Mikorzyńskie, which received close to 20 and 30% of the waters discharged from the two power plants, received waters year round. Lake Ślesińskie, which is part of the long cooling circuit, has been part of the cooling system since 1970, but it is only used to increase the effectiveness of the system during the warmest time of the year, which is usually from May to September (Zdanowski 1994a, Stawecki et al. 2007). Studies to date indicate that

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Table 1
Morphometric and limnological characteristics of the lakes

Parameter	Lake		
	Licheńskie	Ślesińskie	Mikorzyńskie
Surface area (ha)	153.6	148.1	254.3
Maximum depth (m)	13.3	25.7	38.0
Mean depth (m)	4.9	7.5	11.9
Volume (thou. m3)	7471.4	11072.7	29290.6
Maximum length (km)	5.53	4.39	6.62
Maximum width (km)	0.52	0.62	1.01
Coefficient of shoreline development	2.98	2.52	2.52
Theoretical reach of mixing* (m)	5.4	5.4	5.9
Limnological type	monomictic	dimictic	dimictic
Surface area of active bottom (%)	90	35	55
Mean Secchi disk transparency in summer (m)**	1.7	2.3	1.8
Mean chlorophyl (μg l^{-1}) in the epilimnion**	20.6	16.0	16.9
Trophic type	eutrophic	eutrophic	meso-eutrophic
Post-cooling water supply	year-long surface supply	periodic cascade discharge	year-long surface supply

*E =√ 4.4; where D = mean effective length and width of the lake; data from Zdanowski and Korycka (1976), Zdanowski (1994a), Socha and Zdanowski (2001), Stawecki et al. (2007); ** data from IFI Olsztyn from 1995-2010 for lakes Licheńskie and Ślesińskie and from 2003 and 2007-2010 for Lake Mikorzyńskie.

the fast water exchange rate in this ecosystem, which limits water retention times in these lakes, has had a decisive impact on eutrophication (Piotrowska and Przybiński 1991, Zdanowski et al. 1992, Zdanowski 1994b, Socha and Zdanowski 2001, Pyka et. al. 2007, Napiórkowska-Krzebietke 2009) and on the composition and dynamics of invertebrate and fish assemblages (Tereshchenko et al. 2007, Ciemiński and Zdanowski 2009, Bogacka-Kapusta and Kapusta 2013). The aim of the study was to identify thermal and oxygen trends that occur in stratified lakes under the influence of changing thermal and hydrological conditions and also to identify the consequences on their structure and functioning.

Materials and methods

The study was conducted in three stratified lakes in the Konin ecosystem – Licheńskie, Ślesińskie, and Mikorzyńskie, which differ significantly in morphometric, limnological, and trophic parameters, hydrological regime, the degree to which they are heated, and how post-cooling waters are discharged into them (Table 1). Lake Licheńskie, the shallowest of the studied lakes, received the largest load of post-cooling waters and was heated year round. Intense water exchange and shallow depth meant that the lake was monomictic with partial layering in summer, and approximately 90% of the total bottom surface area was within the range of the epilimnion. The two other lakes were dimictic. Lake Mikorzyńskie received a smaller quantity of discharge water. It is the deepest lake in the system, and the share of active bottom was barely 35%. Lake Ślesińskie was included in the power plant long cooling circuit only during the summer, usually from May to September, but from June to August in 2007-2010. This lake is supplied by waters passing over a cascade from Lake Licheńskie, which means that summer water stratification is disrupted locally. The surface area of the active bottom was 55% of the total bottom surface area (Zdanowski and Prusik 1994, Zdanowski et al. 2002, Stawecki et al. 2007; Table 1).

The mean quantity of post-cooling waters discharged into the system from PPP was about 40.0 m^3 s^{-1}, while that from KPP has decreased in recent years about twofold and was 10.8 m^3 s^{-1}.

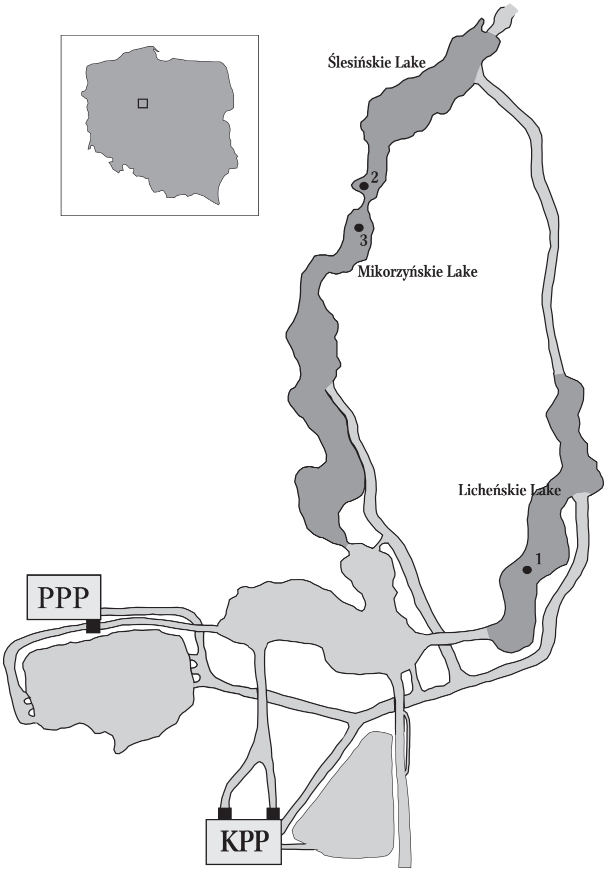

Figure 1. Study area and location of sampling sites.

Simultaneously, the long cooling circuit was used less frequently during this period, and the mean quantity of post-cooling waters pumped from Lake Licheńskie to Lake Ślesińskie decreased from 8.0 to 3.3 $m^3 s^{-1}$ (Table 2). The mean degree of water heating by KPP (4.3°C) and PPP (6.4°C) was lower near the end of the study period by 2.8 and 1.3°C, respectively, than it had been in the 1990s (Zdanowski 1994a, Socha and Zdanowski 2001). The mean concentration of oxygen in the waters of the canals supplying both power plants remained higher than that at discharge at 10.0 compared to 9.4 mg O_2 dm^{-3} and 9.6 compared to 8.7 mg O_2 dm^{-3} at KPP and PPP, respectively. Saturation increased from 96.9 to 102.0 % and from 90.8 to 97.0%, respectively.

The study was based on physicochemical data from the Inland Fisheries Institute in Olsztyn (IFI Olsztyn) from 1995-2010 which was divided into three periods – 1995-1999 (period I), 2000-2004 (period II), and 2005-2010 (period III). These materials were supplemented by unpublished environmental monitoring data collected by the Pątnów-Adamów-Konin Power Plant Group (PAK PPG) in Konin and included infrared aerial photographs, air temperature data from the meteorological station in Gosławice, and the actual quantities of water uptake and discharge in the cooling system. These data were used to calculate water retention time in the lakes, assuming that only water in the epilimnion layer was exchanged during the summer stagnation period.

Field work was conducted with a frequency of up to twelve times annually at stations located in the deepest parts of lakes Licheńskie (station 1) and Ślesińskie (station 2), and in Lake Mikorzyńskie (station 3) in a deep area located in the north near the connection with Lake Ślesińskie in 2003 and 2007-2010 (Fig. 1). Temperature and oxygen content measurements were taken in water layers from the surface to the bottom at 1 m intervals with a YSI 58 dissolved oxygen meter, and transparency was measured with a Secchi disk. The hypolimnetic oxygen deficits in the deeper lakes Ślesińskie and Mikorzyńskie were calculated with the method proposed by Hutchinson (Patalas 1960). Deficit values below 0.033 mg O_2 cm^{-2} d^{-1} indicated oligotrophy, from 0.033 to 0.050 mg O_2 cm^{-2} d^{-1} – mesotrophy, and from 0.050 to 0.140 mg O_2 cm^{-2} d^{-1} – eutrophy.

Results

The coldest month of the year was January with a long-term, mean air temperature of 1.0°C, while the warmest months were July and August at 26.9 and 25.7°C, respectively. The lowest air temperature was -8.0°C in November 1998, and the highest at 36.8°C was in July 2007. The greatest mean increase in air temperature occurred between April and May, while the greatest decrease was between September and October. The mean annual air temperature increased from 12.9°C in 1995-1999 to 15.1°C in the last period of the study (Fig. 2).

Ice cover on Lake Licheńskie (station 1) occurred sporadically for short periods and usually only in the

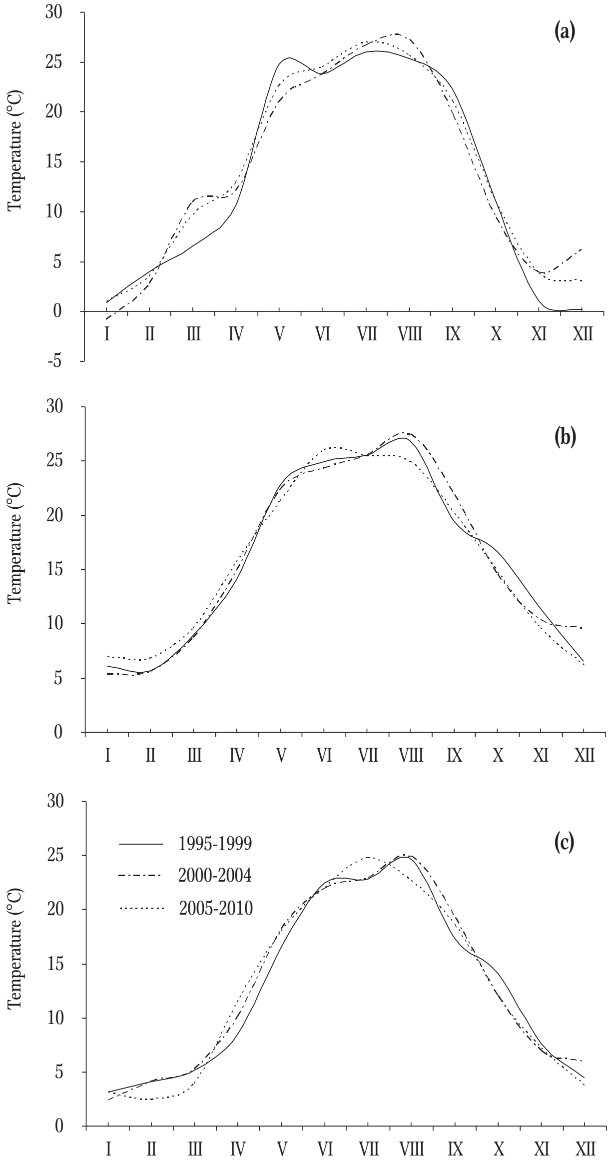

Figure 2. Seasonal variation in the mean air temperature (a) and mean surface water temperature of lakes Licheńskie (b) and Ślesińskie (c) in the 1995-2010.

northern stagnant area. Only in February 2010 did the lake freeze over completely with the exception of the vicinity of the Licheńskie Canal mouth. In the spring months of March and April, the water temperature in the vertical profile did not usually exceed 8.5°C. During this time, the highest oxygen content was usually noted in the surface and near-bottom water layers, respectively, at means of up to 10.5 mg O_2 l^{-1} and 102% saturation and 6.1 mg O_2 l^{-1} and 53% saturation, with maximum values of up to 16.0 mg O_2 l^{-1} and 140% saturation and 14.0 mg O_2 l^{-1} and 120% saturation. The summer stratification occurred late usually by the end of May, but sometimes not until July.

Generally, the clinograde oxygen curve described the vertical oxygen content distribution in the waters of Lake Licheńskie. The maximum heating of surface waters of up to 30.1°C was usually noted in August. The thickness of the epilimnion in period I of the study was usually 8-9 m, and in later periods it decreased to 6-7 m, which was about 95 and 80% of the total volume of lake waters, respectively. The average oxygen content in this layer in summer did not exceed 8.7 mg O_2 l^{-1} and 98% saturation, and the oxygenated (< 1.0 mg O_2 l^{-1}) thermocline layer beneath it usually reached the bottom. Sporadically, the hypolimnion was not very thick (Table 3, Fig. 3). Water mixing usually began in September of October often at water temperatures that exceeded 20°C, and this continued until the subsequent year, and this scenario was noted in September in 1995, 1999, and 2004. Circulation was usually accompanied by equalized temperatures and oxygen content in the vertical profile.

Table 2

Mean quantities (range) (m^3 s^{-1}) of post-cooling waters discharged from the Power Plants into the cooling system and from Lake Licheńskie to Lake Ślesińskie in 1995-2010

	Discharge of heated waters		
Period	Pątnów Power Plant	Konin Power Plant	into Lake Ślesińskie*
1995-1999	40.0 (34.1-46.0)	20.4 (19.2-21.9)	8.0 (2.1-11.1)
2000-2004	41.0 (36.1-44.7)	16.6 (15.3-18.2)	6.4 (1.2-8.6)
2005-2010	40.4 (36.1-42.9)	10.8 (9.8-12.6)	3.3 (0.1-8.4)

*when the long cooling circuit is in operation

Table 3
Mean (± SD) water temperature, oxygen content, and oxygen saturation in the surface and near-bottom water layers in lakes Licheńskie, Ślesińskie, and Mikorzyńskie in the summer periods of 1995-2010

		Lake Licheńskie		Lake Ślesińskie		Lake Mikorzyńskie*	
Parameter	Period	surface	bottom	surface	bottom	surface	bottom
T (°C)	1995-1999	24.9 ±2.3	16.6 ±4.6	21.0 ±5.0	5.2 ±0.8	nd**	nd**
	2000-2004	24.9 ±2.5	12.6 ±1.1	21.9 ±3.1	4.8 ±0.5	23.9 ±2.3	5.1 ±0.1
	2005-2010	24.2 ±3.6	12.9 ±1.8	21.3 ±3.6	5.0 ±0.7	23.3 ±2.6	5.2 ±0.4
O_2 (mg l^{-1})	1995-1999	7.7 ±1.5	1.2 ±0.7	8.6 ±0.8	1.8 ±0.8	nd**	nd**
	2000-2004	7.7 ±1.6	0.6 ±0.3	9.2 ±1.0	0.9 ±0.4	8.3 ±0.7	0.7 ±0.4
	2005-2010	8.7 ±1.6	0.7 ±0.4	10.0 ±1.8	0.8 ±0.4	9.1 ±1.8	1.2 0.8
Saturation (%O_2)	1995-1999	93.8 ±11.6	15.0 ±8.6	97.4 ±9.5	17.1 ±8.6	nd**	nd**
	2000-2004	91.3 ±19.6	4.9 ±2.7	101.2 ±9.8	7.1 ±3.4	92.4 ±9.9	5.1 ±3.3
	2005-2010	97.5 ±20.9	6.3 ±3.5	111.0 ±11.8	6.5 ±3.1	102.7 ±23.2	9.6 ±6.2

* data from: 2003 and 2007 to 2010, nd** – no data

The mean annual temperature of the surface water layer in Lake Licheńskie increased from 315.6 in the second half of the 1990s to 16.4°C in the last period. The average oxygen content increased during this time from 8.8 mg O_2 l^{-1} and 88.9% saturation to 9.3 mg O_2 l^{-1} and 91.9% saturation, respectively. The mean temperature and oxygen content in the near-bottom layer decreased from 12.6 to 11.2°C and from 5.9 mg O_2 l^{-1} and 51.7% saturation to 4.6 mg O_2 l^{-1} and about 40% saturation, respectively (Table 4). Lake Licheńskie had a short water retention time which was an average of four days, and in the last period – five days (Table 5). The water exchange time was usually the shortest in May or June, and the longest in fall and winter at two and nine days, respectively.

The mean temperature of the surface water layer in Lake Ślesińskie (station 2) in the different study periods was similar at about 13°C with an average oxygen content that did not exceed 10.5 mg O_2 l^{-1} and 99% saturation. The average, long-term temperature in the near-bottom water layers was consistently below 5°C, while the mean oxygen concentration decreased to 3.3 mg O_2 l^{-1} (25.5% saturation) in the first period and to 2.6 mg O_2 l^{-1} (20.2% saturation) in the last one. Spring circulation was short, and usually lasted from the ice cover melting to the end of March of the middle of April, during which time the water temperature did not exceed 5°C, and mixing was not usually accompanied by full oxygenation in the vertical profile. The average oxygen content in spring in the in the surface water layers was 12.0 mg O_2 l^{-1} (112% saturation), with a maximum of 19.5 mg O_2 l^{-1} (179% saturation). In the near-bottom water layers it was up to 5.7 m O_2 l^{-1} (44% saturation) and 13.8 mg O_2 l^{-1} (108% saturation), respectively. The beginning of summer layering was usually confirmed in April. This was accompanied by a rather thin (3 to 4 m) epilimnion, which, in May, deepened to an average of about five m. The water temperature of this layer in this period fluctuated from 15.0 to 18.3°C, while that in the hypolimnion did not exceed 5.1°C. The average oxygen content decreased from 10.3 at the surface to 6.1 mg O_2 l^{-1} at the bottom (104 and 19% saturation, respectively).

The ratio of oxygen resources in the hypolimnion to those in the epilimnion (O_2 H/E) in Lake Ślesińskie was 0.25, 0.19, and 0.18 at the beginning of the summer stagnation period compared to 0.02, 0.06 and 0.04 at its peak, respectively, in the three subsequent study periods. The hypolimnion surface oxygen deficit was the highest in the spring-summer period and ranged from 0.037 to 0.087 mg O_2 cm^{-2} d^{-1} in 2003 and 2008, respectively, and increased on average from 0.044 in the first period to 0.057 mg O_2 cm^{-2} d^{-1} at the end of the study. In the summers of 1996, 2000, 2004, 2005, and 2006, oxygen resources in the hypolimnion of this lake were depleted

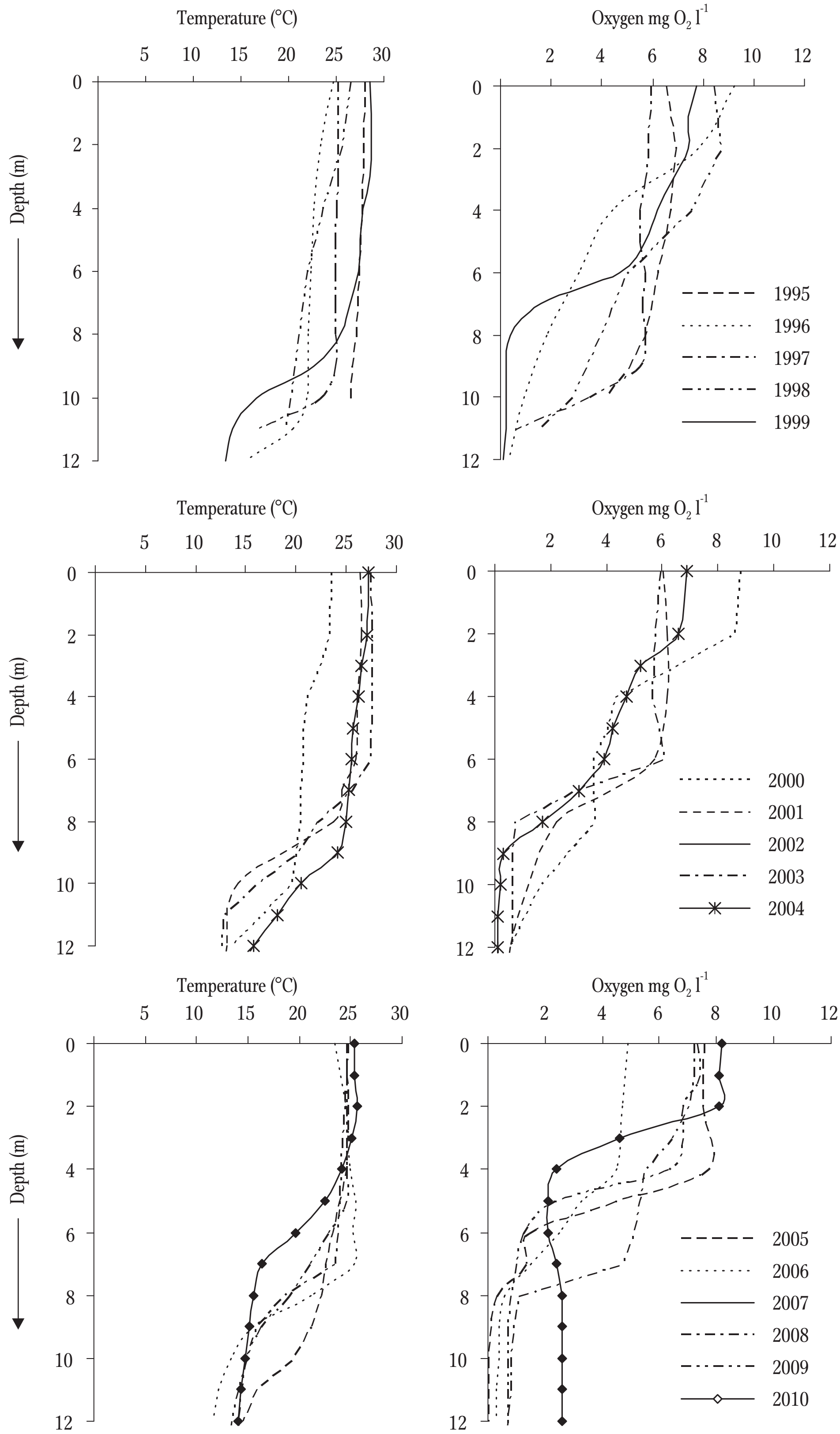

Figure 3. Temperature and oxygen stratification in Lake Licheńskie during summer stagnation (August) in the 1995-2010.

Table 4
Changes (mean ± SD) in temperature, oxygen content, and oxygen saturation in the surface and near-bottom water layers in lakes Licheńskie, Ślesińskie, and Mikorzyńskie in 1995-2010. *data from: 2003 and 2007 to 2010, nd** – no data

		Lake Licheńskie		Lake Ślesińskie		Lake Mikorzyńskie*	
Parameter	Period	surface	bottom	surface	bottom	surface	bottom
T (°C)	1995-1999	15.6 ±8.0	12.6 ±5.6	13.6 ±7.9	4.9 ±0.9	nd**	nd**
	2000-2004	16.3 ±8.0	11.8 ±3.6	13.7 ±8.2	4.7 ±0.5	17.9 ±7.8	5.0 ±0.3
	2005-2010	16.4 ±7.3	11.2 ±3.0	13.4 ±7.8	4.8 ±0.9	14.9 ±8.4	4.9 ±0.8
O_2 (mg l^{-1})	1995-1999	8.8 ±2.1	5.9 ±4.6	10.0 ±2.5	3.3 ±2.7	nd**	nd**
	2000-2004	9.0 ±2.3	4.8 ±3.6	10.4 ±2.9	2.3 ±1.7	9.9 ±3.8	0.7 ±0.3
	2005-2010	9.3 ±1.8	4.6 ±3.0	10.4 ±2.4	2.6 ±1.4	9.9 ±2.5	3.0 ±1.6
Saturation (%O_2)	1995-1999	88.9 ±12.4	51.7 ±27.2	96.1 ±18.9	25.5 ±16.5	nd**	nd**
	2000-2004	91.7 ±19.1	42.8 ±29.1	98.9 ±23.6	19.0 ±10.9	98.2 ±30.5	5.2 ±2.8
	2005-2010	91.9 ±22.6	40.1 ±27.0	98.9 ±25.2	20.2 ±16.4	96.0 ±25.0	23.4 ±17.6

(Fig. 4). At the peak of summer stagnation epilimnion thickness at station 2 increased on average by 6 m, while the surface water layer temperature was the highest at an average of 21.4 and a maximum of 25.7°C (August 2003). The thermocline usually reached depths of 10 to 11 m, and the largest, average thermal gradient (up to 5.9°C m^{-1}) was noted at the border of the epilimnion and metalimnion. The hypolimnion comprised approximately 23% of the lake volume. The clinograde or negative heterograde oxygen curves described changes in oxygen in the vertical profile of Lake Ślesińskie in the summers of 1999, 2001-2003, 2005, 2008, and 2009 (Fig. 4). Fall water mixing usually began in the second half of November. The surface water layer cooled during this time to an average of 6.3°C, while the near-bottom water remained colder (up to 5°C). During this period, the oxygen content at the bottom usually remained at trace amounts (< 1.0 mg O_2 l^{-1}, 2% saturation); only in 2004 was full mixing and homo-oxygenation noted. The oxygen concentration throughout the water mass was at this time about 6.5 mg O_2 l^{-1} (48% saturation). The mean retention time in the the waters of Lake Ślesińskie extended over the long term from 18 to 26 days to a maximum of 36 days. In the summer period after the lake was included in the post-cooling water circuit, the retention time decreased to an average of 7 or 15 days ion the first and third periods, respectively (Table 5).

The average temperature of the surface water layer in Lake Mikorzyńskie (station 3) decreased over the long term to 14.9°C, and it remained stable in summer throughout the study period. The oxygen content at the surface did not exceed 10.0 mg O_2 l^{-1} and 99% saturation, and during the summer stagnation period the mean oxygen concentration in the epilimnion was an average of 9.1 mg O_2 l^{-1}, at a saturation of 103% in recent years. The mean temperature of the near-bottom water layer was about 5°C. The average oxygen concentration increased, however, in the last period to 3.0 mg O_2 l^{-1} (23.4% saturation), and in summer to 1.2 mg O_2 l^{-1} (9.6% saturation) (Tables 3 and 4). Spring circulation usually began in this lake after the ice cover melted, and it usually lasted until the end of March. Mixing was accompanied by equalizing temperatures and oxygen contents throughout the water column. A thin epilimnion occurred in early April, and the temperature of the surface water layer usually already exceeded 12°C, while the oxygen content reached 19.0 mg O_2 l^{-1} (up to 180% saturation). The temperature of the near-bottom layer remained under 5.0°C, and oxygen content usually exceeded 4.0 mg O_2 l^{-1} and 33% saturation. The thickness of the epilimnion and metalimnion in summer was 5 and 7 m, on average, with mean and maximum thermal gradients of 1.9 and 4.2°C m^{-1}. The volume of the hypolimnion was 36% of the total volume of the water basin. At the

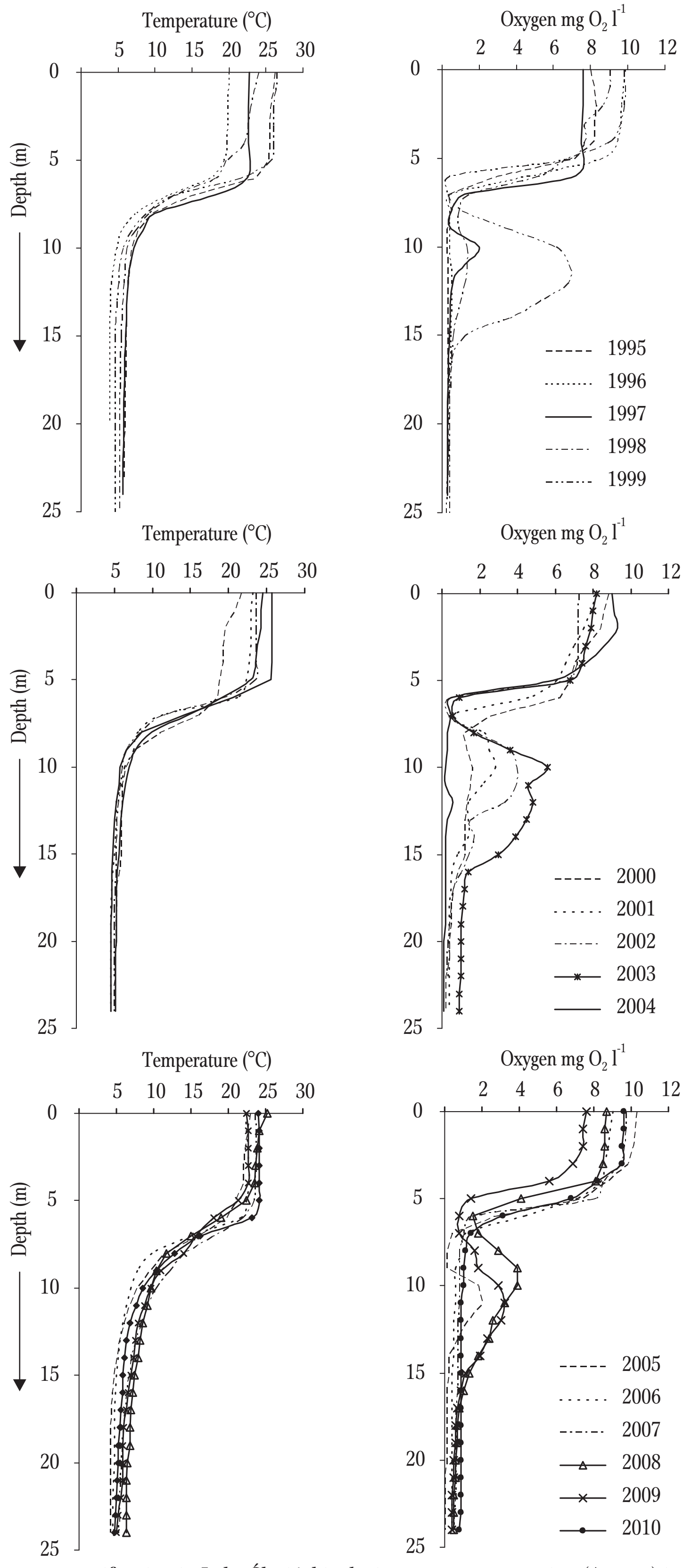

Figure 4. Temperature and oxygen stratification in Lake Ślesińskie during summer stagnation (August) in the 1995-2010.

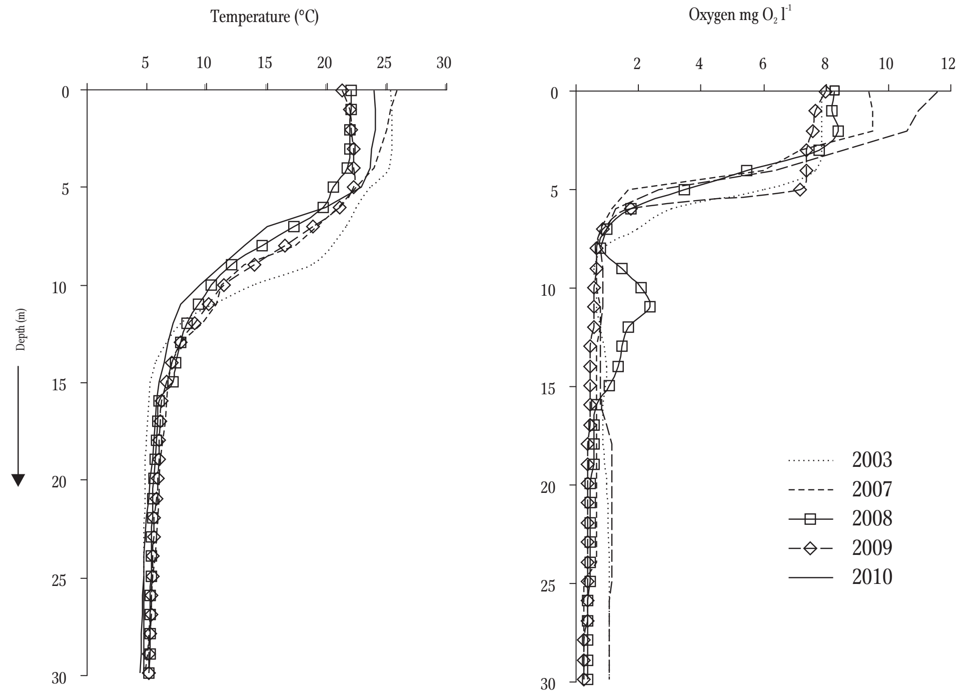

Figure 5. Temperature and oxygen stratification in Lake Mikorzyńskie during summer stagnation (August) in the 2003-2010.

beginning of the summer stagnation in Lake Mikorzyńskie, the hypolimnion to epilimnion oxygen content ratio (O_2 H/E) was an average of 0.59, while at the peak of summer stagnation the O_2 H/E ratio was a mean of 0.07. The oxygen deficit value in the hypolimnion surface in spring decreased from 0.128 mg O_2 cm^{-2} d^{-1} in 2003 to 0.061 mg O_2 cm^{-2} d^{-1} in 2010. As the thermocline developed in the lake, oxygen resources were depleted quickly, and by the end of the summer stagnation oxygen usually occurred in the hypolimnion in trace amounts (<1.0 mg O_2 l^{-1}, 2.5-3% saturation) (Fig. 5, Table 3). The mean water retention time of the waters of Lake Mikorzyńskie lengthened over the long term from 18 to 29 days at a maximum of 59 days. In summer, when water exchange only occurred in the epilimnion, the water retention time was an average of 7 to 13 days (Table 5).

Discussion

Seasonal changes in the Konin lake surface water layer temperatures coincided with annual air temperature changes. More intense water warming was noted in all the lakes in spring from April to May, and quicker cooling was noted in fall between September and October; this was comparable to rhythms typical of temperate zone lakes that are not heated (Patalas 1960).

The quantity and temperature of the post-cooling waters discharged by the Konin and Pątnów power plants generally had an impact on the variation in the thermal conditions in the Konin lakes ecosystem (Stawecki et al. 2007). The highest mean surface water layer temperature throughout the vegetation season and in summer was noted in shallow Lake Licheńskie, which receives heated waters year round, while the lowest value for this parameter was noted in Lake Ślesińskie, which only receives heated waters periodically. The temperatures noted in Lake Mikorzyńskie were usually in between those of the other two lakes. During study period I, the quantities of water power plant uptake and discharge were similar to the those reported in Hillbricht-Ilkowska and Zdanowski (1988a) and Zdanowski and Prusik (1994) in the 1970s and 1980s. In study periods II

Table 5
Mean retention times (range) (days) in the heated Konin lakes in 1995-2010. *data from 2003 and 2007-2010; nd** – no data; summer included, discharges directly into the waters and water flowing from Lake Ślesińskie

	Lake Licheńskie		Lake Ślesińskie		Lake Mikorzyńskie*	
Period	all season	summer	all season	summer	all season	summer
1995-1999	4 (2-5)	4 (2-5)	18 (3-26)	7 (3-10)	nd**	nd**
2000-2004	4 (2-6)	4 (3-5)	20 (4-36)	9 (4-17)	18 (5-32)	7(5-12)
2005-2010	5 (2-9)	4 (2-7)	26 (4-36)	15 (4-34)	29 (6-59)	13 (6-26)

and III, the water requirements of the Pątnów Power Plant fluctuated only slightly, while the quantity the post-cooling waters discharged by the Konin Power Plant decreased significantly as did the use of the long cooling circuit. This resulted in lengthening the mean and maximum retention times in the lakes throughout the season and in the summer, and was particularly evident in the case of Lake Ślesińskie.

The thermal regimes of the lakes studied differ significantly because of the different degrees of heating that stem from how they are used in the power plant cooling circuit (Socha and Zdanowski 2001, Zdanowski et al. 2002, Stawecki et al. 2004) and how they are supplied with post-cooling waters. These waters were discharged into lakes Licheńskie and Mikorzyńskie throughout the year through free-flowing surface canals. The seasonal cascade discharge into Lake Ślesińskie disrupted summer stratification. During the study period, ice cover occurred in winter on Lake Ślesińskie and in the colder, northern part of Lake Mikorzyńskie, while it only occurred in Lake Licheńskie in 2010. Spring mixing in the two lakes was short term, and occurred at low water temperatures from 3.5 to 6.1°C. Summer stratification had begun to form by April, and the relatively warm, shallow epilimnion grew in summer only slightly to obtain a thickness that was similar to the theoretical reach of mixing calculated by Zdanowski and Korycka (1976). The thermocline zone in both lakes was characterized by the occurrence of a significant thermal gradient, and the water temperature in the hypolimnion remained below 5°C. The fall circulation began late, and at it usually was not deep at station 2. These characteristics permit classifying both lakes Ślesińskie and Mikorzyńskie as bradymictic. The thermal and mictic regimes in the shallow Lake Licheńskie were different from those in the other two lakes, because one, long-term period of circulation occurred here usually from September to April or May with one short stagnation period during the warmest time of year. The epilimnion was twofold thicker than that predicted by the theoretical reach of mixing. The continual, year-long input of significant quantities of heated water into this lake (Stawecki et al. 2004, 2007) disrupted thermal layering in spring and summer. The great inertia of the water masses flowing through Lake Licheńskie permitted classifying it as an easily mixed monomictic basin.

The thickness of the epilimnion and the temperature and oxygen content in the near-bottom layer decreased systematically in Lake Licheńskie during periods II and III of the study because of the deceleration and increasing inertia of water inflow. The highest quantities of chlorophyl and the lowest transparency were usually recorded in the surface water layers of this shallow lake (Pyka et al. 2007). However, the continual inflow of well-oxygenated water probably counteracted the destruction of organic matter in this lake, since oxygen occurrence usually covered the entire epilimnion, and summer oxygen deficits in the near-bottom water layer were short term only. This is confirmed by earlier observations that concluded that the flow-through character of the Konin lakes could curb eutrophication in them considerably (Piotrowska and Przybiński 1991, Zdanowski 1994a, Socha and Zdanowski 2001, Zdanowski et al. 2002). It is likely that further reductions in the quantities of the waters discharged from the power plants could result in altered mictic regimes in this lake, i.e.; full water stratification could occur and would lengthen the period of time during which oxygen deficits occur.

The mean temperature of surface and near-bottom waters in Lake Ślesińskie did not differ significantly in the different periods of the study. However, oxygen saturation in the surface water layer has increased in recent years, and especially in summer. The natural direction for water flow from Lake Mikorzyńskie to Lake Ślesińskie (Zdanowski 1994a) switched directions from the moment the long cooling circuit was in operation. This is confirmed by the infrared aerial photographs taken in August of 2003 and 2004 (unpublished data from PAK PPG). The forced flow of substantial quantities of heated water masses across the narrow, shallow connection between the lakes could have caused thermocline erosion at station 2 and increases in the thermal gradient of the uppermost layer. Abrupt increases in water density as depth increased probably caused decreased sedimentation rates. The mineralization of organic matter accumulated in this region at this time caused the depletion of oxygen resources in the metalimnion (transition from a negative heterograde to a clinograde) and the hypolimnion, and, following its depletion, hydrogen sulfide occurred in some years. Relatively small values of the hypolimnion surface oxygen deficit in this lake did not stem just from the slow rate of O_2 usage, but rather from the meager resources of this gas in the near-bottom water layers. In comparison to period I, by the end of the study period the ratio of oxygen content in the hypolimnion to that in the epilimnion decreased by nearly 50%. Previous studies indicate that the periodic cascade discharges of water into Lake Ślesińskie caused local disruptions in stratification and improved oxygen conditions in summer as well as accelerated organic matter mineralization (Stawecki et al. 2007). Limiting the use of the long cooling circuit in recent years resulted in longer water retention times and increased primary production, which could have led to worsening oxygen conditions throughout the lake. Evidence of this could be the lower oxygen concentration and saturation in the near-bottom water layers at station 2 at the end of the study in comparison to period I.

The physicochemical water parameters studied were usually of intermediate values in Lake Mikorzyńskie, which is the deepest of the three lakes studied. This lake had the greatest oxygen resources in the deep, isolated layers, which was supported by the possibility of deeper, longer circulation in fall that was limited sporadically by freezing and the voluminous, cold hypolimnion. The ratio of hypolimnion to epilimnion oxygen content at the beginning of the summer stagnation period was two times higher in this lake than in Lake Ślesińskie (average H/E = 0.59). However, oxygen resources in this lake were also exhausted quickly in summer and the size of the hypolimnion surface layer oxygen deficit from 2003 decreased systematically, while remaining within a range that is typical of eutrophic lakes. The water retention time in Lake Mikorzyńskie in 2003 was close to that reported by Socha and Zdanowski (2001), but in subsequent years it lengthened as a result of the decreasing water flow through the cooling system.

The curtailed use of lakes Ślesińskie, Mikorzyńskie, and Licheńskie in the KPP and PPP water cooling system in recent years resulted in longer water exchange periods in and among the lakes. Consequently, the deeper layers of the shallow Lake Licheńskie became more isolated thus lowering temperature, but also oxygen contents. Similar dependencies were noted in summer in the Lake Ślesińskie hypolimnion. Limited water exchange rates in the system could cause accelerated eutrophication in these lakes, resulting in the mass summer occurrence of algal blooms, especially of cyanobacteria, and decreased transparency (Piotrowska and Przybiński 1991, Socha and Zdanowski 2001). However, recent years have seen improvements in the oxygen conditions in the near-bottom water layer in Lake Mikorzyńskie, the deepest of the lakes studied, along with decelerated increases in oxygen deficits during the spring-summer period.

One of the key factors differentiating the various ecosystems in the Konin lakes in terms of microhabitats is mixing and the occurrence of lotic an lentic zones next to each other (Zdanowski and Korycka 1976, Ciemiński and Zdanowski 2009, Napiórkowska-Krzebietke 2009, Tunowski 2009). Progressive limitations of water exchange in the lakes with the simultaneous decrease in the degree of water heating could result in unstable ecological conditions that could consequently lead to increased habitat heterogeneity and increased abundances of cryophilic flora and fauna species.

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