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Research Article

The increasing of maximum lake water temperature in lowland lakes of central Europe: case study of the Polish Lakeland

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Abstract – The paper presents the results of time-related changes in maximum temperatures in lakes. The analysis was carried out on the basis of 9 lakes located in the northern part of Poland. The analysis was based on daily water and air temperatures in the period 1971–2015. Mann–Kendall's and Sen's tests were applied to determine the directions and rates of change of maximum air and water temperatures. The average increase of maximum water temperature in analysed lakes was found to be 0.39 °C dec^{-1}, while the warming trend of the maximum air temperature was 0.48 °C dec^{-1}. Cluster analysis (CA) was used to group lakes characterised by similar changes of maximum water temperature. The first group included five lakes in which the values of the maximum temperature trends were 0.41 °C dec^{-1}. In the second cluster the average value of maximum water temperature increase was smaller than in the first cluster (0.36 °C dec^{-1}). Comparing the results of cluster analysis with morphometric data show that in the first cluster lakes are having a greater average depth, maximum depth and water transparency in comparison to the lakes of the second cluster.

Keywords: climate change / lake water / maximum temperature / warming trend

1 Introduction

Climate change is currently one of the most serious problems faced by humanity. This situation results from the close dependency between climate and all components of the natural environment, and therefore the observed transformations. A broad range of research concerns the effect of climate change on surface waters (Blenckner *et al.*, 2010; Skowron 2012; Magee *et al.*, 2016; Yao *et al.*, 2016, Choiński *et al.*, 2015). Importantly, in some situations, an increase in the temperature of surface waters can exceed the increase in water temperature in a given region. Changes in lake water temperature are moreover considered as an indicator of climate change (Adrian *et al.*, 2009). It is primarily caused by climatic conditions, consequently triggering other processes (related to eutrophication, intensified absorption of solar radiation, etc.). Transformations of lake ecosystems, resulting from climate change, are of particular importance in lake district areas, where their high abundance determines, among other things, the conditions of water circulation and energy and matter circulation, has an effect on the economic situation, etc. In Poland, such areas mostly occur in the northern part of the country. The numerous lakes existing in the area are mainly related to the last glaciation.

Extreme situations, likely to result in substantial changes in current processes and phenomena (frequently long-lasing or even irreversible), are important for transformations of the environmental conditions. Starkel (2002) emphasises that exceeding threshold values, disturbing the stability of natural environmental systems, will intensify along with the progressing climate warming. Short-term, extreme variations in the weather can have a major effect on the seasonal dynamics of lakes (George *et al.*, 2007). Based on threshold values for lake temperatures, Skowron (2011) designated thermal seasons, significant with reference to water circulation in the lake, ice phenomena, etc. Maximum water temperatures in lakes have been analyzed in many studies (Baba *et al.*, 1999; Edmundson and Mazumder, 2002; Jansen and Hesslein, 2004; Hren and Sheldon, 2012). Gao and Stefan (1999) emphasise that maximum water temperatures (as well as minimum) are the most important for the ecology of lakes as habitat restrictions. In the case of 196 lakes in France, Roubeix *et al.* (2017) found that among 36 environmental parameters, maximum water temperature was of the highest importance for the distribution of fish species.

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Table 1. Lakes morphometric data.

No	Lake	Lake location Latitude N Longitude E	Area (ha)	Volume (10^6 m^3)	Depth (m) Mean Max.	Secchi depth (m)	Meteorological station
1	Sławskie	51.89 16.02	822.5	42.66	5.2 12.3	1.1	Zielona Góra
2	Gardno	54.71 17.39	2337.5	30.95	1.3 2.6	0.7	Łeba
3	Sępoleńskie	53.46 17.51	157.5	7.50	4.8 10.9	1.2	Chojnice
4	Charzykowskie	53.77 17.50	1336	134.53	9.8 30.5	2.1	Chojnice
5	Wdzydze	53.98 17.91	1417	220.80	15.5 69.5	2.9	Chojnice
6	Raduńskie Górne	54.24 17.98	362.5	60.16	15,5 43.0	4.1	Łeba
7	Bachotek	53.30 19.47	215.0	15.39	7.2 24.3	3.6	Toruń
8	Jeziorak	53.72 19.62	3152.5	141.59	4.1 12.9	0.8	Toruń
9	Hańcza	54.27 22.81	291.5	120.36	38.7 106.1	5.2	Suwałki

So far, current studies on long-term changes in the thermal regime of lakes in Poland are usually based on average annual values (Wrzesiński *et al.*, 2015; Ptak *et al.*, 2018a, 2018b). The projection of lake water temperature changes in the examined area, in relation to annual averages, predicts their increase by as much as 4.2 °C by the end of the 21st century (Czernecki and Ptak, 2018). Despite extensive literature on changes in lake water temperature in Poland, no studies on temporal changes of the maximum water temperatures in lakes have been conducted. In order to fill this gap, the objectives of this study were: (1) to determine the tendencies of changes in maximum air and water temperatures in lakes of the Polish Lakeland, (2) to compare the directions of changes in air and water temperatures in the analysed lakes, (3) to determine the similarities and differences between lakes in relation to changes in maximum water temperatures.

2 Material and methods

2.1 Study site

The paper is based on data concerning nine post-glacial lakes located in Poland (Fig. 1). Due to the range of the last glaciation, they are particularly located in the northern part of the country (Choiński, 2006). The genesis of the lakes is associated with erosive or accumulative processes of glacier activity (Ptak *et al.*, 2018a). The location of the lakes, on the background of the southern border of the last glaciation, is presented in Figure 1. Their basic morphometric parameters are presented in Table 1.

2.2 Materials

The analysis was based on daily water temperature measurements performed by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIG) in the years 1971–2015 (in the case of Sławskie Lake until 2014). Temperature measurements were carried out at 6:00 UTC, at a depth of 0.4 m below the water surface. In addition, the daily air temperatures for five IMGW-PIB meteorological stations were included in the analysis (Fig. 1).

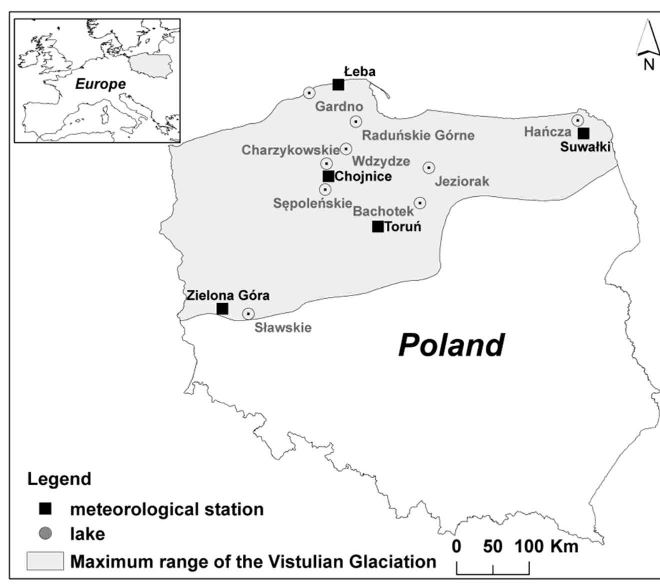

Fig. 1. Study site location.

2.3 Methods

The maximum temperature values for individual months (MMWT) and years (AMWT) were determined on the basis of daily water temperatures. The MMWT and AMWT were the basis for further trend analyses. The trend analysis was carried out for individual months (MMWTT) and one-year periods (AMWTT) using the non-parametric Mann–Kendall test (MK) (Kendall and Stuart, 1968). The trend analysis was carried out for the significance level of 0.05. On the basis of the non-parametric Sen's test (Gilbert, 1987), the magnitude of the linear/monotonic trend for months (MMWTT) and years (AMWTT) was determined. Trend magnitudes of MMWTT and AMWTT are given in degrees Celsius per decade (°C dec^{-1}). The data on monthly (MMAT) and annual maximum air temperatures (AMAT) were analyzed according to the same methodology. The obtained results allowed us to compare the trend magnitude in annual water and air temperature. For this purpose, the significance of differences between annual maximum water temperature trends (AMWTT) and annual maximum air temperature trends AMATT was analyzed based on the non-parametric Kruskal–Wallis test (K-W).

In order to determine the similarities and differences between the analyzed lakes in regard to AMWTT and MMWTT, cluster analysis (CA) was applied. The CA was carried out using the Ward method as a measure of similarity between clusters and the square Euclidean distance was used. To establish the groups and subgroups in the CA method, the cut-off criteria of 66% and 25% were used respectively (Ptak *et al.*, 2018a).

The statistical analyses were performed using the software Statistica ver. 13 (StatSoft, Inc., USA) and R ver. 3.5.2. with the Trend package.

3 Results

3.1 Maximum lake water temperature

The annual maximum water temperatures (AMWT) in the years 1971–2015 varied from 16.0 °C in Gardo Lake to 29.2 °C in Jeziorak Lake (Fig. 2). The average maximum annual temperatures in lakes ranged from 21.8 to 24.4 °C in Raduńskie Górne and Sławskie Lake respectively. Based on the average maximum annual water temperatures the lakes can be ranked in ascending order Raduńskie Górne < Gardno < Hańcza < Wdzydze < Charzykowskie < Sępoleńskie < Bachotek < Jeziorak < Sławskie. However, the greatest variability of the maximum annual temperatures was observed in Lake Gardno (9.4 °C) and the smallest in Raduńskie Lake (5.6 °C). The standard deviation of AMWT ranged from 1.27 °C to 1.95 °C in Lakes Raduńskie Górne and Hańcza respectively. The maximum water temperatures in the lakes occurred mainly in July (44.0%) and August (40.7%), less frequently in June (14.7%). Occasionally the maximum water temperatures in lakes occurred in May (0.5%) and September (0.2%).

The analysis of the maximum monthly temperatures showed that the highest values were generally recorded in July or August (Fig. 3). The highest variability in maximum monthly temperatures in the lakes of Bachotek, Charzykowskie, Hańcza, Raduńskie Górne and Wdzydze occurred in May, but in Sępoleńskie Lake in April, Gardno and Jeziorak Lakes in August and in Sławskie Lake in September. The smallest variability of maximum water temperatures was observed in February. In the case of Lake Gardno the smallest changes in maximum temperatures were observed in October.

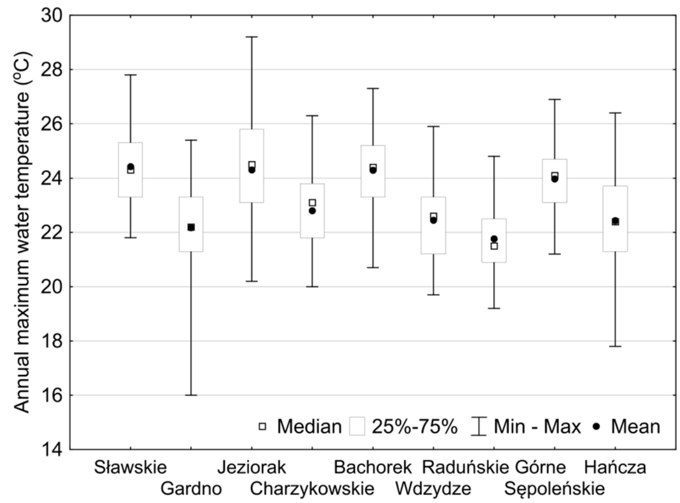

Fig. 2. Annual maximum water temperature changes in the years 1971–2015.

In terms of similarity of AMWT, two main clusters of lake were distinguished (Fig. 4). The first cluster includes the four lakes Sławskie, Jeziorak, Bachotek and Sępoleńskie, where the annual maximum water temperature is 24.2 °C. Lakes of this group are characterized by the lowest average depth. At the same time, there is low water transparency in these lakes. In this cluster, the maximum annual water temperatures in the lakes Bachotek and Sępoleńskie were the most similar to each other; therefore they formed a distinct subcluster. In the second cluster, the maximum monthly water temperatures in Wdzydze and Charzykowskie lakes were the most similar. Joined to this subcluster are Hańcza lake, then Raduńskie Górne and Gardno lakes. Lake Gardno is coastal and according to Girjatowicz (2008) during the winter season there are intrusions of sea water, which can modify the atmospheric dependent pattern of lake temperatures. Lake Hańcza is the deepest lake in Poland (maximum depth 106.1 m), where a significant amount of hypolimnion water is isolated from the direct impact of atmospheric factors, and according to Skowron (2011), more than 75% of its volume is in the hypolimnion layer. Generally, the second cluster of lakes is characterized by those that have a greater depth determining the development of summer thermal stratification. The average maximum water temperature in this cluster is 22.3 °C and it is significantly lower compared to the first cluster.

3.2 Trends of maximum water temperature

An increase of AMWT in the years 1971–2015 was observed in all lakes but for Gardno and Sępoleńskie Lakes the trends were not statistically significant (Tab. 2). No trend in annual water temperatures in Lake Gardno shows that the maximum temperatures were in June (19.1%), July (55.3%) and August (25.5%). In July and August there was a growing trend at a significance level of 0.05, while in June there was a tendency to decrease in water temperatures. In Sępoleńskie Lake the maximum temperatures occurred in May (2.0%), June (14.3%), July (44.9%) and August (38.8%). MMWTT in these months were not statistically significant. Lake Gardno has a direct connection with the Baltic Sea. The inflow of sea

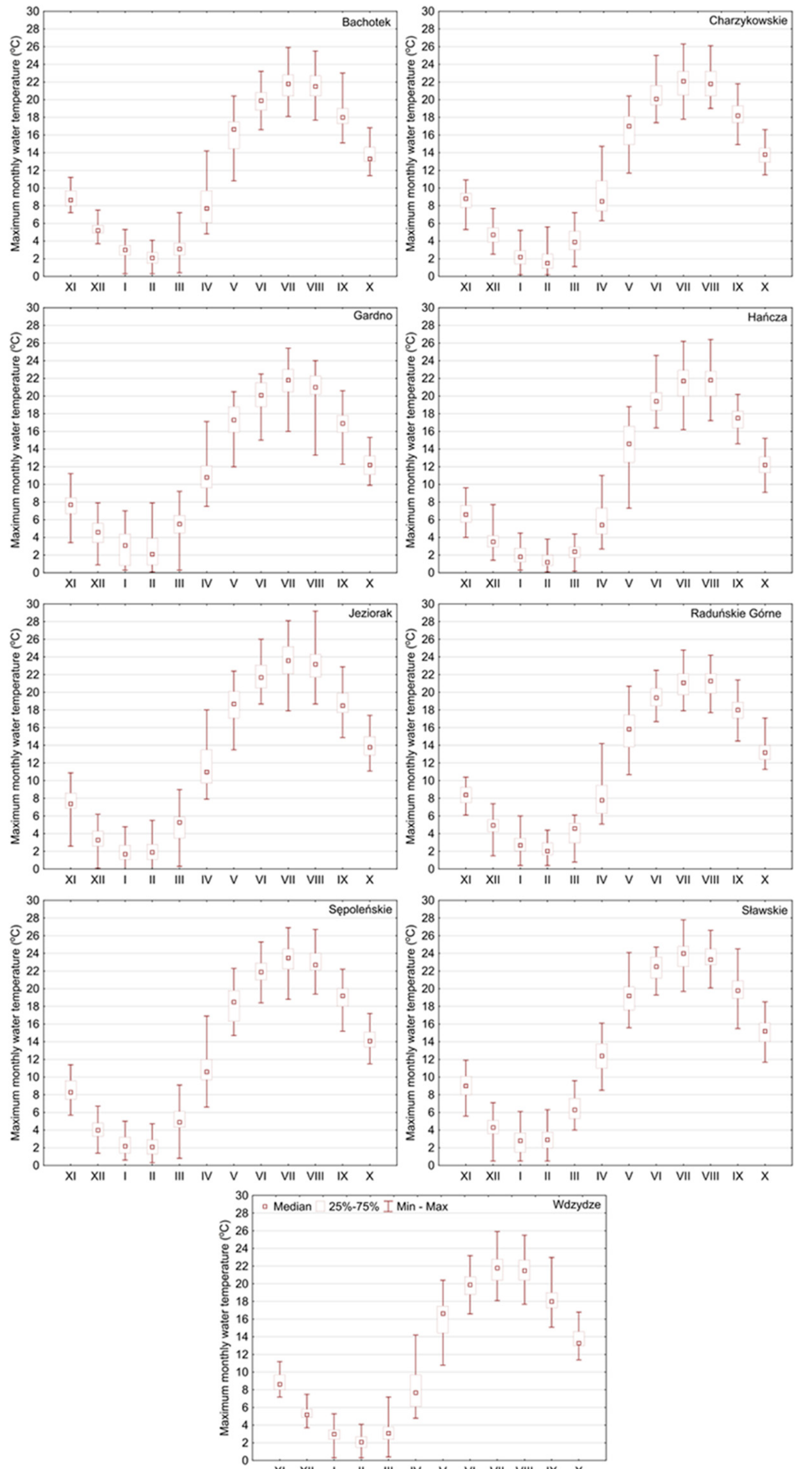

Fig. 3. Monthly maximum water temperature changes in the years 1971–2015.

waters determines its thermal regime. In the case of Sępoleńskie Lake, its close location near urban areas could have influenced the modification of the natural thermal regime. Larger, statistically significant, increases in AMWT were observed in Jeziorak and Wdzydze Lakes (0.56 and 0.52 °C dec^{-1}, respectively), whereas the smallest were observed in Raduńskie Górne and Bachotek lakes (0.30 and 0.38 °C dec^{-1}, respectively) (Fig. 5). More information on maximum temperatures changes in lakes is provided by the analysis of monthly maximum water temperature trends (MMTT). Significant changes of MMTT, with the exception of Hańcza and Gardno lakes, occurred in most months. In the monthly cycle the highest values of increases of MMTT were recorded in April for all lakes. In this month, the trend values ranged

Table 2. The annual and monthly trends of maximum air and lakes water temperatures (°C dec^{-1}).

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Year
Lake													
Sławskie	0.47*	0.22	0.30*	0.20	0.34*	1.00*	0.60*	0.32	0.60*	0.50*	0.42*	0.50*	0.43*
Gardno	0.00	0.03	0.07	−0.12	0.00	0.74*	−0.13	−0.09	0.52*	0.44*	0.32	0.27	0.25
Jeziorak	0.32*	0.27	0.09	0.14	0.20	1.15*	−0.08	0.32	0.59*	0.75*	0.56*	0.59*	0.56*
Charzykowskie	0.21	0.37*	0.25	0.30*	0.53*	1.14*	0.50*	0.12	0.56*	0.62*	0.35*	0.43*	0.45*
Bachotek	0.36*	0.36*	0.23	0.35*	0.20	1.03*	0.48*	0.18	0.46*	0.49*	0.44*	0.65*	0.38*
Wdzydze	0.21	0.20*	0.20	0.14	0.19	1.10*	0.53*	0.27	0.61*	0.67*	0.38*	0.44*	0.52*
Raduńskie Górne	0.32*	0.30*	0.42*	0.41*	0.38*	1.16*	0.79*	0.30	0.48*	0.35	0.24	0.33*	0.30*
Sępoleńskie	0.33*	0.24	0.08	0.04	0.17	0.80*	0.26	0.10	0.32	0.36	0.25	0.47*	0.25
Hańcza	0.05	−0.18	−0.14	0.00	0.14	0.96*	0.65	0.17	0.64*	0.57*	0.16	0.08	0.41*
Meteorological station													
Łeba	0.10	0.07	0.48	0.32	0.24	0.74*	0.11	−0.26	0.47	0.17	0.26	0.00	0.39*
Olsztyn	0.16	0.23	0.53	0.29	0.19	0.85*	0.11	0.07	0.78*	0.39	0.04	0.21	0.50*
Suwałki	0.20	0.13	0.50	0.32	0.26	0.89*	0.20	0.22	0.90*	0.57*	0.11	0.23	0.74*
Toruń	0.19	0.16	0.50	0.43	0.14	0.92*	0.54	0.21	0.77*	0.25	0.31	0.14	0.47*
Zielona Góra	0.13	0.09	0.56	0.36	−0.05	1.00*	0.31	0.30	0.57*	0.24	0.05	0.04	0.41*
Chojnice	0.11	0.04	0.56	0.40	0.18	0.92*	0.19	0.09	0.67*	0.15	0.16	0.17	0.39*

* Trend at $\alpha = 0.05$ level of significance.

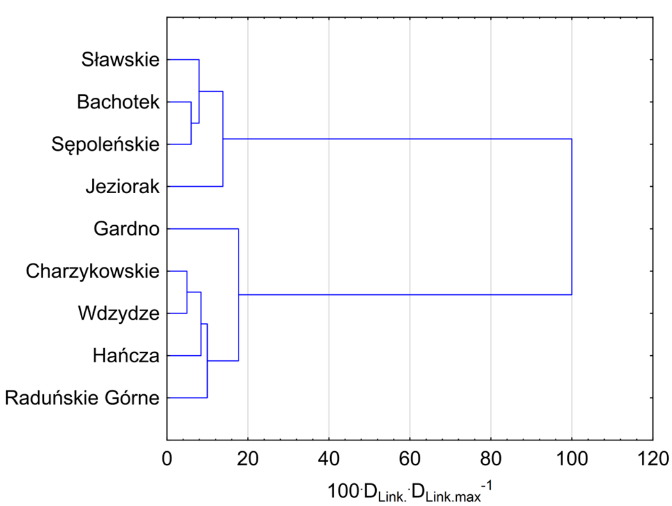

Fig. 4. Grouping lakes by maximum annual water temperature changes.

from 0.74 °C dec^{-1} for Gardno Lake to 1.16 °C dec^{-1} for Raduńskie Górne Lake. In the case of Lakes Gardno and Hańcza maximum water temperature trends in November, December, January, February, March, June, September and October were not statistically significant. In the case of Gardno Lake, as mentioned above, the trend of increase in the maximum temperature is disturbed by intrusions of sea water (Girjatowicz, 2008; Ptak *et al.*, 2018a). The effect of conditions other than strictly climatic on the thermal regime of Lake Hańcza is emphasized by, among others, Woolway *et al.* (2017). Its different character may result from its morphometric parameters (the deepest lake in the Central European Lowland) and as a consequence, *e.g.*, intensive supply of groundwater with lower temperature or conditions of water mixing including the waters of the hypolimnion with considerable thickness (approximately 90 m). In the case of Lake Hańcza in December and January even negative tendencies were observed, although they were not statistically significant. In the typical summer months (July and August) when thermal stratification dominates in this lake, statistically significant increases of maximum water temperature occur.

The highest rate of increase in maximum water temperature was recorded in April (mean 1.01 °C dec^{-1}), and the lowest in January (mean 0.17 °C dec^{-1}) and February (mean 0.16 °C dec^{-1}) (Fig. 6a). The highest variability of trends of changes in maximum water temperature between the lakes was observed in May (0.92 °C dec^{-1}), whereas the lowest was observed in July (0.32 °C dec^{-1}). Also high variability of trend values was observed in March, February, December, January and October (from 0.53 °C dec^{-1} for March to 0.57 °C dec^{-1} for October). The cluster analysis made it possible to divide months into separate groups based on the similarity of maximum water temperature trends (Fig. 6b). The first cluster represents only one month, April, in which the maximum water temperature increase was 1.01 °C dec^{-1}. The increase trend of the maximum water temperature for this month is clearly different from the other months. The second group consists of all months except April. In these months, the increase of the maximum water temperature was not as high as in April and on average was 0.31 °C dec^{-1}. Within the second group there were two distinct subclusters: one comprising January, February March, June, November and December, and the second comprising May, July, August, September and October. In the second subcluster changes of maximum temperature (trends) were larger (average 0.40 °C dec^{-1}) than those in the first subcluster (0.20 °C dec^{-1}).

Cluster analysis, was used to group lakes by similarity of trends of maximum water temperature (Fig. 7). The first group included five lakes (Sławskie, Wdzydze, Bachotek, Charzykowskie and Raduńskie Górne) in which the values of trends of the maximum temperature change varied from 0.30 °C dec^{-1} to 0.52 °C dec^{-1} at the average value of 0.41 °C dec^{-1}. In the

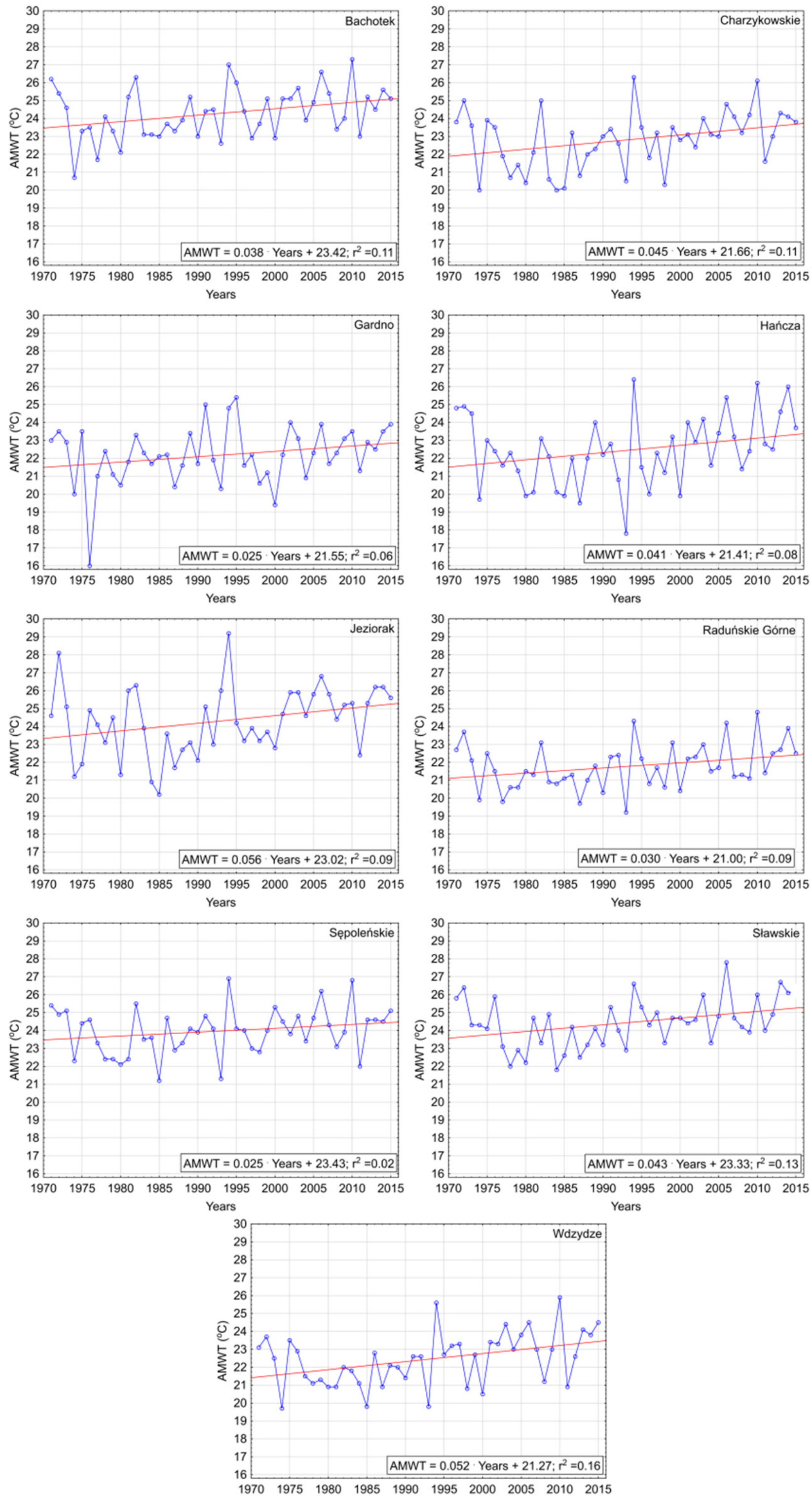

Fig. 5. Annual maximum water temperature trends.

second cluster the average value of maximum water temperature increase (0.36 °C dec^{-1}) was smaller than in the first cluster. Within the first group, the change of the maximum water temperature of Raduńskie Górne Lake was the most different from the others lakes, while in the second group, Hańcza Lake was the most deviating. Comparing the results of cluster analysis with morphometric and hydrological data of lakes (apart from Lake Hańcza), one can find some clear dependencies. Generally, the first cluster is characterized by lakes having a higher average and mean depth and water transparency in comparison to the lakes of the second cluster.

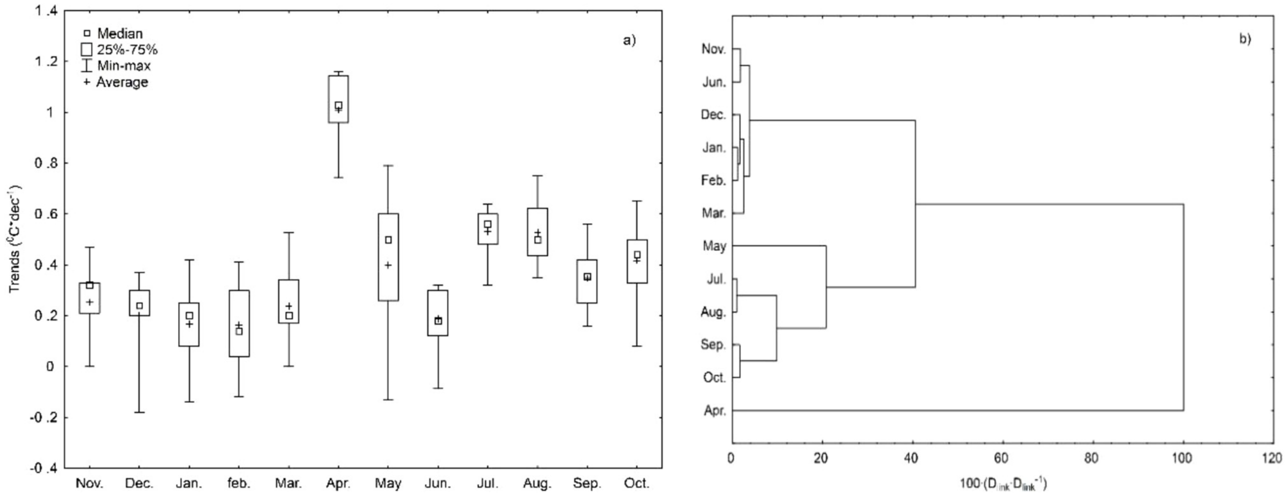

Fig. 6. Monthly maximum water temperature trends in lakes (a) and results of grouping by means of the cluster analysis (CA) (b).

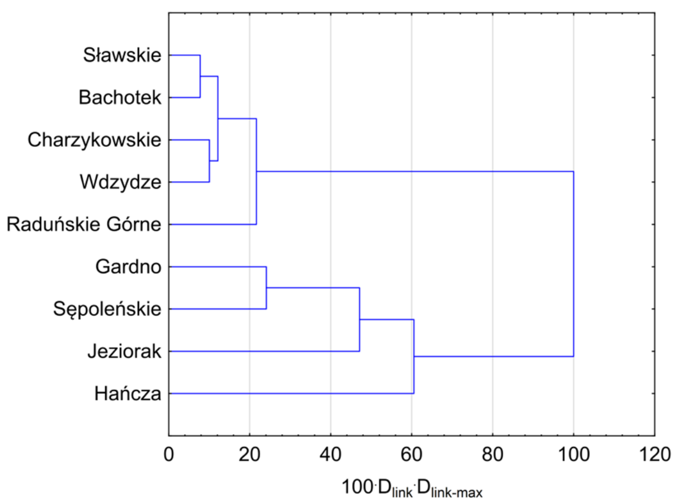

Fig. 7. Grouping lakes based on maximum water temperature trends.

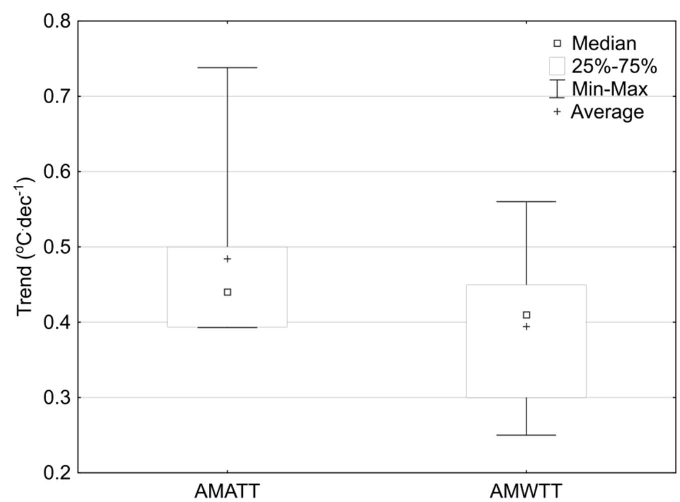

Fig. 8. Comparison of annual maximum water and air temperature trends in the years 1971–2015.

Due to the considerable effect of air temperature on the temperature of surface waters (Haberman and Haldna, 2017; Ptak *et al.*, 2017), the tendency of changes in maximum air temperatures and their relationships with the thermal regime of lakes were analysed. The result of analysis of monthly trends of maximum air temperatures showed that in November, December, January, February, March, May, June (except Łeba station), August (except Łeba station), September and October the changes of maximum air temperatures were not statistically significant (Tab. 2). As in the case of lakes, in April and July in all meteorological stations, there was a statistically significant trend of increasing maximum temperature. For April the trend values were higher than in July. The maximum annual air temperature changes were varied in geographic terms. The highest value of the maximum air temperature increase was for the Suwałki station (0.74 °C dec^{-1}), whereas the lowest was for the Łeba and Chojnice stations (0.39 °C dec^{-1}).

Analysis of the significant differences between the trend values of annual and monthly maximum temperature showed that in January, February and July there were greater increases in maximum air temperatures in relation to the maximum water temperatures in lakes. The differences were statistically significant at the levels α =0.05 and α =0.1, respectively. However, in August, September and October, the increase in maximum temperatures was more dynamic in lakes than air temperatures (differences were significant at the level $\alpha = 0.05$). In April and November also increases in maximum temperatures in lakes were larger than the maximum air temperatures, although these differences were significant at a level of $\alpha = 0.1$. The average rate of increase of the maximum annual air temperature for all stations was 0.48 °C dec^{-1}, whereas the average warming trend of the maximum water temperature was 0.39 °C dec^{-1} (Fig. 8). Slightly lower variability was observed in the case of trends of maximum water temperatures in lakes than air temperatures.

The high dependencies evidenced earlier between maximum water temperature in the analysed lakes and air temperature are confirmed by the data presented in Table 3. All correlations between the maximum monthly water

Table 3. Correlations between the maximum air temperatures and the maximum water temperatures (relations of lakes and meteorological stations located at the shortest distance).

Meteorological station lake	Łeba	Suwałki	Toruń	Zielona Góra	Chojnice
Sławskie				0.953*	
Gardno	0.962*				
Jeziorak			0.947*		
Charzykowskie					0.941*
Bachotek			0.952*		
Wdzydze					0.927*
Raduńskie Górne	0.941*				
Sepoleńskie					0.954*
Hańcza		0.914*			

*Correlation statistically significant at a level of $\alpha = 0.05$.

temperatures and the maximum monthly air temperatures were high and statistically significant. Pearson's correlation coefficient values ranged from 0.91 to 0.96.

4 Discussion and conclusions

Water temperature in lakes is one of its basic parameters (Sharma *et al.*, 2015; Ptak and Nowak, 2016) and research referring to its effect on the functioning of lakes is the focus of many scientific disciplines (Li *et al.*, 2013; Wang and Liu, 2013; Goebel *et al.*, 2017; Woolway and Merchant, 2017). The issue discussed in the paper concerning long-term changes in thermal conditions of lakes corresponds with the related global research trend. The study shows the occurrence of a considerable transformation of the distribution of maximum water temperatures over the last several decades. The key element of changes in maximum water temperatures in lakes is the air temperature. Given the close relationship between air temperature and water temperature, any change in the former will mostly result in a corresponding change in the latter (Mooij *et al.*, 2005). In the case of lakes analysed in this study, this is confirmed by a very strong, significant correlation, the values of which have been indicated above.

The most important threat to lakes is climate change, especially global warming (Carpenter *et al.*, 2011). The increase of maximum water temperature in the years 1971–2015 of the lakes ranged from 0.25 to 0.56 °C dec^{-1}. Kangur *et al.* (2013) observed an increase in maximum water temperature in the summer period for Lake Peipsi (Estonia/Russia). In a broader perspective the response of lakes to climatic changes in this part of Europe is similar to many other cases located in different regions of the world (Austin and Colman, 2007; Hampton *et al.*, 2008; Shimoda *et al.*, 2011; Groß-Wittke *et al.*, 2013; Zhong *et al.*, 2016; Haddout *et al.*, 2018). For instance, for the summer period (July–September) the surface water temperature in the Great Lakes in North America experienced a warming trend at a rate of 1.1 °C dec^{-1} (Austin and Colman, 2007). Also, about 60% of the lakes of the Tibetan Plateau demonstrated an increasing trend in temperature during 2001–2012 with a mean warming rate of 0.55 °C dec^{-1}. Earlier studies referring to changes in thermal conditions of Polish lakes also showed substantial transformations. Ptak *et al.* (2018a), on the basis of average annual values of water temperature in lowland lakes, obtained the average warming trend of 0.42 °C dec^{-1}. Dąbrowski *et al.* (2004), analysing the average annual water temperature in six lakes in the years 1961–2000, recorded an increase varying from 0.05 to 0.28 °C dec^{-1}. Wrzesiński *et al.* (2015) in the period 1971–2010 for twelve studied lakes observed an increase in average annual temperature varying from 0.25 to 0.55 °C dec^{-1}. The rate and scale of changes are determined by regional factors and morphometric parameters of lakes. The importance of the latter is emphasised by, among others, Kraemer *et al.* (2015), referring to the effect of climatic conditions on thermal stratification of lakes. In the case of the analysed lakes in the summer period thermal stratification occurs, and in April and summer months the highest increase in maximum water temperatures is observed (for April the average trend from all analysed lakes is 1.01 °C dec^{-1}). Such a situation is a consequence of processes that occurred earlier, particularly a reduction of the ice cover persistence. Hampton *et al.* (2008), analyzing 60-year data on the temporary changes of the water temperature of Lake Baikal, noted the highest increase of water temperature in the summer.

A characteristic feature of lakes, from the point of view of their thermal properties, is the ice cover formation and decay, which are affected by variations in regional climate, primarily air temperature (Brown and Duguay, 2010). The shift of the period of ice cover disappearance has further consequences and is related to, among other factors, faster thermal stratification and therefore longer time of warming of the epilimnion layer. O'Reilly *et al.* (2015), referring to the above processes, believe that lakes in climatic zones where ice occurs warm up faster than air and faster in comparison to lakes from zones free from ice phenomena. The results obtained by Ptak *et al.* (2018a) reflect the above situation for the changes of average water and air temperature (0.42 °C dec^{-1} and 0.35 °C dec^{-1}, respectively). The situation is different for maximum temperatures. The average rate of increase of the maximum temperature in the waters of the analysed lakes is 0.39 °C dec^{-1}, while the warming trend of the maximum air temperature is 0.48 °C dec^{-1}. As a result, a longer heating time of the surface water layer, lasting from the time of faster disappearance of the ice cap, does not affect the faster growth rate of maximum water temperatures in relation to the maximum air temperatures. The analysis results suggest that the turning point was the second half of the 1980s. From that moment a continuous increasing tendency of maximum water temperatures is observed. Such a situation should be associated with a change of regime of climatic conditions, as documented for example in the case of air temperature (Beaugrand, 2004; Conversi *et al.*, 2010). An increase in air temperature was reflected in the thermal regime of lakes. Schneider and Hook (2010) determined the mean increase in water temperature in the years 1985–2009 at a level of 0.045 ± 0.011°C yr^{-1}. Woolway *et al.* (2017), analysing 20 lakes in Central Europe in terms of water temperature increase, identified 1988 as the turning point in the majority of cases. In the case of Lake Võrtsjärv (Estonia), in the course of the upward trend in water temperature in August there was a significant change in 1989 (Nõges *et al.*, 2010).

As mentioned above, exceeding certain threshold values can cause changes in the functioning of ecosystems. In the case of lakes such a situation can be analysed on two levels in reference to physical and chemical as well as to biological processes. The transformation of the former was discussed earlier in the paper and concerns ice phenomena among others (Wrzesiński *et al.*, 2015; Magee and Wu, 2017) or conditions related to stratification (Wahl and Peeters, 2014; Michelutti *et al.*, 2016). The response of hydrobiological conditions to climate warming is a broad issue. The majority of related papers point to a close dependency between the two. Pełechata *et al.* (2015) observed changes in the structure of phytoplankton in a Chara-dominated lake in western Poland caused by shorter and warmer winters. Jeppesen *et al.* (2012), analysing the ichthyofauna of 24 European lakes, observed considerable changes in the fish composition body size and/or age structure with an increase in temperature. Further, the authors emphasise that the response of fish to warming was exceptionally fast and strong over the last decades. Changes in the species composition of fish were also analysed by Hayden *et al.* (2017). In the case of 18 sub-Arctic lakes they identified, among other observations, changes in the structure of salmonids and cyprinids. The occurrence of high temperatures results in the initiation of a number of other processes in lakes. Exceeding certain thermal thresholds can cause the proliferation of non-native fish species (Roubeix *et al.*, 2017). In extreme cases they can cause the death of organisms. Such a situation was described by Kangur *et al.* (2016). In Lake Võrtsjärv their observations included high water temperature (up to 24.5 °C), the pH of up to 9.2, short-term stratification and low oxygen content. In consequence the combination of factors led to the death of fish. Another threat is posed by cyanobacterial blooms. They can directly negatively affect human health (Funari *et al.*, 2017). One of the necessary factors for their occurrence is favourable water temperature (Piontek *et al.*, 2017). The effects of high water temperature values on the development of cyanobacteria are documented in many papers (Elliott, 2010; Gallina *et al.*, 2011; Bukowska *et al.*, 2017).

In the context of the projected further increase in temperature in inland waters (Bui *et al.*, 2018; Czernecki and Ptak, 2018), which may increase on average by 3.3 °C at maximum lake temperatures (Fang and Stefan 2009), further dynamic transformations of lake ecosystems are to be expected.

Considering that the key factor for the physical, chemical and biological water parameters is its temperature, it should be emphasised that its changes will trigger transformations in lakes. In the context of exceeding threshold values above which substantial changes in the functioning of the entire system are observed, the maximum water temperature is of key importance. As evidenced based on the literature presented above, the occurrence of high water temperatures sometimes brings catastrophic effects including a direct threat to living organisms – including man. This is an important issue, especially in times of global warming, so it is important to precisely determine the response of lake ecosystems to this process. The study results suggest the occurrence of a considerable increase in maximum water temperatures in Polish lakes over the last several decades, which is consistent with the research carried out in various regions of the world on the thermal conditions of lake waters.

Limiting the process of increasing lake water temperature resulting from climate warming currently is necessary but seems to be very difficult. In the local or regional approach, such a solution can be found in the hydrotechnical regulation of water exchange in lakes (Ptak *et al.*, 2018a) or spatial management of lake catchments, etc. On a macro scale, operations limiting this unfavourable trend in lakes must have a global character, including through arrangements for the reduction of greenhouse gases, which will directly reduce the rate of increase in air temperature and indirectly the temperature of water in lakes. Considering the current geopolitical situation, this condition cannot always be met.

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