Bulletin of Geography. Physical Geography Series, No. 29 (2025): 133–152
http://doi.org/10.12775/bgeo-2025-0014

Thermal regime of lakes in the Polish Lowlands in the light of climate change

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Abstract. Based on data for the years 1961–2020 regarding surface water temperature, summer thermal structure and ice phenomena in lakes in northern Poland, changes in the thermal regimes of the lakes during the period of climate change were determined. The average annual surface water temperatures in all lakes (13 lakes) were characterised by an average positive trend at the level of 0.044°C·year[1] with 0.015°C·year[1] in January and 0.069°C·year[1] in May. In turn, in the summer (from 20 July to 20 August), the average water temperature within the epilimnion (to a depth of 5 m) was characterised by a positive trend at the level of 0.05–0.07°C·year[1], whereas below this layer a negative trend was noted in all lakes. A characteristic feature observed in all lakes was a decrease in the thickness of the epilimnion with a trend at the level of 0.07–0.11 m·year[1]. The hypolimnion layer showed a negative trend for its water temperature, which ranged from 0.02°C·year[1] (Raduńskie Górne) to 0.07°C·year[1] (Miedwie). The ice cover appeared on average in the middle of the third decade of December and its trend was characterised by negative values (0.1–0.2 days·year[1]). In turn, the dates of its disappearance were recorded earlier and earlier, most often in the second decade of March. The consequence of the initial and final dates with ice cover is the length of its occurrence, which was shortened on average by 0.7–0.8 days·year[1]. The general trend of the period with ice cover shortening was also accompanied by a clear decrease in ice cover thickness (with a trend of 0.2–0.4 cm·year[1]).

Key words:
lakes,
water temperature,
ice phenomena,
Poland

Introduction

The thermal regime of standing water bodies is a composite reflection of how many factors shaped over many years have affected the natural environment. It is a dynamic system characterised by a specific repeatability (cyclicality) of physical, chemical and biological processes occurring in it, daily and in individual seasons, years and multi-year periods alike. In the past, long-term fluctuations in the water level in lakes, their inclusion in the surface runoff system, and a significant reduction in their resources (capacity) as a result of regulatory and hydrotechnical procedures conducted since the end of the 17th century were of particular importance for inland water bodies (Niewiarowski 1977; Kaniecki 1997). In the last 50–60 years, these changes have certainly been the effect of climate fluctuations and various forms of anthropogenic impact (Choiński 2007). Although these effects are of a delayed nature, their continuous impact on the lake ecosystem may ultimately lead to permanent abiotic and biotic changes in the lakes. These include, above all, direct and indirect discharges of sewage and waters that differ thermally from the natural course, which may lead to thermal distinctiveness of the lake or part thereof (Pietrucień and Skowron 1984; Skowron 1999). Such an impact has the effect of significantly increasing the water temperature in Lake Gopło in the winter months (by 1.5–2.5°C) and changing the conditions of the formation and course of ice phenomena (Sojka et al. 2023). These situations have been well documented in the case of the Konin lakes (Chojnowski 1972), and their effects have had a significant impact on the heat balance of the lakes, causing a 3.5-fold increase in the sum of annual evaporation, intensification of heat exchange from the water surface, a several-degree increase in average monthly and annual water temperatures, deepening of the epilimnion, loss of thermal stratification, a shift in the maximum of primary production, lower oxygen concentrations, unfavourable habitat changes and changes in fish species (Zdanowski et al. 1992; Blenckner 2001; Kubiak 2003).

Location, morphometry and bathymetry of lakes

The lakes analysed in this work are located in northern Poland within the Polish Lowlands (Pomeranian Lakes – 11 lakes, Masurian Lakes – 18 lakes and Kuyavian-Pomeranian Lakes – 5 lakes (Fig. 4, 5). For data relating to surface water temperature (13 lakes) and ice cover (23 lakes), their areas ranged from 107 ha (Lake Biskupińskie) to 7020 ha (Lake Łebsko), while average depths ranged from 1.3 and 1.4 m (Lake Jamno and Bukowskie) to 38.7 m (Lake Hańcza). For four lakes, average depths were greater than 15 m, while for seven lakes, average depths did not exceed 5 m. Some of them were included in the study of thermal water structure. In general, the vertical distribution of water temperature studies covered over 700 lakes. In this work, 44 lakes (Table 4), were taken into account for which at least ten measurements were taken from the summer stagnation period (Skowron 2022). For the lakes for which studies on the thermal structure of water were conducted, the most important are the horizontal and vertical dimensions. Of particular importance are: the average and maximum depth, the vertical distribution of capacity and depth indicators (compactness index and relative depth index). For the analysed lakes, the largest average depth, apart from Lake Hańcza (38.7 m), is for lakes Babięty Wielkie and Wukśniki (respectively, 23.9 and 23.4 m). In the vertical distribution of lake capacity to a depth of 5 m, the smallest share is held by lakes Hańcza (6.1%), Babięty Wielkie (9.8%) and Wukśniki (10.3%), indicating at the same time the deep and clearly incised nature of their basins. The morphometric parameter that well reflects the nature of horizontal and vertical relations of the lake basin is the relative depth index (CR), functioning as the quotient of the average depth and average width of the lake (Skowron 2006). The value of this index clearly corresponds to the depth of the thermal jump layer, its gradients and the temperature of the hypolimnion. The value of this index is 56.1 for the lakes Hańcza 49.6 and Użewo 48.3. For the shallowest lakes, it is only 3.7 (Jeziorak), 4.2 (Gopło) and 6.2 (Borzymowskie).

Materials and methods of the study

The lakes were accepted for analysis based on the availability of measurement and observation materials. In the case of surface water temperature measurements, water temperature measurements in the period 1961–2020 were taken on 13 lakes in the coastal zone using a scoop thermometer at a depth of 0.4 m daily at 7:00 a.m. The same period applies to lake ice-cover data. These data were obtained from shore observation and concern: the start and end dates of ice phenomena and ice cover, and ice cover thickness, as well as breaks in its occurrence. Lake ice-cover observations are made during the winter months daily at 7:00 a.m., noting the start and end dates of ice phenomena and ice cover, determining their range within individual lakes, whereas the thickness of the cover is measured every five days, with an accuracy of 1 cm. In turn, based on measurements of the vertical distribution of water temperature during the summer stagnation period in the period 1961–2023, those lakes that had at least 20 years of observations were selected. In these verticals, the temperature was measured in at least three verticals from the surface to the bottom every 1 m; in some cases, measurements to a depth of 15 m were concentrated every 0.5 m. On this basis, the following, among others, were determined and calculated: the average water temperature in the lake (t_j), the difference in water temperature between the one-metre surface and bottom layer (Δt), the thermal stratification coefficient (μ), the extent of the epilimnion (mixing depth) (D_E), the average temperature of the epilimnion (TE), the depth of the lower boundary of the metalimnion (D_M), the thickness of the metalimnion (Tc_M), the average temperature gradient in the metalimnion (Tm_{gr}), the thickness of the hypolimnion (D_H), the average temperature of the hypolimnion (T_H), the heat content in the lake (MJ × 106), the heat content per unit volume (J·cm^{-3}) and the % share of the volume of the epilimnion, meta- and hypolimnion (Skowron 2022).

All statistical data calculations were performed using Excel spreadsheet and Corel Quattro Pro 8, while graphic processing was presented using Corel Draw 9.

Climatic conditions

The last 200 years over the area of Central Europe and the southern Baltic Sea were characterised by a clear increase in air temperature. This is confirmed by the courses of average annual air temperatures and their trends for Warsaw, Vilnius and Tallinn (Fig. 1). For Warsaw they were 0.65°C per 100 years, and for Vilnius and Tallinn 0.56°C per 100 years.

The analysis of almost 200 years of observations (Kraków air temperature series from 1826–2000) indicates that maximum and minimum temperatures are characterised by rising trends (Trepińska 2005), with the increase in minimum temperature being greater. The increase in minimum temperature in the summer months is half or even one third the size of the increase in the winter months (Czernecki and Miętus 2011). It is commonly accepted that, after 1980, winter periods in Central Europe generally became warmer compared to earlier winters (Przybylak et al. 2005; Kaszewski 2015). They unanimously assume that, in the southern and eastern part of the Baltic Sea catchment area (the area of Poland, Lithuania and Belarus), the main cause of climate change should be considered to be the variability in atmospheric circulation and properties of air masses, which shape the climate of Central Europe.

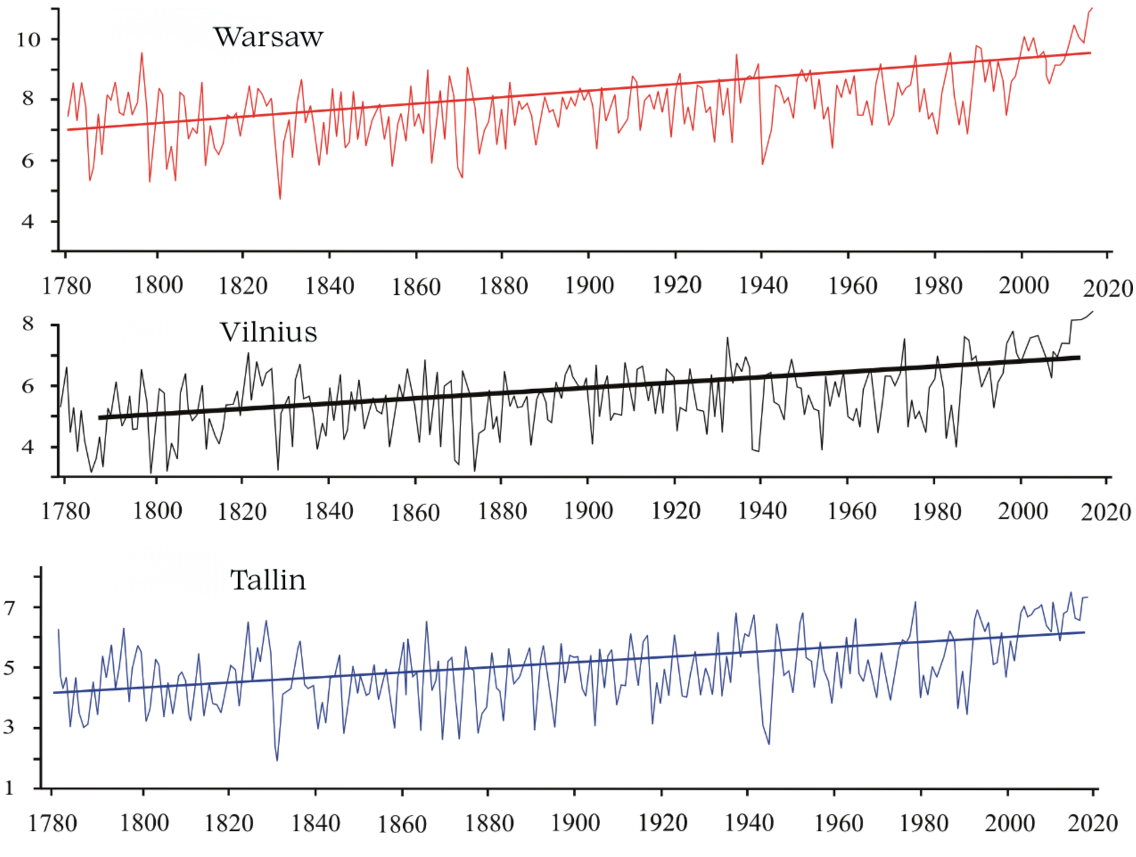

Fig. 1. Course of annual air temperature values and the trend line in Warsaw (1780–2003) after Boryczka (2004), in Vilnius (1778–1999) after Bukantis et al. (2001) and in Tallin (1779–2000) after Bijak (2005)

The increase in the average annual air temperature is most influenced by the temperature of the winter period (Piotrowicz 2002), in which the greatest temperature variability is also observed. In Poland, the occurrence of so-called "nuclearless" winters is becoming common, in which the December drop in air temperature is followed by an increase in temperature. These features are associated with the revival of zonal atmospheric circulation and the increase in oceanic climate features (Marsz 1999; Kożuchowski and Żmudzka 2001; Degirmendžić et al. 2002), causing warming of winter seasons, especially in January and February (Degirmendžic et al. 2000; Fortuniak et al. 2001). The occurrence of positive values of the winter NAO index is accompanied by an increase in the inflow of air masses from western directions over Poland. Such a situation in winter causes a significant increase in air temperature, but also an increase in cloudiness, a reduction in air temperature drops at night, and spatial differentiation of snow cover. The analysis of numerical NAO indices according to Jones et al. (1997) and Hurrell (1995) confirmed the occurrence of close relationships between circulation changes and air temperature in the Olsztyn Lakeland (especially in the period from December to March).

Further confirmation of climatic warming effects in the natural environment is provided by the glacier recession clearly documented in many regions of the world. The processes accompanying these changes are clearly visible through the shortening of glacier tongues, and by reductions in their area and thickness. In Europe, this phenomenon was first noticed in the Alps, but it has also been observed in Scandinavia and the Svalbard Archipelago. For example, the area of the six valley glaciers of Kaffiöyra (Oscar II Land) on Svalbard decreased by an average of 34% between 1900 and 1995, while their length shortened by 21% (Lankauf 2002).

The spatial image of the differentiation of the course of thermal conditions in the Polish Lowlands (Fig. 2) is best visible in the winter months. This course is well illustrated by the 10-year-average air temperatures and the frequency of negative air temperatures in mid-winter (Table 1). In all the selected decades, a visible increase in the average annual values and a decrease in the frequency of negative air temperatures was observed towards the east, from 8.1°C in the years 1961–1970 to 9.7°C in the years 2011–20 in Łeba and from 6.0 °C to 7.7 °C in Suwałki. This pattern is confirmed by the frequency of negative air temperatures in January

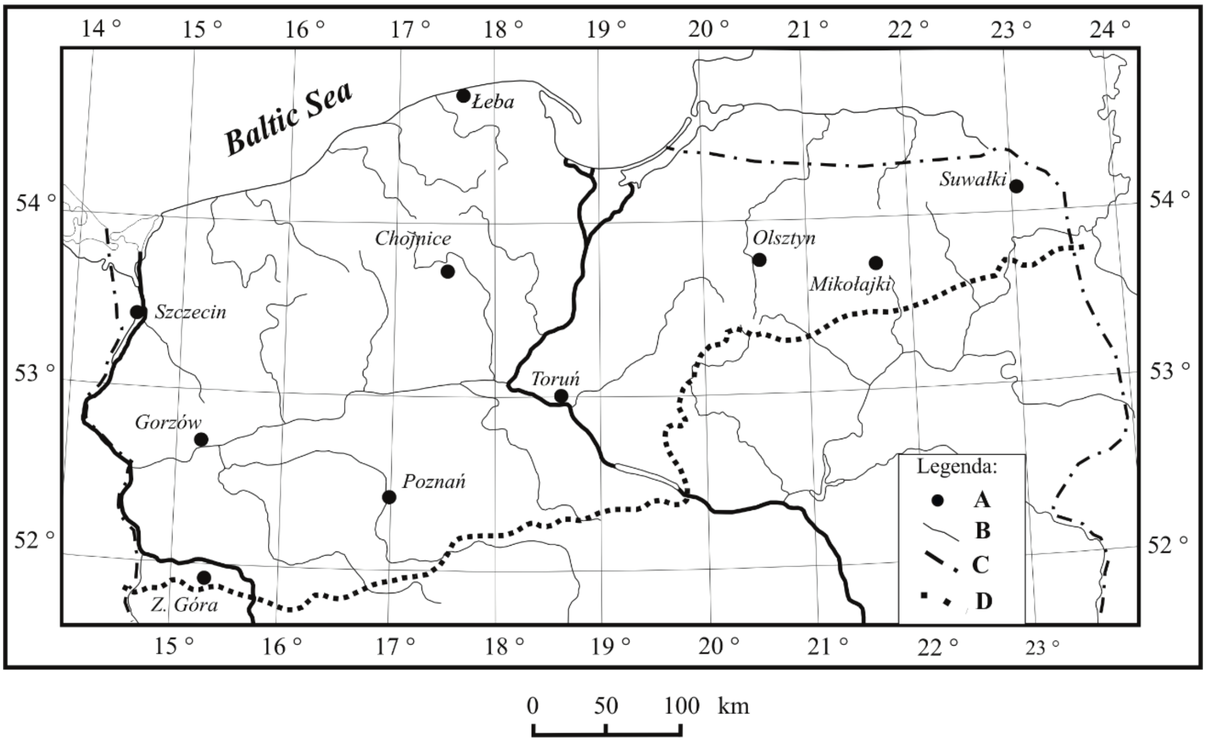

Fig. 2. Location of meteorological stations: A – meteorological stations, B – rivers, C – border of Poland, D – maximum extent of the Vistulian glaciation

and February from 34.2% in the years 1991–2000 in Łeba to 93.3% in Suwałki in the years 1961–1970.

The last 200 years over the area of Central Europe and the southern Baltic Sea were characterised by a significant increase in air temperature. This was not without significance for changes in the natural environment. It has been recognised beyond dispute that lakes, as inland ecosystems, are particularly sensitive to any changes occurring in the environment in recent decades (Lampert and Sommer 1996). Danilovish (2005) indicates that, in the years 1988–2002, a significant increase in air temperature of 1.1 °C was observed in Belarus, causing changes in basic processes in lakes and artificial reservoirs in Belarus. The effect of these changes is that water temperatures of 0.2, 4 and 10°C in spring have occurred earlier, by even 5 to 11 days, and temperatures of 0.2°C in autumn have come 7 days earlier. The period with water temperature between 0 and 2 °C was significantly shortened, as was the duration of ice phenomena (by 5 days) and ice cover (by 6 days). On the other hand, for the areas of Karelia in the years 1950–99 the trend for the annual air temperature was positive, and the average annual air temperature increased by 0.6°C (Filatov et al. 2003).

In the last 50 years, research has begun on the consequences of this influence for the thermal regimes of lake waters (Skowron 1997, 1999; Magnuson et al. 2000; Endoh et al. 2001; Gronskaya et al. 2001; Järvet 2001; Lemeshko and Borzenkova 2001; Dąbrowski et al. 2004; Marszelewski and Skowron 2006; Naumenko et al. 2006). European researchers have reached a unanimous conclusion that most winters in northern Europe are becoming warmer. The thermal regime of lakes in Estonia in the years 1946–2000 indicated that the last decades of thermal spring were extended by two weeks. In Estonian lakes, the period of summer thermal stagnation occurred a week earlier. The thermal winter became 17 days shorter and the period with ice cover was almost a month shorter (Järvet 2001).

Table 1. 10-year-mean annual air temperature values recorded at the selected stations in period 1961–2020 (based on the data obtained from the Institute of Meteorology and Water Management, PIB)

Meteorological station	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2020
Szczecin	8.1	8.4	8.8	9.0	9.1	9.7
Gorzów	8.0	8.2	8.6	8.9	9.3	9.9
Zielona Góra	8.2	8.3	8.5	8.8	9.6	10.1
Poznań	8.0	8.2	8.5	8.7	9.3	10.1
Chojnice	6.7	6.9	7.2	7.6	8.0	8.6
Łeba	7.3	7.4	7.8	8.0	8.4	8.9
Toruń	7.4	7.7	8.2	8.5	8.8	9.4
Olsztyn	6.8	6.9	7.3	7.5	7.9	8.6
Mikołajki	6.6	7.0	7.2	7.6	8.0	8.5
Suwałki	6.0	6.0	6.3	6.7	7.1	7.7

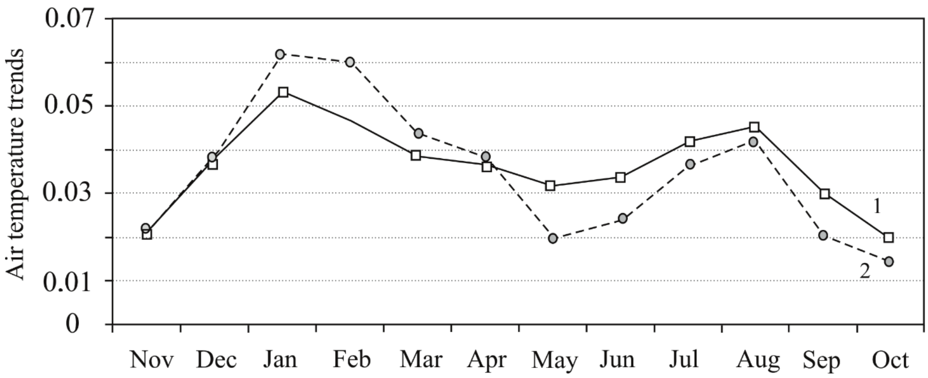

Fig. 3. Trend of mean monthly air temperature (°C·year¹) in the Polish Lowland in period 1961–2024: 1 – mean for six stations located to the West of the River Vistula, 2 – mean for five stations located to the east of the River Vistula (based on the data obtained from the Institute of Meteorology and Water Management, PIB)

Research results

A large number of collected observations on the thermal regime of lakes in the years 1961–2020 authorises the authors to present the characteristics of its features relating to the surface water temperature, thermal structure of water and the course of ice phenomena.

Surface water temperature in lakes (Fig. 4). Studies have shown that the surface water temperature in all lakes is characterised by a positive trend on average, at the level of 0.044°C·year^{-1}. The largest increase was observed at Lake Lubie at 0.057°C·year^{-1}, and the smallest, at 0.029°C·year^{-1}, at Lake Hańcza. Average monthly water temperatures are characterised by positive trends at levels ranging from 0.015 °C·year^{-1} in January to 0.069 °C·year^{-1} in May (Skowron and Sukhovilo 2022).

In all lakes in the Polish Lowlands, the surface water temperature in these years was divided into two periods: the first with a negative trend until 1980 and the second being significantly warmer with a positive trend after 1980. In the clearly colder period (1961–1980), the average trend was at –0.04°C·year^{-1} and was statistically insignificant, whereas in the warmer period (1981–2020) it ranged from +0.04 to +0.05°C·year^{-1}. The average annual surface water temperature in the warmer period was 10.03°C and was 0.81°C higher compared to the cold period (Skowron 2022).

The course of the average annual values of surface water temperature in the years 1961–2020 was varied. This is confirmed by the values for 10-year periods (Table 2). The highest water temperatures definitely occurred in the 10-year periods 2001–2010 and 2011–2020. In general, a systematic increase in water temperature was observed in all lakes (except in the years 1971–1980). In addition, a gradual decrease in water temperature was noted towards the east, except for the coastal lakes (Jamno, Gardno and Łebsko) and Lake Raduńskie Górne.

Similar trends were observed in various lakes in the northern hemisphere, especially in the lakes of the Baltic Sea catchment area, which showed a significant increase in the second half of the 20th century (Skowron 1997; Pernaravičiūtė 2004; Naumenko et al. 2006; Skowron and Sukhovilo 2022). These changes correlate with changes in thermal seasons in the territory of Lithuania (Pempaitė 1997). In turn, Kilkus and Valiuskevicius (2001) indicate that, in 1981–1985, during the three decades of July, the

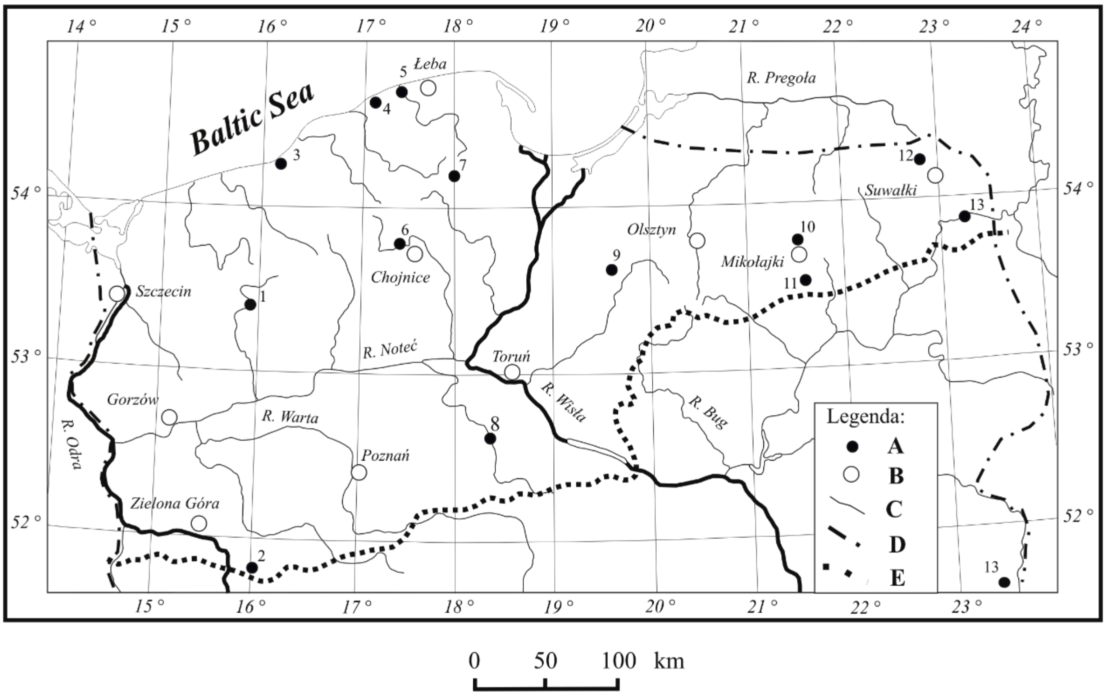

Fig. 4. Distribution of lakes covered by surface water temperature measurements in 1961–2020: A – lakes: 1. Lubie, 2. Sławskie, 3. Jamno, 4. Gardno, 5. Łebsko, 6. Charzykowskie, 7. Raduńskie Górne, 8. Gopło, 9. Jeziorak, 10. Mikołajskie, 11. Nidzkie, 12. Hańcza, 13. Studzieniczne; B – towns; C – rivers; D – border of Poland; E – maximum extent of the Vistulian glaciation

changes in surface temperature in some Lithuanian lakes ranged from 0.5°C (Tauragnas) to 3°C (Totoriskes). Also in the central part of the deep zone of Lake Ladoga, which is the most representative for determining surface water temperature trends, mean annual temperatures were characterised by a positive trend of 0.05–0.07°C·year^{-1}. The same author states that the surface water temperature in lakes can be an excellent indicator of climate change, especially in the period free from ice phenomena (Naumenko et al. 2006, 2008).

Lake ice. Another factor that well determines the dynamics of the lake ecosystem, aside from water temperature, is that of ice phenomena. For lakes in the temperate zone, ice phenomena not only determine the time of their dynamic impact on the water mass, but also affect the water temperature, change the direction of heat exchange with the environment and increase the stability of thermal-density systems. Their diverse occurrence, especially characteristic in the transitional climate of the temperate zone, creates completely new conditions for biological life.

Full series of data on lake ice cover in the Polish Lowlands are available for 23 lakes, ten of which are located in the Pomeranian Lakes, ten in the Masurian Lakes and three in the Wielkopolska-Kujawskie Lakes (Fig. 5).

The most important factors for the formation of ice phenomena are climatic conditions during the winter months. This situation is well characterised by the course of thermal winter, treated as the period in which average daily air temperatures are equal to or lower than 0°C. The beginnings of thermal winters and their courses in the last 50 years confirm the very high variability of thermal conditions in this time of year.

Only in the areas of north-eastern Poland was an unbroken thermal winter recorded every year. In the remaining areas, however, the course of thermal winter was interrupted by warm periods. The beginning of this period usually fell in the first decade of December and its end in the second decade of March (Czarnecka and Nidzgorska-Lencewicz 2017). There were years when thermal winter did not occur in Poland for three consecutive years (1988, 1989 and 1990) or for two consecutive years (2007 and 2008). In general, the duration of thermal winter ranged from 40 days in the north-western part of Poland to 90–100 days in the Suwałki Lakeland.

The data included in Table 3 refer to the beginning and end of ice phenomena and ice cover, their duration, maximum thickness of ice cover, number of breaks in the occurrence of ice cover in the winter season and percentage share of ice cover in the course of ice phenomena.

The first ice phenomena on lakes – in the form of shore ice – appeared on average between the first ten days of December (Jeziorak and Nidzkie) and the first ten days of January (Osiek). On the other hand, the average disappearance of ice phenomena took place between the first ten days of March (Bukowo) and at the turn of March and April (Studzieniczne). Generally, the average dates of the beginning of ice phenomena appear 8.6 days earlier than the

Table 2. Average annual surface water temperatures in decadal ranges in selected lakes in the period 1961–2020 (based on the data obtained from the Institute of Meteorology and Water Management, PIB)

No.	Lakes	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010	2011–2020
1	Sławskie	10.4	10.2	10.5	10.9	11.4	12.1
2	Lubie	9.5	8.5	9.3	9.7	10.3	11.1
3	Jamno	9.0	8.8	9.2	9.1	9.8	10.5
4	Gardno	8.7	8.4	8.6	8.7	9.4	9.8
5	Gopło	10.5	10.3	10.8	10.4	11.6	12.1
6	Hańcza	8.5	8.0	8.4	8.6	8.9	9.4
7	Charzykowskie	9.3	9.1	9.2	9.5	10.0	11.1
8	Raduńskie Górne	8.6	8.5	8.8	9.2	9.8	10.2
9	Łebsko	8.6	8.7	9.2	9.3	9.7	10.1
10	Jeziorak	9.5	9.4	10.0	10.5	10.6	11.5
11	Mikołajskie	9.4	9.1	9.4	9.6	10.2	10.7
12	Nidzkie	9.2	9.3	9.6	9.7	10.3	11.0
13	Studzieniczne	9.4	9.1	9.3	9.6	10.2	10.7

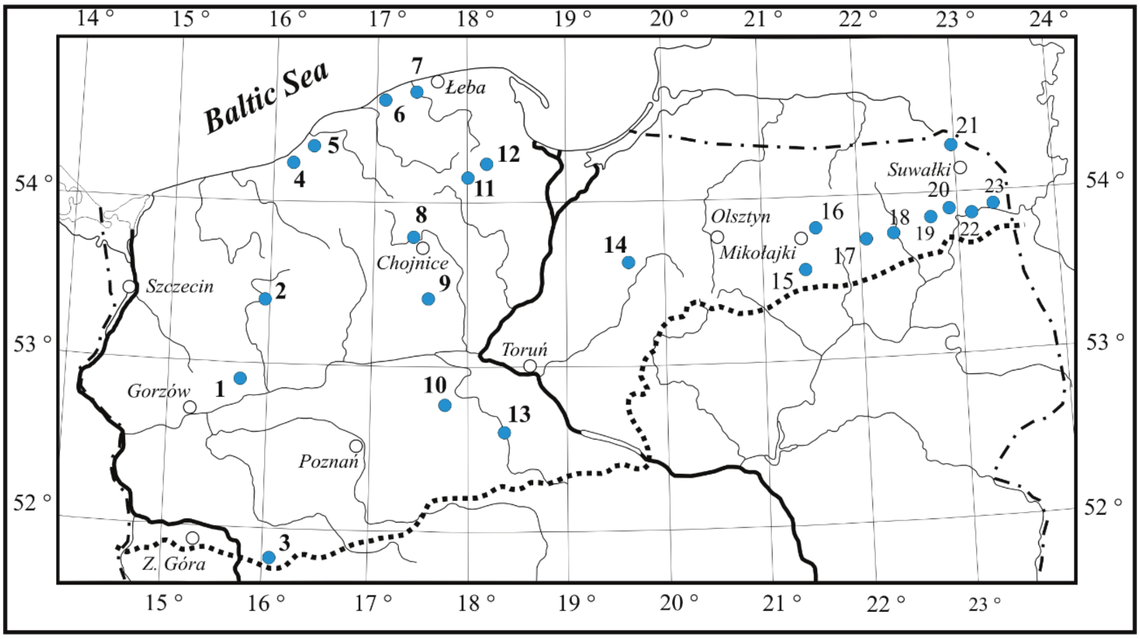

Fig. 5. Distribution of lakes covered by ice cover measurements: lakes (according to Table 3) (other symbols as in Fig. 4)

beginning of ice cover, while their end occurs 7.8 days later (Sobolewski et al. 2014).

The average dates of ice formation on the lakes of the Polish Lowlands occurred between mid-December in the shallowest lakes (Jeziorak – 16 December) and the first decade of January (Lubie – 12 January and Raduńskie Górne – 9 January). On the remaining lakes, the average dates of ice formation stabilised in the middle of the third decade of December.

The earliest ice cover appeared in mid-November (Bukowo and Jamno – November 15, 1966). The latest dates were at the turn of February and March (Hańcza 28.02.1983, Raduńskie Górne 3.03.1988). The earliest average dates of the end of ice cover occurred in shallow lakes of the Baltic Coast in the last days of February (Jamno 26.02, Bukowo 27.02 and Gardno and Łebsko 28.02) and in Lake Gopło – February 28. The latest dates were in lakes to the east of the Vistula and fell in the third decade of March (Studzienniczne 26 March; Serwy 21 March) (Table 2). The disappearance of ice cover was most often recorded in the second decade of March (58% of lakes), then in the first decade of March (27% of lakes). The ice cover disappeared earliest in 1989 on Lake Jamno (6 December) and latest in 1978 on Lake Hańcza (28 April).

The duration of ice cover on lakes in northern Poland reflects the course of thermal winter. In the analysed multi-year period, the average duration of ice cover ranged from 50.3 days for Lake Bukowo and 52.1 days for Lake Łebsko to 93.2 days for Lake Studzieniczne (Table 2). For the remaining lakes, it ranged from 64 to 72 days, with an average value of 67.5 days. Slightly different values are reported by other authors (cf., Pasławski 1982; Skowron 1997, 2001, 2003, 2008, 2009; 2011; Marszelewski and Skowron 2006; Choiński et al. 2014), which results from the analysis of different time intervals. In general, on lakes located west of the Vistula, the average length of ice cover was over 18 days shorter than on the east of it. The longest ice cover was in 1996, when an absolute record was recorded for Lake Jeziorak, which was 145 days. In the analysed period, years were also recorded when ice cover did not occur at all. Such situations occurred in the winter seasons of 1975, 1988, 1989 and 1990 in several lakes to the west of the Vistula (Sławskie, Gopło and Charzykowskie).

In the discussed 60 years, the maximum ice thickness on the analysed lakes of the Polish Lowlands was clearly differentiated and generally increased eastwards (Table 2). On average, it ranged from less than 20 cm on the lakes west of the Vistula (Osiek 19.2 cm and Gopło 19.7 cm) to over 34 cm in the eastern part of Poland (Studzieniczne – 34.2 cm). The average thickness of the ice cover in the individual winter seasons on the analysed lakes was significantly differentiated (Sziwa 2002; Skowron 2009, 2011). It ranged from 0 to 57 cm in the lakes in the western part of Northern Poland to 65 cm in the lakes in the eastern part (Marszelewski and Skowron 2009). In 1996, record ice cover thicknesses were recorded on many lakes. The maximum values in eastern northern Poland exceeded 60 cm (Studzieniczne 64 cm), while in the western part of the Polish Lowlands they rarely exceeded 50 cm.

The thermal regime of lakes, especially during the period of ice cover, is greatly shaped by numerous breaks in the occurrence and the degree of durability of the ice cover (Skowron 2003, 2011; Marszelewski and Skowron 2006). In the 60-year period, both parameters exhibit clear differentiations. The average number of breaks in the occurrence of ice cover in the lakes of the Polish Lowlands is 0.45 and clearly decreases eastwards. In turn, the degree of ice cover durability ranges from 79.3% (Gardno) to 98.9% (Studzieniczne), with an average of 92.3%. The number of breaks in the occurrence of ice cover was largest in lakes in western Poland. In turn, in the lakes in the eastern part of the Polish Lowlands, no breaks in the ice cover were found until 1974. They appeared only in 1975, and their frequency clearly decreased eastwards.

The calculated trends of the main features of the ice cover course in the period 1961–2020 confirm previous studies (Skowron 1997, 2003; Choiński et al.

Table 3. Selected properties of the course of ice phenomena in the lakes in Poland during the period 1961–2020 (based on data obtained from the Institute of Meteorology and Water Management)

No	Lake	Beginning of		End of		Duration of		Maximum thickness of ice cover [cm]	Duration of ice cover divided by total period of ice cover [days]	Degree of durability of ice cover [%]	Mean proportional part of ice phenomena in long-term period [%]
		ice phenomena	ice cover	ice cover	ice phenomena	ice cover	ice phenomena				
		date [DD/MM]				days					
1	Osiek	28/12	05/01	09/03	15/03	54.5	63.5	19.2	0.6	85.1	77.1
2	Lubie	07/01	11/01	8/03	09/03	54.8	57.7	22.8	0.1	97.9	87.3
3	Sławskie	14/12	26/12	3/03	06/03	55.1	66.4	20.9	0.6	85.5	75.9
4	Jamno	18/12	22/12	26/02	07/03	52.2	62.0	21.0	0.8	79.5	76.7
5	Bukowo	18/12	26/12	27/02	03/03	50.3	62.9	24.7	0.5	86.9	88.7
6	Gardno	10/12	19/12	28/02	09/03	55.2	69.4	20.7	0.8	79.3	74.3
7	Łebsko	14/12	24/12	28/02	07/03	52.1	65.7	21.7	0.8	81.6	73.0
8	Charzykowskie	29/12	05/01	12/03	18/03	60.2	69.8	23.8	0.3	91.9	79.3
9	Sępoleńskie	21/12	25/12	09/03	14/03	66.8	74.8	23.9	0.6	91.0	85.7
10	Biskupińskie	17/12	23/12	06/03	11/03	64.1	76.2	24.6	0.7	87.3	80.6
11	Raduńskie Górne	31/12	09/01	16/03	27/03	55.4	71.1	23.1	0.6	91.0	73.3
12	Ostrzyckie	20/12	22/12	19/03	20/03	79.2	84.0	24.6	0.5	90.8	93.8
13	Gopło	14/12	21/12	28/02	09/03	59.0	74.1	19.7	0.6	84.8	74.5
14	Jeziorak	06/12	16/12	15/03	19/03	80.5	92.6	26.8	0.5	90.8	85.2
15	Nidzkie	08/12	20/12	19/03	29/03	84.9	102.5	29.0	0.3	95.4	81.4
16	Mikołajskie	19/12	01/01	16/03	30/03	69.6	91.9	29.2	0.5	93.0	71.0
17	Orzysz	13/12	28/12	17/03	26/03	75.9	97.4	28.2	0.3	95.5	74.7
18	Ełckie	21/12	29/12	12/03	24/03	68.2	89.7	29.0	0.3	95.0	73.0
19	Olecko Wielkie	16/12	28/12	20/03	28/03	72.8	90.1	29.3	0.4	92.7	78.2
20	Necko	17/12	29/12	15/03	22/03	73.8	94.4	30.4	0.1	96.9	75.4
21	Hańcza	27/12	04/01	19/03	28/03	71.4	89.5	28.6	0.2	96.3	77.7
22	Studzieniczne	15/12	22/12	26/03	01/04	93.2	103.8	34.2	0.2	98.9	89.0
23	Serwy	19/12	28/12	21/03	29/03	81.6	98.1	30.5	0.1	98.6	81.2

2014) on the earlier appearance of ice cover on most lakes in Poland (0.1–0.2 day·year^{-1}). This also applies to the earlier dates of the end of the ice cover, which are also characterised by a negative trend at the level of 0.5–0.6 day·year^{-1}. The changes in initial and final dates with ice cover result in a shortening length of its occurrence, which averages 0.7–0.8 day·year^{-1}. The general trend of the period with ice cover shortening is also confirmed by a clear decrease in its thickness. All lakes (except for Lake Jamno) are characterised by a negative trend (0.2–0.4 cm·year^{-1}), with the trend value clearly increasing eastwards.

Water temperature stratification. To document this problem, which is important for the functioning of the lake ecosystem, lakes were selected for which long series of measurements of the vertical distribution of water temperature were completed during the summer stagnation period (from July 20 to August 20). The deepest lakes in the analysed group were: Hańcza, Drawsko, Wigry, Morzycko and Miedwie, for which the average depths exceed 15 m, while the shallowest were the lakes whose maximum depths were less than 20 m (Tarnowskie Duże, Długie Wigierskie, Gopło, Wisala and Narost) (Table 4).

The results of the measurements of the vertical distribution of water temperature showed that its average five-year values to a depth of 10 m were characterised by multidirectional variability. In turn, in the layers located below the thermal jump (at depths of 20, 30, 40 m and deeper) the water temperature decreased and generally showed a downward trend. The decrease in water temperature in the hypolimnion layer was especially visible after 1985. This applies primarily to the deepest lakes, with the exception of Lake Raduńskie Górne. The results of the studies are presented in Tables 4, 5 and 6. The decrease in water temperature in the hypolimnion is also confirmed by studies conducted on other lakes (Borowiak et al. 2008).

A more telling character of changes in thermal stratification of water was recorded during the period of summer stagnation. This is documented by calculated trends for the most important parameters of thermal stratification of water, which are presented in Figs 5 and 6. While the average water temperature within the epilimnion (at a depth of 5 m) in the period 1971–2009 was characterised by a positive trend at the level of 0.05–0.07°C·yr^{-1}, below this layer in all lakes a negative trend was noted. This trend was greatest at a depth of 10 m and amounted to 0.1–0.3°C·yr^{-1}, clearly decreasing with depth. Below 30 m it ranged from 0.01 to 0.04°C·yr^{-1}.

A measurable effect of water temperature changes in the vertical distribution during the summer stagnation period is seen in clear changes in the ranges of thermal layers and the thermal stratification coefficient. The nature of these changes was similar in all the lakes studied. A characteristic feature observed in all the lakes is the decrease in the thickness of the epilimnion with a trend of 0.07–0.11 m·yr^{-1}. In Lake Gopło, the thickness of the epilimnion decreased from about 10 m in the early 1970s to 8.2 m at the end of the first decade of the 21st century. This trend was observed in all time intervals of the multi-year period of 1961–2005 (Fig. 6). The position of the lower boundary of the metalimnion in all the lakes also tended to become shallower with a trend of 0.04–0.1 m·yr^{-1}. However, due to the varied surface area of the lakes and their shape, this tendency was within a wide range (0.003–0.17 m·yr^{-1}).

Another element of the thermal structure of water in which changes were observed during the summer stagnation period is the hypolimnion layer. The main observation here was a drop in temperature (Fig. 7). This phenomenon was observed in all the lakes. The negative trend for the hypolimnion temperature ranged from 0.02°C·yr^{-1} (Raduńskie Górne) to 0.07°C·yr^{-1} (Miedwie). In contrast to the deep lakes in Italy (Ambrosetti and Barbanti 1999), where an increase in the hypolimnion temperature was observed, the opposite situation occurs in Polish lakes. The reasons for the differences in this phenomenon should be sought in the significantly greater eutrophication of lakes in the Polish Lowlands.

Discussion of results and conclusions

It has been recognised beyond doubt that lakes, as inland ecosystems, are particularly sensitive to any changes that have been occurring in the environment in recent decades (Lampert and Sommer 1996). Air temperature plays a special role, becoming a very important factor influencing water thermals, especially in the surface layer.

Analysis of long-term changes in surface water temperature in lakes in Europe indicates a clear increase since the beginning of the 1980s and the first 20 years of the 21st century (Järvet 2002;

Table 4. Parameters of water thermal structure during summer stratification in the lakes of the Polish Lowlands in the period 1971–2020

Lake	Number of measurements	Average lake water temperature	Water temperature difference (surface-bottom)	Thermal stratification factor	Range of epilimnion [m]	Average water temperature in epilimnion [°C]	Total heat resources [10^6 MJ]	Heat content per unit volume [J·cm^{-3}]	Water temperature at the bottom [°C]	% share epilimnion in the lake volume	% hypolimnion in the lake volume	Thermal type
Morzycko	30	13.18	14.8	0.458	6.5	20.2	2752.6	55.2	5.9	37.1	43.3	H/M
Chełmżyńskie	15	19.46	14.6	0.590	8.0	20.7	1254.2	81.5	6.7	84.4	3.3	M/E
Miedwie	19	12.36	14.8	0.517	9.4	19.6	37226.9	54.6	5.5	38.4	42	H/M
Będzin	12	19.05	9.2	0.794	7.8	19.3	501.1	80.2	11.4	90.9	2.6	E
Wisala	14	18.10	12.8	0.676	4.7	20.6	809.5	75.8	8.7	81.9	7.9	M/E
Ińsko Duże	15	11.40	14.9	0.493	7.3	20.0	2989.4	47.7	5.6	43.9	39.4	H/M
Krzemień	10	15.13	13.6	0.562	5.7	19.8	1387.9	63.4	7.2	47.2	26.3	M
Wielkie Dąbie	10	19.31	2.9	0.946	5.7	20.0			16.6	72.9	0	M/E
Drawsko	11	12.17	15.2	0.470	6.5	19.9	16916.6	51.0	5.5	30.7	54.7	H/M
Krępsko Długie	19	16.01	14.5	0.589	3.9	20.7	356.9	67.0	6.7	45.8	17.6	M
Ostrowite	14	14.25	16.3	0.417	6.4	20.5	1788.9	59.7	5.0	45.9	29.7	M
Raduńskie Górne	43	13.02	14.8	0.461	6.8	19.9	3279.6	54.5	5.7	38.2	40.7	H/M
Stelchno	14	20.26	8.2	0.860	6.0	21.2	627.9	84.8	13.6	83.7	1.2	M/E
Jasień Południowe	11	16.87	12.5	0.618	6.4	19.5	1839.6	70.6	7.8	64.9	12.8	M/E
Okonin	10	17.65	13.7	0.747	4.8	21.6	210.1	75.6	8.5	55.9	12.8	M
Ciche	13	18.31	14.6	0.698	5.0	21.9	583.1	76.7	8.0	60.6	9.6	M/E
Łąkorz	12	14.14	16.8	0.444	5.8	21.3	1109.4	59.2	5.5	43.2	34.5	M
Robotno	14	17.46	16.5	0.560	4.4	21.8	211.8	73.1	6.0	80.3	14.3	M/E
Zbiczno	14	13.62	17.0	0.394	5.1	21.2	858.4	57.0	4.9	38.5	34.8	H/M
Bachotek	56	18.09	14.1	0.603	5.5	21.5	1145.1	75.7	8.2	62.3	14.5	M/E
Skarlińskie	13	18.27	11.0	0.766	7.5	20.0	1694.8	76.5	9.7	78.6	3.8	M/E
Płaskie	10	20.45	1.1	0.981			1308.0	85.6	19.6	100	0	E
Jeziorak	11	20.45	7.8	0.843	6.9	20.3	12124.5	85.6	14.7	93.8	0.6	E
Wukśniki	20	9.37	16.7	0.360	6.2	20.6	1112.5	39.2	4.4	23.7	62.9	H
Babięty Wielkie	12	9.25	17.0	0.402	5.0	21.0	2321.2	334.6	4.6	18.8	67.2	H
Piłakno	11	13.42	15.6	0.461	5.9	20.9	1898.8	56.2	5.7	37.3	43.3	H/M
Tałty Ryńskie	10	14.79	13.4	0.513	7.8	20.1	15376.6	61.9	7.5	47.2	35.8	H/M
Mikołajskie	11	17.13	12.1	0.647	6.9	20.9	3997.0	71.7	9.6	52.4	19.4	M
Jegocin	10	15.56	17.2	0.430	6.4	21.5	747.2	65.2	4.7	51.2	24.7	M
Ełckie	10	11.89	16.4	0.418	5.6	20.7	2857.6	49.8	5.0	30.9	48	H/M
Hańcza	25	7.88	17.7	0.353	6.1	21.0	3780.5	31.4	3.9	14.2	75.5	H
Długie Wigierskie	26	15.01	14.8	0.621	4.2	20.9	328.5	62.8	6.4	42.3	20.1	H/M
Wigry	13	12.30	15.0	0.450	6.6	20.0	17345.9	51.5	5.6	32.9	50.2	H/M
Gremzdel	17	19.36	7.3	0.864	3.3	18.1	159.2	81.1	13.7	72.7	10.5	M/E
Trześniowskie (Ciecz)	10	11.29	17.5	0.415	5.7	21.6	1697.7	47.3	4.8	26.3	52.4	H/M
Głębokie (near Międzyrzecz)	11	16.26	15.5	0.541	6.6	21.2	784.9	68.1	6.2	52.8	22.1	M
Śremskie	27	11.01	17.8	0.363	5.5	21.8	1094.0	46.1	4.5	24.7	56	H
Jaroszewskie	10	12.41	16.2	0.436	6.0	20.6	679.5	52.0	5.1	35.8	32.6	H/M
Tarnowskie Duże	30	21.72	4.6	0.919	4.3	22.3	318.6	90.9	17.4	79.8	0	M/E
Gopło	21	19.69	10.4	0.801	9.2	19.7	6413.1	82.4	10.3	97	0.4	E
Mąkolno	16	21.63	2.7	0.961			236.9	90.5	19.7	100	0	E
Borzymowskie	21	20.50	7.7	0.852	6.1	21.1	632.0	85.9	14.1	84	11.6	M/E
Białe (near Gostynin)	12	17.76	14.7	0.641	8.6	20.7	1088.9	74.4	6.5	63.8	13.1	M/E

Table 5. Lake Morzycko. Five-year average water temperature values in the selected layers in August in the years 1971–2010

Depth [m]	Years							
	1971–1975	1976–1980	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010
	Mean of temperature water [°C]							
0–5	20.4	18.4	22.6	20.5	19.7	20.0	22.4	20.5
6–10	18.7	16.0	17.7	17.0	14.6	13.4	15.5	14.3
11–15	11.7	9.6	10.4	10.0	8.5	7.8	8.3	7.7
16–20	8.4	8.1	9.7	7.9	7.8	6.8	7.0	6.9
21–25	7.7	6.8	8.2	7.6	7.4	6.5	6.8	6.5
26–30	7.2	6.7	6.7	7.3	7.2	6.4	6.6	6.3
30–40	7.0	6.5	6.7	6.9	7.2	6.3	6.5	6.2
40–50	7.0	6.3	6.4	6.7	7.0	6.2	6.3	6.1
50–60	7.0	6.2	6.4	6.6	6.6	6.2	6.2	6.0

Table 6. Lake Raduńskie Górne. Five-year mean water temperatures in selected layers in August in the period 1971–2010

Depth [m]	Years							
	1971–1975	1976–1980	1981–1985	1986–1990	1991–1995	1996–2000	2001–2005	2006–2010
	Mean of temperature water [°C]							
0–5	19.8	19.7	19.22	19.69	20.42	19.96	21.29	20.58
6–10	16.8	16.0	14.31	14.50	13.79	14.94	14.47	14.97
11–15	10.0	7.8	8.05	7.96	7.45	8.17	7.27	7.76
16–20	8.0	6.2	6.89	7.02	6.45	6.62	6.42	6.73
21–25	7.2	5.7	6.25	6.36	5.96	5.90	6.03	6.10
26–30	6.7	5.5	5.82	6.01	5.69	5.62	5.80	5.83
> 30	6.5	5.3	5.57	5.81	5.57	5.47	5.66	5.71

Nõges et al. 2010; Dokulil 2013; Woolway et al. 2017). Studies in Poland have also confirmed a similar trend (Skowron 2011, 2022; Sobolewski et al. 2014).

The increase in air temperature observed in the last 50 years has caused significant changes in the entire lake ecosystem. This applies in particular to the surface water temperature in lakes, its thermal structure (increase in the epilimnion temperature and its range, deepening of the thermocline position, increase in temperature gradients in the thermocline) (Skowron 2011, 2022; Woolway et al. 2017).

Based on long-term direct surface water temperature measurements from 20 lakes in central Europe, large-scale water temperature increases over the last 50 years have been found to be consistent with trends in lakes worldwide (George et al. 2007; Livingstone and Padisak 2007; Austin and Colman 2008, Kangur et al. 2016; Magee et al. 2016). This is supported by the trend of surface water temperature increases in many European lakes (Dokulil 2013). Lake Windermere (England)

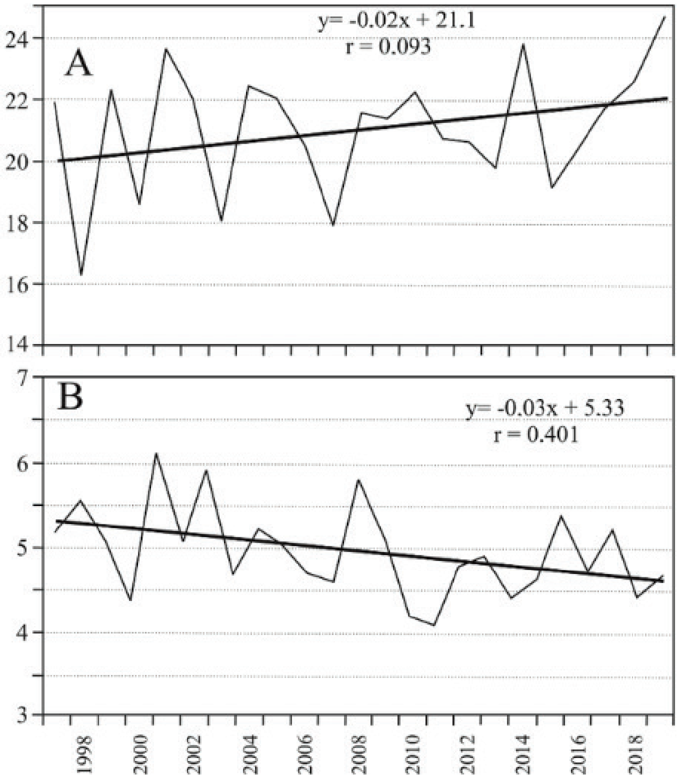

Fig. 6. Lake Morzycko. The course of parameters of the thermal structure of water during the summer stagnation in the years 1974–2008: A – epilimnion thickness (D_E) (m), B – mean temperature of hypolimnion (T_H) (statistical significance $\alpha<0.02$)

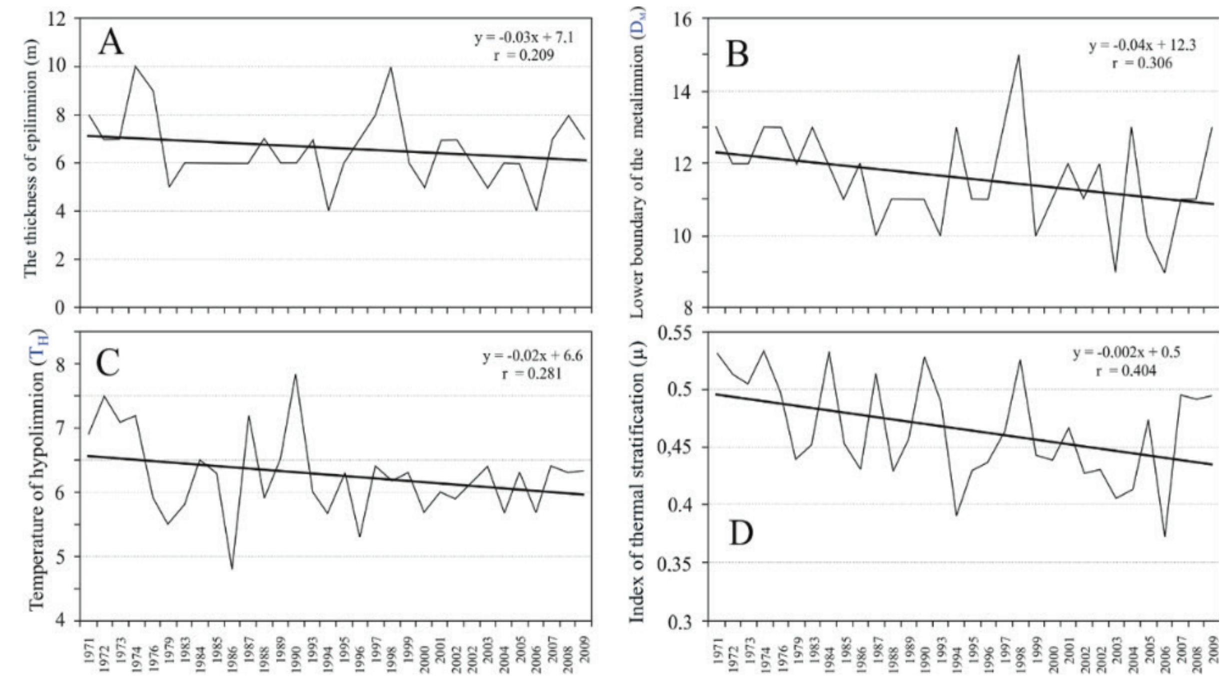

Fig. 7. Lake Raduńskie Górne. The course of parameters of the thermal structure of water during the summer stagnation in the years 1971–2009, and trend line: A – the epilimnion thickness (DE) [m], B – location of the lower limit of the metalimnion (DM), C – mean temperature of hypolimnion (TH), D – thermal stratification coefficient (μ) (statistical significance $\alpha=0.15$–0.01)

increased by 1.4°C between 1960 and 2000, and Lough Feeagh (western Ireland) increased by 0.7°C between 1960 and 1997. The average water temperature in Lake Zurich in Switzerland increased by 0.16°C per decade from 1950 to 1990, and in Lake Constance by about 0.1°C (Strajle et al. 2003). This trend is complemented by exceptionally high increases of 1.6°C per decade in Lake Stensjön in Sweden (Adrian et al. 2009). Surface water temperatures in many lakes in Finland, Austria and Switzerland also increased during the summer by averages of 0.38°C, 0.43°C and 0.29°C per decade, respectively (Arvola et al. 2010; Dokulil 2013). These conclusions are supported by more detailed results from regional studies (Livingstone and Dokulil 2001; Skowron and Sukhovilo 2019).

Comparing the relatively cold summers in Sweden in the period 1982–88 against the warm summers in the period 1989–95, it was noted that the surface water temperature in May in the largest Swedish lakes (Vänern, Vättern and Mälaren) increased from 0.6 to 4.7 °C (Weyhenmeyer et al. 2005). In the lakes of Latvia in the years 1946–2002, the long-term mean annual surface water temperature in the lakes showed a statistically significant positive trend at the level of 0.4–0.8°C (Apsīte et al. 2014). This is also confirmed by studies on large lakes in Estonia (Peipus and Võrtsjärv), where the temporal variability of the climatic seasons was determined in the years 1946–2000 (Järvet 2002). The most significant trend was observed for winter (ice cover period), which was shortened by 17 days. In Lake Ladoga, a positive trend was observed at the level of 0.05–0.07°C·year^{-1} (Naumenko et al. 2006).

The results of studies conducted on Lithuanian lakes showed that the average annual surface water temperature in 1991–2000 was 0.6°C higher than the average for 1981–90 (Pernaravičiūtė 2004). In turn, the increase in water temperature in Lithuanian lakes began in 1981–85 and has continued to this day (Kilkus and Valiuskevicius 2001). Similar increases in water temperature were observed in lakes and artificial reservoirs in Belarus (Danilovish 2005). The effect of these changes is that water temperatures of 0.2, 4 and 10°C occur earlier in spring by up to 5 to 11 days and in autumn by up to 7 days.

Lakes on the American continent have also undergone similar changes. A more than 100-year series of surface water temperatures in Lake Superior (Great Lakes) shows that summer open-water temperatures in the lake have increased by about 3.5°C over the past century, with most of this warming occurring in the last three decades of the 20th century. During the summer (July–September), surface water temperatures in many lakes have increased by a rate of 1.1°C·dec^{-1} (Austin and Colman 2008). Based on the average daily surface water temperatures in coastal areas for the American Great Lakes (Michigan, Huron, and Erie), it was determined that the average annual water temperatures in the years 1916–1992 showed a positive trend (~0.01°C·year^{-1}), which extended the potential duration of the period with thermal stratification (McCormick and Fahnenstiel 1999; Schmid and Köster 2016). For a large group of lakes in north-western Ontario, 20 years of climatic, hydrological and ecological observations confirmed an increase in air and water temperature in the lakes of almost 2°C, while the period without ice phenomena extended by three weeks (Schindler et al. 1990). The response to global climate warming in Canada is the duration of the ice cover on the lakes, which has decreased significantly since the second half of the 20th century. Calculated trends for 1951–2000 apparently show earlier dates of ice sheet retreat (Duguay et al. 2006), especially in Western Canada.

Surface water temperature studies conducted on lakes in Poland covering the period 1961–2020 also confirm the positive trend occurring in European lakes. For most lakes it ranges from 0.2°C to 0.9°C and only in Lake Łebsko and Jeziorak do they exceed 1°C per decade (Skowron 2001, 2011; Sobolewski et al. 2014; Skowron and Jaszczyk 2023).

Numerous studies conducted on lakes in the Polish Lowlands indicate a statistically significant warming trend in all lakes, with an average increase of 0.35°C per decade. Monthly trends were most pronounced in June, September, and November, exceeding 0.50°C per decade in some cases (Ptak et al. 2025). For 25 lakes in northern Poland, the impact of future climate change on lake surface water temperature (LSWT) predicted by an air–water model that relies solely on daily air temperature (AT) as model input was found (Piccolroaz et al. 2021). Based on data from 1972–2019, studies of Lake Śniardwy showed that the mean annual surface water temperature increased on average by 0.44°C·dec^{-1} and was higher than the increase in air temperature (0.33°C·dec^{-1}). In the monthly cycle, the most dynamic changes occurred in April (0.77°C·dec^{-1}) (Ptak et al. 2020). Similar results were observed for Lake Miedwie. Based on model data, long-term changes in water temperature were determined, which historically (1972–2023) amounted to 0.20°C·dec^{-1}. According to the adopted climate change scenarios, by the end of the 21st century, the mean annual water temperature will be 1.8°C higher (Ptak et al. 2024a). Studies on two lakes in Poland (Biała Augustowskie and Studzieniczne), with the longest continuous surface water temperature measurements (1954–2023), revealed a relatively stable thermal regime until the end of the 1980s and a significant change over the last three decades, during which water temperature increased at a rate of 0.5°C·dec^{-1} (Ptak et al. 2024b).

For several lakes in Central Europe and Poland, lake ice observation data from the last seven decades (1954–2023) were used to determine changes. The results showed that for all lakes, ice appearance was delayed by 1.8 days per decade, and its disappearance tended to be earlier by 3.6 days per decade. In this respect, the duration of ice cover decreased on average by 6.5 days per decade. Ice cover duration decreased by 40, 32, 40 and 45% for the four lakes, respectively, while for all lakes the maximum ice thickness decreased on average by 3.3 cm per decade (Zhu et al. 2025). For six decades (1961–2017), an analysis based on a one-dimensional hydrodynamic model showed that, in five lakes in northern Poland that differ in morphometry, the duration and thickness of ice cover decreased by 5.4 days per decade and 2.5 cm per decade, respectively (Bartosiewicz et al. 2021). The rate of change will be greater in smaller lakes than in larger ones, especially those located further inland. Despite the relatively small study area, significant variability was observed, with mean differences of 26 days for the onset of ice cover, 17 days for its end, 15 cm for ice cover thickness, and a 30-day difference in the mean duration of ice cover. Key factors included lake volume, mean depth, and land use in the immediate catchment (Ptak et al. 2024c). An analysis of the temporal and spatial variation of ice cover occurrence on 67 lakes of varying area in the Drawsko Lake District for the years 1984–2022 was presented based on satellite data from the Landsat 4, 5, 7, 8 and 9 missions. It was shown that the extent of ice cover on lakes is determined by the lakes' surface area; average and maximum depth, volume, length and width; and altitude above sea level (Sojka et al. 2023). The work of Ptak and Sojka (2021) found that, in all the studied lakes of northern Poland in the years 1960–2019, there was a successive decrease in the extent of ice cover on lakes, clearly visible in individual parameters: the formation of ice cover is delayed by 3.0 days·dec^{-1} (on average for all lakes), its disappearance occurs earlier by 3.8 days·dec^{-1}, and the length of the ice cover is shorter by 6.8 days·dec^{-1}.

Measurements of water temperature in lakes in Europe have confirmed the increasing influence of zonal atmospheric circulation, especially since the early 1990s (Hurrell 1995; Straile et al. 2003; Dokulil 2013). The intensity of air mass inflow over the area of Western Europe, the Baltic Coast and the East European Lowland is determined by the activity of permanent atmospheric pressure systems – the Icelandic Lowland and the Azores High, expressed by the NAO (North Atlantic Oscillation) coefficient. Studies have shown that the North Atlantic Oscillation has the greatest impact on the thermal regime of lake waters in the analysed area, especially in winter (Skowron 2011; Wrzesiński et al. 2015).

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Received 3 June 2025
Accepted 10 October 2025