Current Climatic Conditions of Lake Regions in Poland and Impacts on Their Functioning

Andrzej Górniak

Contents

Abstract The condensed characteristics of the climate of Poland are presented with particular emphasis on the areas of lake districts. More detailed studies were provided on 19 lakes with daily hydrological and thermic observations in the calendar years 2000–2016. Climate warming is clearly observed in observational temperature data, with increases of 0.2–0.4°C per decade. Slightly lower air temperatures and a higher annual sum of precipitation in relationship to neighboring regions are specific for the Polish Lakelands. Mean annual air temperature in the eastern part is 1.5°C lower than in the western regions. Much greater variation of precipitation and climatic water balance was noted, where the Wielkopolskie and Lubuskie Lake Districts have a permanent water deficit that is not observed in the rest of the Lakelands. Polish postglacial lakes are characterized by generally small fluctuations in water level, whereas variations in artificially regulated lakes are higher than in lakes with a natural regime, as well as a higher frequency of decreasing water level trends. Only a few lakes have a statistically significant increase of lake water temperature, mostly in northeastern Poland. A simulation indicated that in year 2050 the annual lake water temperature will be 1.1–1.9°C

A. Górniak (✉)
Department of Hydrobiology, Institute of Biology, University of Białystok, Białystok, Poland
e-mail: hydra@uwb.edu.pl

E. Korzeniewska, M. Harnisz (eds.), *Polish River Basins and Lakes – Part I*,
The Handbook of Environmental Chemistry 86,
https://doi.org/10.1007/978-3-030-12123-5_1

higher than at present. We can expect more evident changes in lake functioning in spring and summer, shifting lakes toward higher trophy, but dystrophic lakes will remain more humic when their hydrology is stable.

Keywords Climate · Global change · Lakes · Tendency · Water temperature

1 Introduction

The thin gas cover of the Earth, the atmosphere, has been constantly evolving, as has that for other spheres, during its existence over several billion years. On the geological scale, changes in the atmosphere reflect the spatial changes of the land, as well as its biotic structure. After the postglacial restructuring of the environment, a zonal climate system was created on Earth. The climatic conditions varying in different locales are a vector of six fundamental climatic factors: latitude, Earth–Sun relationships, position on the continent, atmospheric and oceanic circulation, topography, and local features [1].

Until recently, it was recognized that the weather system in a given place for at least 30 years can be considered as characteristic for the geographic regions or smaller parts of the continents. Global climatic classification by Köppen (or its modifications), Thornthwaite, Holdrige, and Budyko are used to show climatic differences of the Earth [1]. In Poland, the W. Okołowicz climatic classification has a tradition of long use [2].

Global weather observations in the twentieth century, constantly improved, expanded, and automated, indicate climate change and the need for constant monitoring. The World Meteorological Organization (IPCC groups) recently suggested climate evaluation in 10-year periods to better recognize the direction and rate of climate change [3].

Constantly increasing human activity and its various effects are considered the most important factors in the recorded changes of the Earth's climate in time and space. In addition to natural causes, anthropogenic causes of climate change on a global scale are primarily air pollution (emission of heat, gases, dusts), deforestation, and alterations in the water cycle. Direct effects are the mechanisms of global warming, such as local urban heat islands, melting of the ice cover, smog, and desertification, which are contributing to difficulties in economic management and reducing the scale and value of environmental services. Natural disasters, which are now occurring with greater frequency, will increase social unrest and provoke political tensions on a national or international scale [3].

Climatic changes do not remain unrelated to natural environmental processes, both chemical and biological, which directly or indirectly affect human beings to different degrees. The hydrosphere is considered the most sensitive part of the geosystem during climate changes, because it is an energy storage system, a carrier of elements or chemical compounds during circulation and between different organisms, and thus regulates the ecosystem energy budget.

The aims of this present study are the minimized characteristics of the Polish climate and its changes, with particular emphasis on lake districts, where freshwaters are more frequent. Two of the many functional aspects of the lakes, that is, the dynamics of water resources and the thermic regime, were selected to show the emerging effects of climate change in Poland. Considerations for the prediction of the effects of climate change on the functioning of lakes in the near future are summarized.

2 Material and Methods

Daily weather observations and hydrological data came from the database of the Institute of Meteorology and Water Management in Warsaw and data published by the Governmental Statistical Office of Poland [4]. The authors' calculations of monthly and annual means of climatic parameters for seven meteorological stations were made from data of the years 2000–2016, when evident climate changes are seen. Chosen stations represent longitudinal differentiation of climatic conditions in postglacial Lakeland regions in Poland. I have added a Włodawa station from the Polesie Lubelskie region (Southeast Poland), where the small lakes groups occur (Fig. 1, Table 1). Evapotranspiration for each month and station in the calendar years 2000–2016 was calculated using the Ivanov formula, which is frequently used in hydroclimatic studies.

For detailed analysis, I selected 19 lakes, including 6 lakes where the water level is modified by man for waterway communication or energy production. In this group the dimictic lakes dominate; only the Łebsko Lake is polymictic, where Baltic

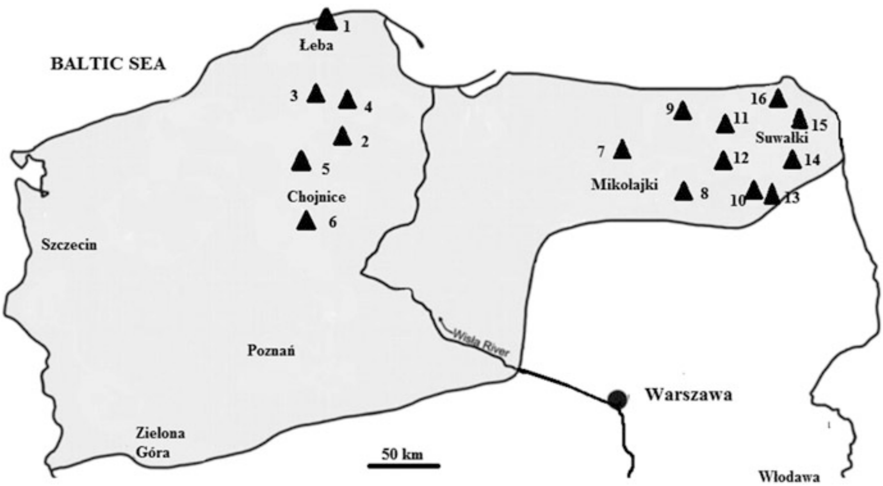


Fig. 1 Location of meteorological stations and lakes under study

Table 1 Description of locations from which meteorological data originated in relationship to Polish lake districts

Meteorological stations	Station elevation [m a.s.l.]	Lakeland names
Suwałki	184	Suwalskie
Mikołajki	128	Mazurskie
Chojnice	164	Pomorskie-East
Łeba	2	Shoreland
Poznań	87	Wielkopolskie
Zielona Góra	192	Lubuskie
Szczecin	1	Pomorskie-West
Włodawa	177	Łęczyńsko-Włodawskie

seawater can flow into the lake during storms. Selected lakes include the largest in Poland, Mamry Lake, and also the deepest, Hańcza Lake. For these lakes, almost complete series of water level up to the year 2017 were available, with daily water temperature measurements also available for 16 lakes. For 2 lakes only, Wigry and Hańcza, longer series of water temperature are presented as examples of much longer trends. The mean monthly lake water level and water temperature (measured at depth 0.4 m of the inshore zone) were calculated in calendar years. Data of the Hurrell North Atlantic Oscillation (NAO) Index for the winter period (December–March) originated from the USA National Center for Atmospheric Research [5].

Data computation utilized the statistical program Past [6]. A Mann–Kendall test was used for trend detection in time data series, in which Z (statistic test) and p (level of significance) were computed.

3 The Climate of Poland and Its Changes

3.1 Climatic Conditions of Poland

The terrain of Poland allows unrestricted latitudinal air exchange, whereas free meridian movement of air is difficult, especially from the south, because of the mountain range. The location of Poland in Central Europe means that climatic conditions have features typical of the temperate zone with domination of western air mass circulation as well as the main wind direction. The Azores anticyclone and Iceland low pressure center are important in the creation of weather types, although the continental air masses (arctic from the northeast or tropical from the southeast direction) also periodically reach Poland. A polar maritime air mass has the highest frequency (more than 60% of days) in the year; the frequency of arctic masses is three times smaller, nearly a 12% polar continental mass of air. These geographic features cause the climate of Poland to experience a transitional nature between oceanic and continental varieties. This nature is manifested by increasing maritime features toward the west and increasing continentalism toward the east. As a consequence, Okołowicz [2], in his climate classification, distinguished in Poland a temperate transitional climate and also a local mountain climate for the Carpathian and Sudety Mountains in the southern part of the country. The transition of the climate of Poland from the continental to the oceanic variety is also manifested in the existence of two additional seasons, early winter and early spring.

An important feature of the climate of Poland is the significant variability of weather from day to day, as well as large differences in weather at the same time of the year but in different years.

The latitudinal layout of the geographic regions is also reflected in the thermal and humidity diversity of the country (Table 2). Current spatial variation of mean annual air temperature (in the past decade, 2001–2010) is in the range of 7.9°C in mountain regions, 8.5°C in uplands, 8.8°C in the lowlands, and 8.7°C in shorelands [7]. Latitudinal thermal differentiation of the country is more prominent than longitudinal. Decrease of air temperature amplitude from east to west is also characteristic. In the western part of the country, there are no frosts for 4 to 5 months a year, while in the eastern part of the country only in July and August do frosts not occur. Hot days (T_{max} >25°C) occur from 15 to 20 times a year on the coast and from 25 to more than 30 times a year in the south in the center of the Poland. Heat waves are noted to be very rare, about 3 to 8 occurrences in the years 2000–2010. Air temperature variability in space and time is connected to the duration of the thermal growing season, which varies from 200 days in northeast Poland to 240 days in the southwest regions [8].

Mean annual precipitation in Poland increases from 450 mm in the Wielkopolskie Lakelands to 900 mm in submontane and Pomeranian Lakelands regions, and up to 1,800 mm in the highest parts of the Tatry and Sudety Mountains. Summer precipitation is the highest (maximum, July); in the lowlands it is about 20% of the annual

Table 2 Latitudinal (A) and longitudinal (B) variability of mean air temperature and precipitation in Poland

Group	Stations	Latitude N	Longitude E	Temperature		Precipitation	
				1971–2000	2001–2016	1971–2000	2001–2016
A	Łeba	54.75	17.53	7.7	8.5	632	699
	Suwałki	54.13	22.95	6.3	7.2	591	634
	Chojnice	53.70	17.55	7.3	8.1	547	633
	Toruń	53.03	18.58	8.1	8.9	528	568
	Łódź	51.73	19.40	8.0	8.8	571	590
	Częstochowa	50.82	19.10	8.0	8.9	617	645
	Kraków	50.08	19.78	8.1	8.9	662	684
	Zakopane[a]	49.30	19.95	5.4	6.3	1,107	1,163
B	Terespol	52.07	23.62	7.5	8.4	512	551
	Włodawa	51.55	23.53	7.5	8.4	515	577
	Warszawa	52.17	20.97	8.1	9.0	519	566
	Kalisz	51.73	18.08	8.4	9.3	507	492
	Poznań	52.42	16.83	8.5	9.4	507	545

Data from Governmental Statistical Office [4]
[a]Mountain station (elevation 840 m a.s.l.)

total and in the Lakelands and uplands more than 30%. Precipitation occurs mainly in the form of rain; sleet and snow are only about 12% of the annual total precipitation. The total duration of rainfall in Poland is 10% of the year, and precipitation occurs on 150 to 180 days in a year [9]. An increase in the ratio of precipitation in the cold period to precipitation in the warm period is observed. The precipitation yield is the highest in the summer, and periodically extreme precipitation causes local floods (flash floods) or regional floods, as, for example, in the summers of 1997, 2005, and 2010.

Snow cover in Poland (except in mountainous areas) occurs from October to April; the longest duration, nearly 100 days, occurs in the eastern lake districts, and the shortest, about 40 days, in the west [10]. The winter snow season is the sum of several periods with a snow cover, and the height of the snow cover differs greatly between consecutive winters. Snow cover duration indicates an 8-year periodicity in Poland [11].

The sum of evapotranspiration in the growing season from April to September exceeds 500 mm in most areas of Poland, with a mean of 520 mm. It is commonly assumed also that periods with drought occur in Poland once every 4 to 5 years [12], especially in the southern part of the Polish Lakelands (Wielkopolskie, Lubuskie). Drought usually begins in western Poland, moves through the central part, and eventually reaches the eastern side of the country. A tendency toward an increasing number of dry days is observed.

The spatial diversity of cloudiness in the country is not great, around 5.0–5.6 oktas on the octant scale; only in the mountains is this higher. Minimal rates of cloud cover are in May and August; the maximum values fall in November and December. Full and nearly full overcast skies (7–8 oktas[1]) are the most frequent condition in Poland, near 35–40% of the days in a year [13]. The largest number of cloudless skies was recorded in March, April, and August. Mean annual sunshine duration (in hours) is more variable than cloudiness, with the range of 1,400–1,650 h/year showing decreasing values from east to west.

Three first-order climates exist in Poland in the light of the global climate map with the scheme by Köppen [14]: these are C-mesothermal and D-microthermal, both in the wet suborder (constantly moist), with warmest months <22°C, and the H-mountain type of climate. Climate Cfb (mesothermal with significant precipitation in all seasons and warmest month averaging below 22°C) is dominant over Dbf (microthermal with warm summer, fully humid with snow cover in winter): the latter occurs only in the northeastern part of Poland.

3.2 Climate of the Polish Lakelands

Polish lake districts are slightly elevated in relationship to the surrounding regions, and thus are characterized by slightly lower air temperatures and an increased annual sum of precipitation. Currently, the mean annual air temperature is between 8.1 and 9.6°C; only the most eastern outskirts of the Suwałki Lake District are definitely cooler (Table 3). The highest thermal variation was observed in the coolest and

[1]Scale of cloud cover is measured in oktas.

Table 3 Rates of selected climatological parameters in the Polish Lakelands in the years 2000–2016

Parameters	Suwałki	Mikołajki	Chojnice	Poznań	Włodawa	Szczecin	Zielona Góra
Annual air temperature	7.2	8.1	8.2	9.5	8.4	9.6	9.4
Annual precipitations	618	615	628	547	584	571	599
Annual evapotranspiration	500	536	540	704	599	586	722
Annual sun duration [h]	1,715	1,797	1,877	1,868	1,827	1,719	1,733
Sun duration (May–Aug)	997	1,025	1,040	1,038	1,034	955	929
Cloudiness [octants]	5.2	5.2	5.5	5.1	5.3	5.1	5.2
Days with snow cover	80	65	54	39	66	28	46
Days with rain	118	121	133	122	109	142	126
Days with snow	52	49	44	33	50	29	41
Days with storm	22	27	25	22	30	19	28
Days with wind >10 m/s	26	8	28	29	30	30	5
Wind [m/s]	3.6	3.1	5.5	3.6	3.7	3.8	3.0

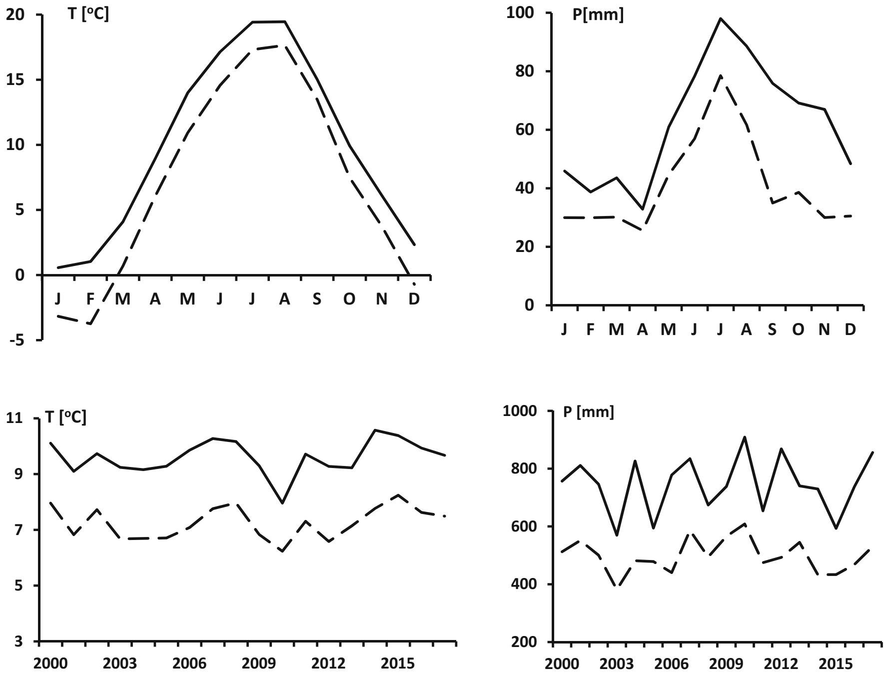


Fig. 2 Seasonal (*upper panel*) and multiannual (*lower panel*) variability of air temperature and precipitation in Lakelands regions in years 2000–2016 (minimum and maximum data for stations in Table 3)

hottest periods (Fig. 2). Pluvial differences of the Polish Lakelands with the highest intensity are observed in the second part of the year, with the maximal variation in July and the least in April.

The current climatic water balance (precipitation − evaporation) of the Polish Lakelands is very different in different locations: the eastern and more northern parts have a positive balance (Suwałki, 118 mm; Mikołajki, 79 mm), but the Lakelands located to the west and south have a negative water balance (Poznań, 257 mm) (Table 3).

This difference in balance is the result of the seasonal differences of the relationship of precipitation (P) to evaporation (E): in the Suwałki Lake District the predominance of evaporation over rainfall lasts on average 3 months (April–June), whereas in the western and southern parts of the Polish lake districts this pattern continues for 6 months, from April to September (Fig. 3).

Another climatic difference between the eastern and southwestern lake districts concerns the seasonality of cloudiness and sun duration, wherein the eastern parts have better solar conditions then the western part (Fig. 3, Table 3). Also, sunshine duration has decreased in the past 17 years in the eastern lake districts, although in the remaining areas this tendency was not observed (Figs. 4 and 5).

Also, anemometric conditions varied in the Polish Lakelands, where the East Pomeranian Lakelands and the shorelands area (not presented in Table 3) have a

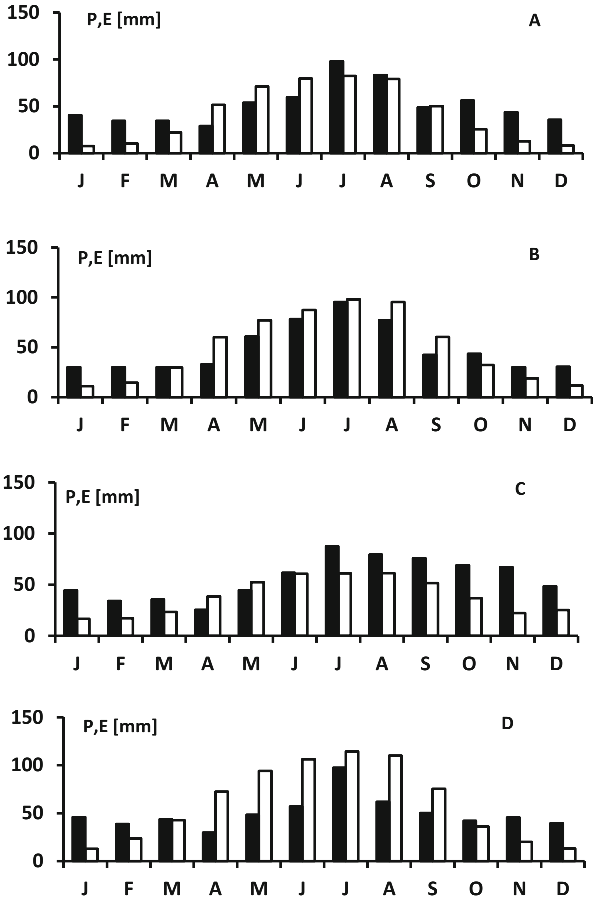


Fig. 3 Mean monthly precipitation (*black bars*) and evapotranspiration (*white bars*) in the years 2000–2016 in selected meteorological stations: (**a**) Suwałki, (**b**) Włodawa, (**c**) Łeba, (**d**) Zielona Góra

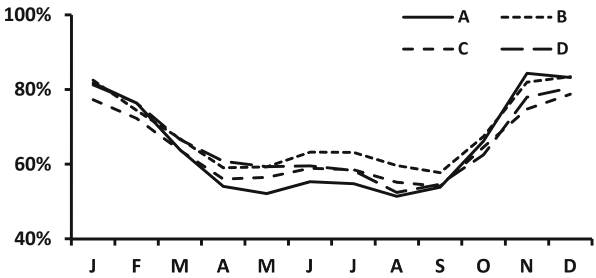


Fig. 4 Mean monthly cloudiness data (recalculated from octant scale to % of sky) in selected stations in the period 2000–2016: A, Suwałki; B, Chojnice; C, Poznań; D, Włodawa

significantly higher average wind speed in a year than occurs in other locations. In the period from October to March, wind speed was about 20% higher than in the period from April to September (Fig. 6). Moreover, in Mikołajki and Łeba stations in the analyzed period 2000–2014, a significant increase of mean annual wind velocity was noted.

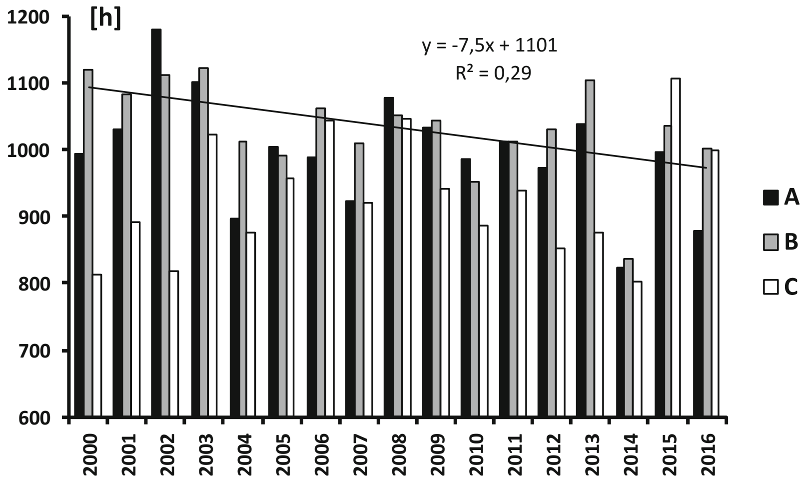


Fig. 5 Multiannual changes of sun duration in May–August periods in selected stations in years 2000–2017: A, Suwałki; B, Włodawa; C, Zielona Góra; trend line for Włodawa station

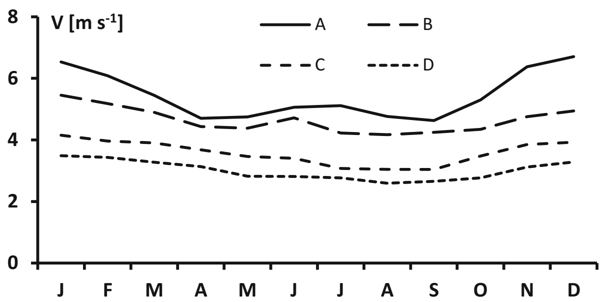


Fig. 6 Mean monthly wind speed [m s^{-1}] in the different lake districts in Poland in the years 2000–2016: A, Chojnice; B, Łeba; C, Suwałki; D, Zielona Góra

As the latest Intergovernmental Panel on Climate Change (IPCC) report emphasizes, the climate of the earth continues to warm, and the rising temperature trend is superimposed on the inherent natural variability [15]. The recent trend of annual mean temperature in Central Europe exceeds the global mean land trend. The temperature is expected to rise by about 1.2°C by 2035 (probability, 50%) and precipitation to increase by 5–7% [3]. IPCC authors point to a very likely increase in the number of warm days and nights and a decrease in the number of cold days and nights. Also indicated are general increases in the intensity and frequency of extreme precipitation, especially in winter [16].

Wójcik and Miętus [7] noted that changes of annual air temperature in Poland show a statistically significant increase with an average rate exceeding 0.2°C per decade. In the decade 2001–2010, the rate in February was more than 0.5°C/ 10 years. The highest rate of temperature increase was detected in northern Poland, including the Lakeland regions, whereas the lowest rate of increase is observed for the highlands and the Sudety Mountains.

In the short analyzed period of 17 years (2000–2017), by climate analyses no statistically significant changes were noted in the majority of the present climate parameters of Polish lake districts. Such changes can be detected only over a longer period of time. It is widely recognized that global warming began to increase at the end of the 1970s, and from that time on, increasing environmental effects could be expected during climate change [3].

4 Polish Lakes Under Climatic Changes

4.1 Lake Water Storage Changes

One of the effects of climate change is the transformation of the water cycle on the lands, including lake water resources. As Bajkiewicz-Grabowska emphasized [17], the reaction of lakes to changes in the nature of the water cycle can vary depending on location in the water system, conditioned by the geological structure, and especially the relationship between lakes and groundwater. Therefore, in the 19 Polish lakes analyzed, both a statistically significant decreasing tendency of the level of Lakes Jasień, Raduńskie, and Dzierzgoń and an increase in the amount of water in Lakes Sępoleńskie, Rospuda, and Studzieniczne were noted (Table 4, Fig. 7). However, for the majority of the lakes analyzed there are no significant changes in water level attributable to climate change, because in many of these the water level is artificially regulated within waterways or for the operation of hydroelectric plants [18]. The noted changes in the water abundance of these lakes are usually caused by human activity and result from climate change to only a small extent.

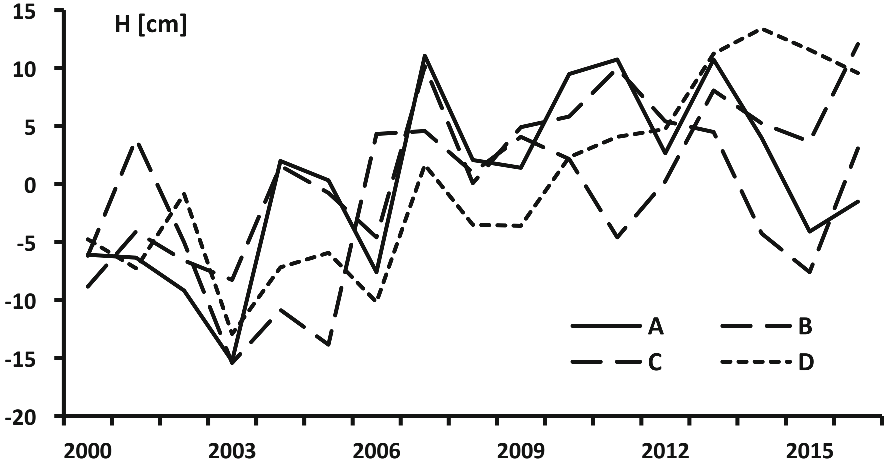
It is interesting to note that for lakes with larger areas and with artificially regulated water levels (lakes italicized in Table 4), a decreasing tendency is detected, although this is not significant statistically.

The mean annual amplitudes of water level in these regulated lakes were also higher than in unregulated lakes, in which this amplitude is rather lower than 30 cm and the standard deviation of water level variation is less than 20 cm (Table 4). The monthly amplitude of lake water level was small, in the range 5–20 cm, except in Łebskie Lake, which is located in the shoreline and is hydrologically both a catchment and one impacted by the Baltic Sea. Variability of lake water level results from the different shape of the catchment and the types of geological structures in postglacial areas; in consequence, the intensity and amount of flowing water from the basin to the lakes varies [19]. Mean annual amplitude of lake water level has no regular fluctuations as in the Jasień Lake (Fig. 8C), where these are the smallest from all lakes analyzed. Only in two lakes, Sępoleńskie and Charzykowy, have I detected a significant decrease of amplitude rates (Fig. 8A, B). This condition has probably resulted in a negative water balance in past years, when groundwater accumulated

Table 4 Basic morphological data of lakes studied and parameters of lake water levels in the years 2000–2016

No.	Lakes	Area	Volume	Mean depth	Elevation	Mean monthly amplitude	SD	Max amplitude	Water level tendency
		ha	mm^3	m	m a.s.l.	cm	cm	cm	
1	Łebsko	7,142	118	1.6	0.9	38.8	14.1	180	
2	Wdzydze	1,417	221	15.2	133.8	8.7	15.1	73	(–)
3	Jasień	577.2	283	5.0	112.7	5.0	5.5	36	–
4	*Raduńskie*	363	60	15.5	161.6	7.0	5.7	43	–
5	Charzykowskie	1,364	135	9.8	120.2	8.6	11.2	71	(–)
6	Sępoleńskie	158	8	4.8	112.8	13.0	10.9	76	+
7	Dadaj	978	121	12.0	122.5	12.8	24.0	136	
8	*Mikołajskie*	424	56	11.2	116.7	7.2	13.0	70	(–)
9	*Mamry*	9,851	1,003	9.8	115.8	7.8	13.4	74	(–)
10	Selmęt Wielki	1,208	99	7.8	120.7	9.1	23.4	76	
11	Litygajno	155	10	6.0	132.8	14.1	10.1	122	
12	Ełckie	382	57	15.0	118.9	15.5	14.5	101	
13	*Rajgrodzkie*	1,503	143	9.4	118.4	19.2	30.5	147	(–)
14	*Studzienicze*	244	22	8.7	123.4	7.3	5.9	39	+
15	Wigry	2,118	337	15.8	131.9	5.9	10.3	51	(+)
16	Hańcza	292	120	38.7	227.3	10.7	11.9	77	
17	Dejguny	765	93	12.0	116.8	6.6	14.1	73	
18	Dzierzgoń	834	296	6.4	81.5	11.4	29.7	151	–
19	Rospuda F	323	50	15.0	170.3	7.3	10.8	64	+

Italicized lake names indicate regulation of water level
SD, standard deviation of all monthly water levels
Brackets indicate tendency not significant by Mann–Kendall test



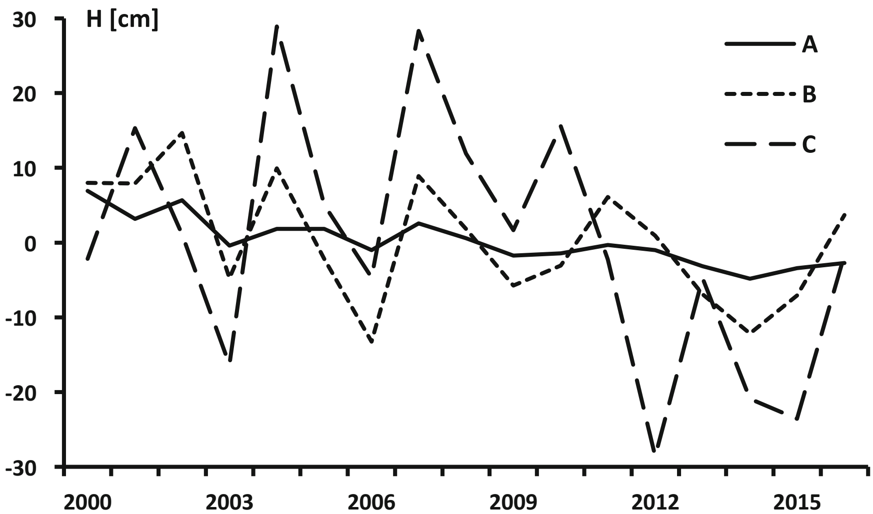


Fig. 7 Changes of annual lake water level in the years 2000–2016: *upper*, lakes A, Wigry; B, Sępoleńskie; C, Mikołajskie; D, Rospuda; *lower*, lakes A, Raduńskie; B, Rajgrodzkie; C, Wdzydze

new rain portions, filling its own resources and limiting the load in lakes. A similar water level regime with no regular fluctuations was observed in lakes in northeastern Poland [20], located in the Łęczyńsko–Włodawskie lake district [21, 22].

The varied response of lakes to atmospheric water input and/or surface runoff is even better seen in the analyses of monthly water level runs (Fig. 9). The earliest lake hydrological reaction was observed in the East Pomeranian Lakes (group C) with a maximum water level in February or March, except Charzykowy Lake, and in March or April in most Polish lakes. Lakes from the Suwałki group have a similar

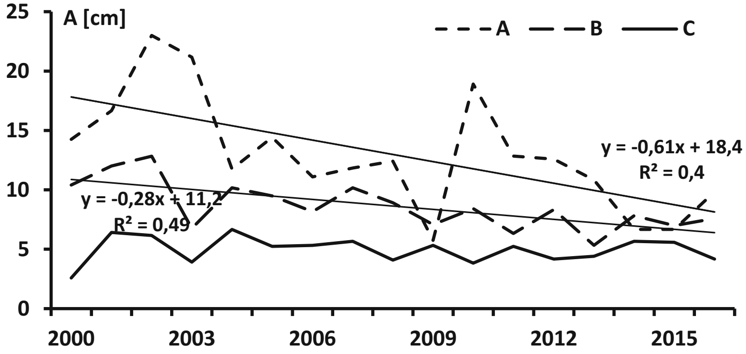


Fig. 8 Multiannual changes of mean annual amplitudes of water level in selected lakes: A, Sępoleńskie; B, Charzykowskie; C, Jasień; in the years 2000–2016

hydrological system. In the other groups presented in Fig. 9, there is a distinct type of lake with a maximum of water seen later, such as Ełckie Lake, Rajgrodzkie Lake, or Charzykowskie Lake. Łebskie Lake has a completely different hydrological seasonality with a maximum in December and January. An equally exceptional lake is Jasień Lake (in the E group in Fig. 9), with a very uniform level of water throughout the year that very rarely reacts to the inflow of atmospheric waters.

Summing up, it can be stated that Polish postglacial lakes are characterized by generally small fluctuations in their water level. Only in lakes with artificially regulated water level can there be significant amplitudes of variations, for example, Lake Rajgrodzkie, or a reduced amplitude of level fluctuations, for example, Lakes Mamry and Mikołajskie. As most of these are through-flow lakes, they are included in water systems in which local hydrogeological conditions determine the rate of water circulation and react differently to both atmospheric supply and anthropogenic changes in water discharge [17, 18, 23]. Weyhenmeyer [24] showed that a response to climate change seen in one lake may be very different in another. In the majority of analyzed lakes there are no long-term tendencies of changes in water level, which indicates a generally limited reaction of lakes to progressive climate changes because local river–lake systems exhibit high self-regulation abilities. Therefore, these systems are relatively resistant to climate-driven changes, which confirms that lakes can act as sentinels of climate change [25].

During long-term water deficits in lake basins (drought), the network of streams connecting the lakes frequently disappears. For lakes with a smaller surface area droughts are a significant threat, because the small underground sub-basin is not able to compensate for the loss of evaporating water. In large lakes, the share of horizontal groundwater supply is significant, because their basins are characterized by substantial underground retention and unit outflows are two or more times higher than observed in lowland basins [17, 18]. Lakes can show various hydrological functions even in the same system, whether drainage, retention, or convertible, depending on precipitation rate in a given period [18]. It is thus explained why

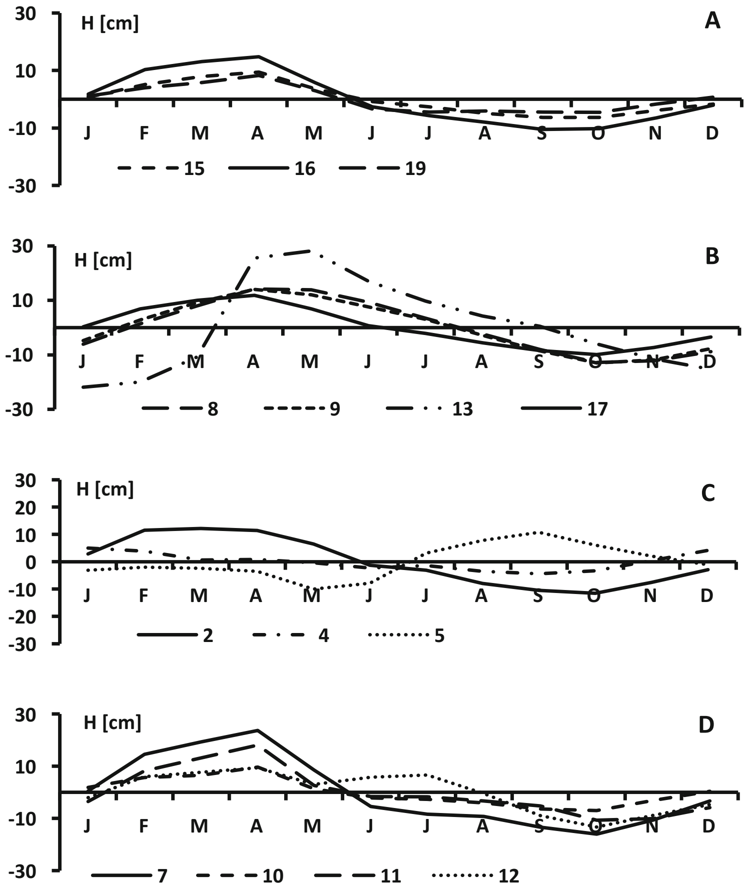


Fig. 9 Mean monthly lake water level (in relationship to mean level) in the years 2000–2016. Lake numbers as in Table 4: A, Suwałki group; B, Mazurian group; C, Pomeranian–East group; D, Ełk group; E, specific lakes group

lakes in the same climatic location have varying tendencies, as shown by the data presented here.

4.2 Lake Water Temperature Regime and Recent Tendency

Surface and epilimnetic water temperatures, which can be highly correlated with regional-scale air temperatures, exhibit a rapid and direct response to climatic forcing, making epilimnetic temperature a useful indicator of climate change [25, 26]. In the Polish lakes the recent mean water temperature is in the range

Table 5 Mean of selected monthly, annual, and maximum temperatures and results of Mann–Kendall time series test of lake water temperature in the years 2000–2016

No.	Lakes	Mean water temperature [°C]					Max.	Mann–Kendall test		
		Feb	May	Jul	Nov	Year		*Z*	*p*	Significance
1	Łebsko	1.5	14.0	19.7	5.4	9.8	25.2	2.16	0.03	+
2	Wdzydze	1.9	13.5	20.4	7.5	10.4	25.9	1.86	0.06	–
3	Jasień	1.7	14.5	20.6	8.0	10.7	25.4	1.20	0.23	–
4	*Raduńskie*	1.8	12.7	19.3	6.8	9.9	24.8	1.40	0.16	–
5	Charzykowskie	1.6	13.7	20.2	7.2	10.3	26.1	3.31	0.00	+
6	Sępoleńskie	1.5	15.3	21.3	6.9	10.9	26.8	1.90	0.06	–
7	Dadaj	1.3	14.3	21.3	7.0	10.5	27.5	2.98	0.00	+
8	*Mikołajskie*	1.1	13.2	20.8	7.5	10.3	27.2	2.11	0.03	+
9	*Mamry*	1.0	13.4	20.5	6.1	9.8	26.9	2.54	0.01	+
10	Selmęt Wielki	1.2	14.2	21.1	6.6	10.3	26.6	1.92	0.05	–
11	Litygajno	1.1	14.2	21.3	5.9	10.2	26.7	1.87	0.06	–
12	Ełckie	1.3	14.8	21.4	6.8	10.5	27.1	0.37	0.71	–
13	*Rajgrodzkie*	1.3	14.4	21.7	6.8	10.5	28.1	0.96	0.33	–
14	*Studzienicze*	1.3	14.6	21.4	6.0	10.3	27.4	2.52	0.01	+
15	Wigry	1.3	14.1	21.5	6.6	11.5	27.6	2.34	0.02	+
16	Hańcza	0.9	10.9	20.0	4.9	9.0	26.2	1.04	0.30	–

Italics indicated the lakes with an artificial water level regulation

9–12°C with a monthly minimum in February and a maximum in July (Table 5, Fig. 10).

In the period 2000–2016, the maximal water temperature of 28.1°C was noted in Rajgrodzkie Lake. It should be noted that the discussed lake water temperature results come from one-time daily measurements at 6.00 (UT - universal time) and do not take into account the variation of temperature that occurs commonly throughout the day. During the day in spring and summer, the amplitude of water temperature change in the epilimnion of large lakes can reach several degrees Celsius (Górniak, unpublished data).

The highest monthly surface water temperature variation among Polish lakes is noted in April and May: in the rest of the year two changes less than 2°C were seen. The Mann–Kendall test for the period 2000–2017 indicated that only 40% of the lakes have a statistically significant increase of lake water temperature, located mostly in the eastern lake districts (Mazury and Suwałki Lakelands) (Table 5, Fig. 11), where a larger climatic gradient exists. Computed trends of lake water temperature were in the range 0.28–0.38°C per decade for the years 2000–2016. This trend results mainly from higher rates in the summer and spring, but in Jasień Lake from Pomeranian Lakeland, specific higher autumn rates were larger by effects of the groundwater supply (Fig. 10).

Only in Charzykowy Lake have I detected a strong increase of water temperature, with the trend of 0.081°C/year.

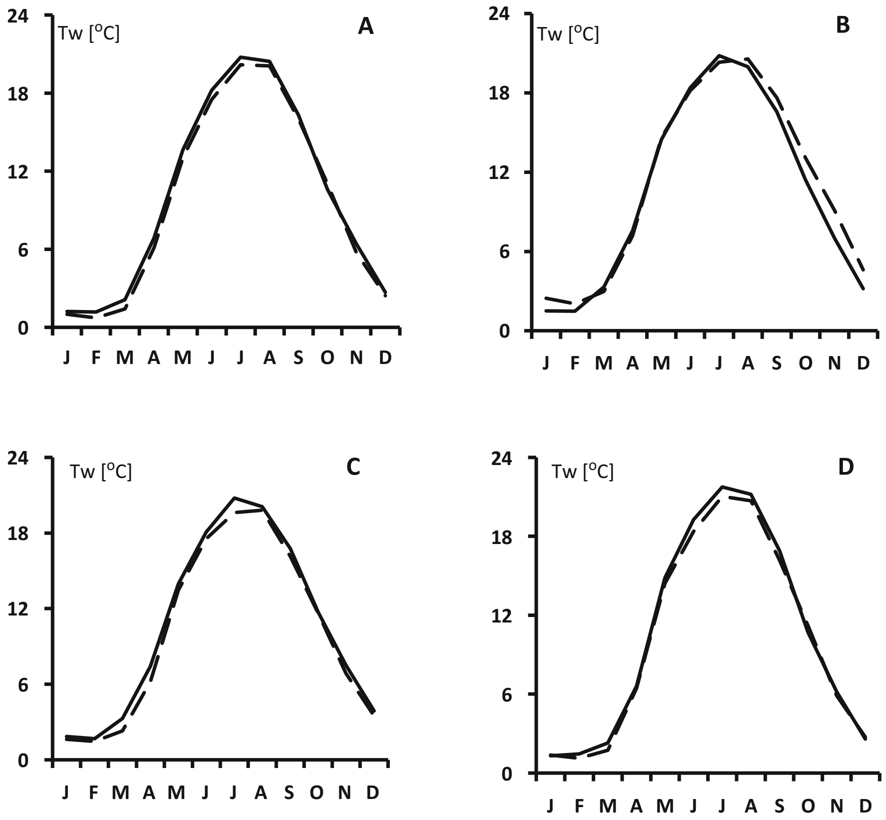


Fig. 10 Seasonality of monthly water temperature in lakes (**a**) Mamry, (**b**) Jasień, (**c**) Charzykowskie, and (**d**) Studzieniczne in two periods: 2000–2007 (*dashed line*) and 2008–2017 (*solid line*)

Skowron [27] documented that the Polish lake water temperature in spring increased fastest among seasons, about 0.2–0.5°C per decade. My results for Polish lakes from the period 2000–2016 are in agreement with global analysis, where national lake water temperature trend has been estimated as 0.34°C per decade in the years 1989–2009 [28] and for air temperature 0.25°C per decade [3].

Across the state of Wisconsin (USA), whole lake water temperatures increased with an average trend of 0.042°C/year (for the years 1990–2012). In large (>50 ha) lakes, the positive temperature trend was similar across all depths. In small lakes (<50 ha) the warming trend was restricted to shallow waters, so they respond differently than large lakes [29].

The recorded increase of air temperature in the spring season and early termination of ice phenomena is in agreement with Choiński et al. [30, 31], who showed that in long-time data series (1951–2010) average ice phenomena duration and ice cover decreased with a rate of 0.5 day/year. In winters with a positive NAO phase, the ice

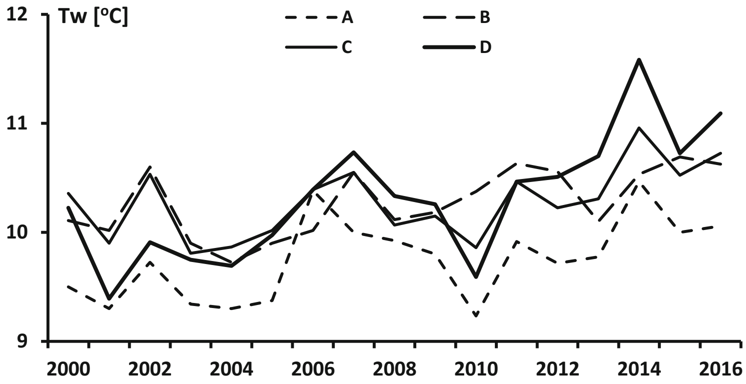


Fig. 11 Changes of annual lake water temperature (depth 0.4 m) in Łebsko Lake (A), Studzieniczne Lake (B), Mikołajskie Lake (C), and Charzykowskie Lake (D) in calendar years 2000–2017

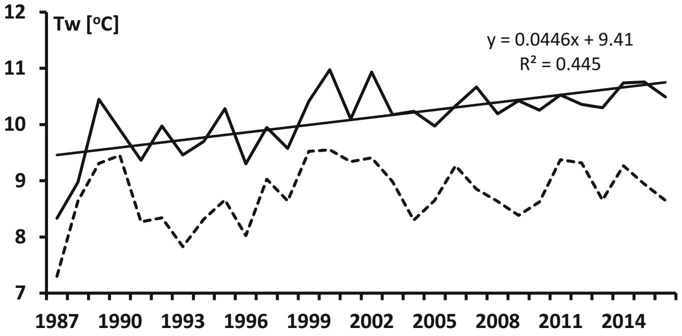


Fig. 12 Long-term variation of annual lake water temperature (depth 0.4 m) in Wigry Lake (*solid line*) and Hańcza Lake (*dashed line*) in calendar years 1987–2016; all data from Institute of Meteorology and Water Management

phenomena duration is significantly shorter than during negative NAO phases [32, 33].

Similar to the tendency for air changes, the analyzed period 2000–2016 is too short to find significant changes in the temperature of lake waters. For the aforementioned period there were no statistically significant trends in changes of Wigry Lake water temperature, whereas for a longer period (1987–2016) the trends proved to be statistically highly significant. However, for Hańcza Lake, the deepest in Poland, analysis for the 17-year and 30-year periods (Fig. 12) did not indicate any significant changes in water thermic regime under the influence of climate changes.

I have noted that there are significant statistical relationships between yearly water temperature in lakes and mean annual air temperature measured at the nearest meteorological station (Table 6). As presented in Table 6, the formulas show a high rate of R^2 and can be used for the prediction of lake water temperature during climate

Table 6 Relationships between annual air temperature and rate of increase of lake water temperature in selected lakes computed for the period 2000–2016

Station	Lakes	R^2	Formula	T_w 2050 [°C]
Suwałki	Studzieniczne	0.51	0.41*x* + 7.21	1.2
	Wigry	0.72	0.43*x* + 7.40	1.3
Mikołajki	Mikołajskie	0.51	0.38*x* + 7.21	1.1
Łeba	Łebskie	0.52	0.45*x* + 5.92	1.4
Chojnice	Sępopolskie	0.60	0.54*x* + 6.48	1.6
	Wdzydze	0.56	0.48*x* + 6.50	1.4
	Charzykowskie	0.50	0.62*x* + 5.32	1.9

R^2, determination index for $p < 0.001$; in formula x, mean air temperature [°C] is used

change. Assuming an increase in average annual air temperature in Poland as presented by Wójcik and Miętus [7], in 2050 the average temperature of lake waters should be expected to increase by 1.1–1.9°C. Predicted changes of water temperature in Wigry Lake using the formula from the multiannual lake water trend line (Fig. 12) and from the relationship between air temperature and lake water temperature were the same, that is, 1.3°C.

Whole lake water temperatures increased across the state of Wisconsin (USA) from 1990 to 2012, with an average trend of 0.042°C/year. In large (>50 ha) lakes, the positive temperature trend was similar across all depths. In small lakes (<50 ha), the warming trend was restricted to shallow waters, so they respond differently than do large lakes [29].

Analysed lake water temperature tendencies of the four seasons in the period 2000–2016 were significant only for a small group of lakes (Table 7), located mainly in the western part of Poland with warmer climatic conditions. Charzykowskie Lake stood out from the others because in all seasons the trends were statistically significant. Also, in Jasień Lake negative lake water temperature tendencies (all statistically significant, $p < 0.001$) clearly manifested a change in the water cycle in the catchments. In this specific lake a higher winter water supply of the lake from groundwater, with a constant temperature (6–8°C), gives a "warming" effect. On the other hand, this may be an effect of the decreased role of surface runoff in the lake supply, which may also result in an increase of heat resources in the epilimnion of the lake. Tendencies of increasing temperature were much higher in the warm season (summer, autumn) than in the colder periods. For most lakes, the winter increase of water temperature was about 0.3–0.4°C per decade, close to the rate of air temperature change indicated earlier by Wójcik and Miętus [7].

Confirmation of significant changes of winter thermal conditions during climate warming in Central Europe is also found an increase in western circulation connected with the positive phase of NAO [32, 33]. I have found a significant correlation between the Hurell NAO Index and water temperature in most of the lakes under study (Table 6). NAO effects in Europe are known; also, most Polish lakes react with increased winter water temperature and reduced duration and intensity of ice phenomena [33–35].

Table 7 Tendency of lake water temperature for seasons in years 2000–2016 and determination coefficient (r^2) in correlation between mean lake water temperature in the period December–March and Hurrel NAO Index for these months

Lakes	Lake water tendencies [°C/year]				DJFM (period from December to March)	
	Spring	Summer	Autumn	Winter	r^2	p
Łebsko	0.04			0.033	**0.43**	**0.003**
Wdzydze		0.027		0.037	**0.30**	**0.031**
Jasień			**−0.180**	**−0.860**	0.01	
Raduńskie		**0.041**			**0.40**	**0.003**
Charzykowskie	**0.08**	**0.085**	**0.078**	**0.073**	**0.39**	**0.005**
Sępoleńskie		0.036		0.029	**0.37**	**0.007**
Dadaj		**0.068**	**0.056**	0.029	0.09	
Mikołajskie	0.03			0.034	0.15	
Mamry	0.04	0.068		0.036	0.16	
Selmęt Wielki					**0.42**	**0.003**
Litygajno	0.03			0.035	**0.29**	**0.021**
Ełckie	0.02				**0.29**	**0.039**
Rajgrodzkie					0.02	
Studzienicze			0.034	0.036	0.12	
Wigry					0.17	
Hańcza					**0.26**	**0.031**

Data from USA National Center for Atmospheric Research
Bold font indicates statistically significant tendencies ($p < 0.05$) in the Kendall–Mann test

4.3 Predicted Climate Change Impact on Lake Functioning

Lakes are commonly affected by multiple interacting stressors [36, 37], which could confound the signals from climate change. However, variations in surface water temperatures were highly synchronous (coherent) and related to fluctuations in air temperature, as also documented earlier for European lakes located more southwest from Poland by Dokulil et al. [38]. The same authors emphasize physical lake properties as a beginning of freshwater response to climate-driven change, which launched cascades down from physical parameters via chemical and nutrient variables to biological entities. The main and possible factors and climate-related drivers changing freshwaters have been identified and classified by Adrian et al. [25].

I have used their proposals of estimation of possible changes in Polish lakes under global warming with respect to seasonality and response features such as increase, decrease, shift, and meaningful fluctuations (Table 8). It should be mentioned that all freshwater ecosystems have a certain memory (physical, biochemical or biocenoitic) of past extreme events, the effects of which may appear with some delay, with an intensity not always predictable.

Moreover, the effects of changes in climatic conditions on hydrobionts are complex, difficult to distinguish from other influences, and not easy to generalize [3].

Table 8 Predictions of future changes in selected variables in Polish lowland lakes during climate changes

	Climate-related responses	Months											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Water level			◊	◊	◊	◊	◊	◊				
2	Water temperature		↔				↑	↑	↑		↔		
3	Stratification					↔							
4	Ice phenomena duration	↔									↔		
5	Turbidity (littoral)					◊							
6	Oxygen (meta- and hypolimnion)			◊	◊		↓						
7	TOC littoral			↑	↑			◊	◊	◊		◊	
8	Diatom development			↔									
9	Cyanobacteria blooms						↑						
10	Primary productivity			↑			↑						

↔ – shift in time, ↓ – decrease, ↑ – increase, ◊ – large fluctuations
TOC total organic carbon

All types of variables used in this proposal can be classified in four groups: hydrological (1), physical (2–5), chemical (6–7), and biocenoitic (8–10) (limited to producers only). According to the present scenario, summer and spring will be the seasons with significant changes in the functioning of lakes. Climate signals such as changes in water level, temperature, and ice-off time in the spring will determine the variable response of diatom multiplication in high dissolved silica and total organic carbon (TOC) resources [39]. TOC resources will also be an important source of nutrients for planktonic organisms. The rate of spring diatom development, determined by the time of ice melting, is also affected in the spring primary production of lake photic zones. Wagner and Adrian [40] pointed out that the spring regime of abiotic and biotic lake parameters will manifest more clearly, with lesser effects appearing in summer.

I predicted an intensive summer changes in lake functioning affected by climate change. The forecast lake water temperature increase and the accompanying extremely high precipitation, together with the deep mixing of the epilimnion, will result in acceleration of the circulation of matter. Also, increasing warming of the epilimnion will cause changes in stratification, but the magnitude of stratification responses to climate change across lakes will be associated with the lake average temperature and morphometry, but not with warming rates [41].

Catchment origin nutrient load to the littoral zone will slowly become an important driver for the increase of lake water trophy, being especially more frequent in oligo- and mesotrophic lakes. Rigosi et al. [42] highlighted that nutrients had a larger role in oligotrophic lakes whereas temperature was more important in mesotrophic lakes.

In many scenarios more substantial cyanobacterial development in eutrophic and hypertrophic lakes [42] is predicted. As lakes become more eutrophic, the *Cyanobacteria* will become more sensitive to the interaction of nutrients and temperature, but ultimately nutrients are the most important predictor of cyanobacterial biovolume. Similarly, *Microcystis* is more sensitive to temperature than is *Anabaena* [42]. Linking the increased allochthonous organic load to the lakes with trophic increases and the browning process during climate change is becoming more and more common [43–45]. On the North American continent, the greatest effects of these processes are visible in increase of the murky lakes type, according to nutrient-color status [46], which in Poland were previously referred as humo-eutrophic (auxotrophic) [47]. This lake type exhibits high chlorophyll *a* and total phosphorus concentrations and cyanobacterial densities [44].

It is highly probable that climate change in Poland will contribute to an increasing number of humo-eutrophic lakes, especially in the group of small lakes surrounded by eutrophic wetlands. It will be accompanied by an increase in CO_2 emission and the preservation of strong heterotrophic ecosystems. On the other hand, during climate changes in small oligotrophic dystrophic lakes surrounded by bogs, an increase in TOC concentration, change in water color, and the formation of a stronger thermal stratification of these lakes are predicted [48]. Climate change may also lead to a change to a mictic type for some of the large, previously dimictic, lakes, when ice cover becomes permanently absent.

5 Conclusions

As presented here, the effects of global change on Polish freshwaters, narrowed to only the main stressors and the first trophic level in aquatic ecosystems, clearly show that lakes will be exposed to several changes. Previous Polish research on warmed lakes in Poland (presented in this volume also) has indicated a significant change in the trophic structure of the aquatic ecosystem created by increasing lake water temperatures. Hillbricht-Ilkowska [49], more than 25 years ago, pointed out a wide spectrum of future and possible lake changes based on earlier observations from heated lakes in the Konin region in Poland. All her suggestions are still valid and find confirmation in current research [24, 36, 38]. She has predicted that during temperature increases a change will lead to the permanent elimination of cold and stenothermic species, reducing the species diversity of planktonic organisms and other groups such as Insecta, Mollusca, or fish species that prefer cold waters. A new arrangement of thermal and mictic lake conditions may create opportunities for mass colonization of alien species or massive development of species that so far are few in number.

In addition to typical natural changes in lake functions, changes in the extent of lakes and wetlands are expected. This potential must be included in local zoning plans.

References

1. Rohli RV, Vega AJ (2018) Climatology4th edn. Jones & Bartlett Learning, Burlington
2. Okołowicz W (1969) Basic climatology. PWN, Warsaw
3. Hartmann DL et al (2013) IPCC fifth assessment report, climate change 2013: the physical science basis (Stocker TF et al, eds). Cambridge University Press, Cambridge
4. Governmental Statistical Office of Poland (2017) Environment. Warsaw
5. Hurrell JW, National Center for Atmospheric Research Staff (eds) (2013) The climate data guide: Hurrell North Atlantic Oscillation (NAO) Index (PC-based). Accessed 18 Aug 2018
6. Hammer Ø, Harper DAT, Ryan PD (2001) PAST: paleontological statistics software package for education and data analysis. Palaeontol Electron 4(1):9
7. Wójcik R, Miętus M (2014) Some features of long-term variability in air temperature in Poland (1951–2010). Przegl Geogr 86(3):339–364. (in Polish)
8. Krasowicz S, Górski T, Budzyńska K, Kopiński J (2012) Agricultural characteristics in the territory of Poland. In: Pastuszak M, Igras J (eds) Temporal and spatial differences in emission of nitrogen and phosphorous from Polish territory to the Baltic Sea. National Marine Fisheries Research Institute – Institute of Soil Science and Plant Cultivation – State Research Institute – Fertilizer Research Institute, Gdynia, pp 47–107
9. Kożuchowski K (2017) Precipitations. In: Jokiel P et al (eds) Hydrology of Poland. PWN, Warsaw, pp 36–44. (in Polish)
10. Paszyński J, Niedźwiedź T (1991) Climate. In: Starkel L (ed) Geography of Poland: natural environment. PWN, Warsaw, pp 296–355. (in Polish)

11. Falarz M (2004) Variability and trends in the duration and depth of snow cover in Poland in the 20th century. Int J Climatol 24:1713–1727
12. Łabedzki L (2007) Estimation of local drought frequency in central Poland using the standard ized precipitation index SPI. Irrig Drain 56(1):67–77. https://doi.org/10.1002/ird.285
13. Filipiak J, Miętus M (2009) Spatial and temporal variability of cloudiness in Poland 1971–2000. Int J Climatol 29:1294–1311
14. Kottek M, Grieser J, Beck C, Rudolf B, Rubel F (2006) World map of the Köppen-Geiger climate classification updated. Meteorol Z 15:259–263. https://doi.org/10.1127/0941-2948/2006/0130
15. Kundzewicz Z, Juda-Rezler K (2010) Climate change related risk. Nauka 4:69–76. (in Polish)
16. Kundzewicz ZW, Matczak P (2012) Climate change regional review: Poland. WIREs Clim Change 3:297–311. https://doi.org/10.1002/wcc.175
17. Bajkiewicz-Grabowska E (2002) Circulation of matter in the river-lake systems. Warsaw University Press, Warsaw
18. Choiński A (1995) Physical limnology of Poland. UAM, Poznań
19. Wrzesiński D, Ptak M (2016) Water level changes in Polish lakes during 1976–2010. J Geogr Sci 26(1):83–101. https://doi.org/10.1007/s11442-016-1256-5
20. Górniak A, Piekarski K (2002) Seasonal and multiannual changes of water levels in lakes of northeastern Poland. Pol J Environ Stud 11(4):349–354
21. Michalczyk Z, Chmiel S, Turczyński M (2011) Lake water stage dynamics in the Łęczna-Włodawa Lake District in 1991–2010. Limnol Rev 11(3):113–122
22. Michalczyk Z, Mięsiak-Wójcik K, Sposób J, Turczyński M (2017) The state of and changes in water conditions in the Łęczna-Włodawa Lake District. Przegl Geogr 89(1):9–28. (in Polish)
23. Polderman NJ, Pryor SC (2004) Linking synoptic-scale climate phenomena to lake-level variability in the Lake Michigan-Huron basin. J Great Lakes Res 30(3):419–434
24. Weyhenmeyer GA (2008) Rates of change in physical and chemical lake variables – are they comparable between large and small lakes. Hydrobiologia 599:105–110
25. Adrian R et al (2009) Lakes as sentinels of climate change. Limnol Oceanogr 54(6):2283–2297
26. Livingstone DM (2003) Impact of secular climate change on the thermal structure of a large temperate central European lake. Clim Change 57:205–225
27. Skowron R (2011) The differentiation and variability of chosen elements of the thermal regime of water in lakes on Polish lowland. Nicolaus Copernicus University Press, Toruń. (in Polish)
28. O'Reilly CM et al (2015) Rapid and highly variable warming of lake surface waters around the globe. Geophys Res Lett 42:10773–10781. https://doi.org/10.1002/2015GL066235
29. Winslow LA, Read JS, Hansen GJA, Hanson PC (2015) Small lakes show muted climate change signal in deepwater temperatures. Geophys Res Lett 42:355–361. https://doi.org/10.1002/2014GL062325
30. Choiński A, Ptak M, Skowron R (2014) Trends to changes in ice phenomena in Polish lakes in the years 1951–2010. Przegl Geogr 86(1):23–40. (in Polish)
31. Choiński A, Ptak M, Skowron R, Strzelczak A (2015) Changes in ice phenology on Polish lakes from 1961–2010 related to location and morphometry. Limnologica 53:42–49
32. Górniak A, Pękala M (2001) Ice phenomena in lakes of north-eastern Poland. Przegl Geofiz 46(1–2):91–109. (in Polish)
33. Wrzesiński D, Choiński A, Ptak M (2015) Effect of the North Atlantic Oscillation on the thermal characteristics of lakes in Poland. Acta Geophys 63(3):863–883. https://doi.org/10.1515/acgeo-2015-0001
34. Marszelewski W, Skowron R (2006) Ice cover as an indicator of winter air temperature changes: case study of the Polish Lowland lakes. Hydrol Sci J 51(2):336–349
35. Marszelewski W, Skowron R (2009) Extreme ice phenomena on the lakes of Northern Poland. Limnol Rev 9(2–3):81–89
36. Yan ND et al (2008) Long-term trends in zooplankton of Dorset, Ontario, lakes: the probable interactive effects of changes in pH, TP, DOC and predators. Can J Fish Aquat Sci 65:862–877

37. Christensen MR, Graham MD, Vinebrook RD, Findlay DL, Paterson MJ, Turner MA (2006) Multiple anthropogenic stressors cause ecological surprises in boreal lakes. Glob Change Biol 12:2316–2322
38. Dokulil MT, Teubner K, Jagsch A, Nickus U, Adrian R, Straile D, Jankowski T, Herzig A, Padisák J (2010) The impact of climate change on lakes in Central Europe. In: George G (ed) The impact of climate change on European lakes. Springer, Dordrecht, pp 387–409
39. Blenckner T et al (2007) Large-scale climatic signatures in lakes across Europe: a meta-analysis. Global Change Biol 13:1314–1326
40. Wagner C, Adrian R (2009) Exploring lake ecosystems: hierarchy responses to long-term change? Global Change Biol 15:1104–1115. https://doi.org/10.1111/j/1365-2486.2008.01833.x
41. Kraemer BM et al (2015) Morphometry and average temperature affect lake stratification responses to climate change. Geophys Res Lett 42:4981–4988. https://doi.org/10.1002/2015GL064097
42. Rigosi A, Cayelan C, Bas W, Ibelings J, Brookes D (2014) The interaction between climate warming and eutrophication to promote cyanobacteria is dependent on trophic state and varies among taxa. Limnol Oceanogr 59(1):99–114
43. Creed I, Bergström AK, Trick CG et al (2018) Global change-driven effects on dissolved organic matter composition: implications for food webs of northern lakes. Global Change Biol 24:3692–3714. https://doi.org/10.1111/gcb.14129
44. Leech DM, Pollard AI, Labou SG, Hampton SE (2018) Fewer blue lakes and more murky lakes across the continental U.S.: implications for planktonic food webs. Limnol Oceanogr. https://doi.org/10.1002/lno.10967
45. De Wit HA et al (2016) Current browning of surface waters will be further promoted by wetter climate. Environ Sci Technol 3:430–435. https://doi.org/10.1021/acs.estlett.6b00396
46. Williamson CE, Morris DP, Pace ML, Olson OG (1999) Dissolved organic carbon and nutrients as regulators of lake ecosystems: resurrection of a more integrated paradigm. Limnol Oceanogr 44:795–803
47. Górniak A (1996) Humic substances and their impact on freshwaters ecosystems functioning. Warsaw University Press, Białystok. (in Polish)
48. Houser JN (2006) Water color affects the stratification, surface temperature, heat content, and mean epilimnetic irradiance of small lakes. Can J Fish Aquat Sci 63:2447–2455. https://doi.org/10.1139/f06-131
49. Hillbricht-Ilkowska A (1993) Lake ecosystems and the global climate changes. Kosmos 42(1):107–121