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Thermal structure of water during the summer in lakes of the Polish Lowlands as a result of their varied morphometry

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Abstract: The paper discusses the impact of lake morphometric parameters on the thermal structure of water during the period of summer stagnation. The summer period in the lakes is characterized by clearly expressed properties of the thermal structure of water, differentiating lakes from one another. The study was carried out on 141 lakes in northern Poland, for which at least 3 vertical water temperature measurements were taken in different years. They showed a significant influence of lake basin morphometry upon the thermal structure of water in lakes. In general, measurements of the vertical distribution of water temperature showed clear diversity, and depending on the depth also thermal layers (epi-, meta- and hypolimnion). The results of the analysis of 8 lake morphometric parameters and 10 thermal stratification parameters revealed the existence of significant dependencies between them. The best-preserved relations (statistically significant) occurred between the parameters characterizing the lake depth and meta- and hypolimnion properties, as well as the thermal stratification factor and heat content in a unit of volume.

Key words: lakes, summer thermal stratification, morphometry, dependencies

Introduction

Water temperature in lakes of the temperate zone, regardless of their area and depth, presents a characteristic sinusoidal course throughout the year. This character is particularly clearly preserved during the period of summer water stagnation. It is well known that surface water temperature in temperate zone lakes depends on geographical location. This dependency is present in several dozen lakes located in the area of southern Finland, Latvia, Lithuania and northern Poland (Fig. 1). Relations between the average surface water temperature during the summer (June-August) (t_{sum}) and latitude clearly show that lakes located north of 60° N latitude are characterized by much lower surface water temperatures (below 17.5°C), whereas those located south of 55° N latitude have temperatures higher than 19.5°C.

The thermal stratification of water in lakes, resulting from the influence of many factors, determines the intensity and scope of most biological, physical and chemical processes including water circulation, oxygen conditions, biomass production, vertical distribution of organisms and availability of nutrients. Despite the fact that the diversity of water mass in lakes is also determined by the nature of the lake catchment (hydrological type, type of management and slopes), one should also take into account the optical properties of water, determining heat transfer deep into the lake, conducive to the increase of the euphotic zone range and general heat accumulation. The conditions associated with the influence of wind and the extent of water mixing, as well as the intensity of horizontal water exchange (Patalas 1960; Chomskis 1969; Skowron 1991, 2007, 2011; Kilkus 2000; Borowiak and Borowiak 2001) also play an important role. Water temperatures in the lakes in the years 1972-2016 were characterised by a higher rate of increase of 0.43°C dec^{-1} than the air temperature decrease of 0.34°C dec^{-1} (Ptak et al. 2018)

It is assumed that the amount of solar radiation reaching the water surface in lakes located in northern Poland is only slightly varied (average annual sums of total radiation are within 340-370 kJ cm^{-2}). In turn, it should be noted that the highest values of direct solar radiation intensity at lowland stations in Poland (Kołobrzeg, Mikołajki and War-

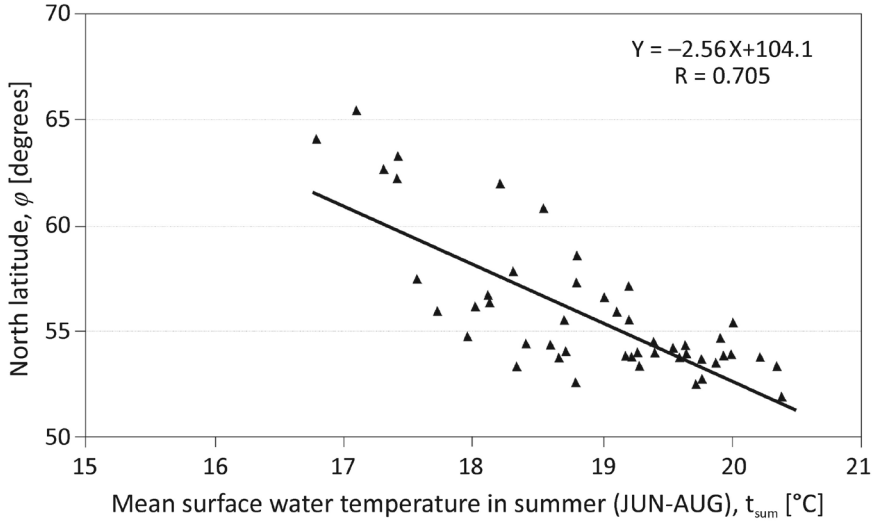

Fig. 1. Dependency between mean surface water temperature in summer (t_{sum}) in selected lakes located in the Baltic Sea drainage basin and geographical latitude (φ) (according to Korhonen and Haavanlammi 2012; Pernaravičiūtė 2004 modified; Apsīte et al. 2014 modified, and author)

saw) fall in spring (April-May), decreasing by 0.8-2.6% on average in the summer months (Uscka-Kowalkowska 2019). This course has a significant impact on surface water temperature increases, when the biggest increases occur from mid-April to the first 10 days of May (Skowron 2011). There-fore, it is important to study what other factors may cause such significant differences in water tempera-ture between individual lakes.

These differences concern both the surface layer of the lakes and its internal structure. They relate both to the value of water temperature in particular lakes located a short distance from one another and also to time variations. Varied vertical distributions of water temperature during the summer stagnation (August) are presented with respect to several lakes (Fig. 2).

The measurements of water temperature in the lakes located over the relatively small area of the Bory Tucholskie National Park also provide confirmation (Choiński et al. 2012). It was found be-

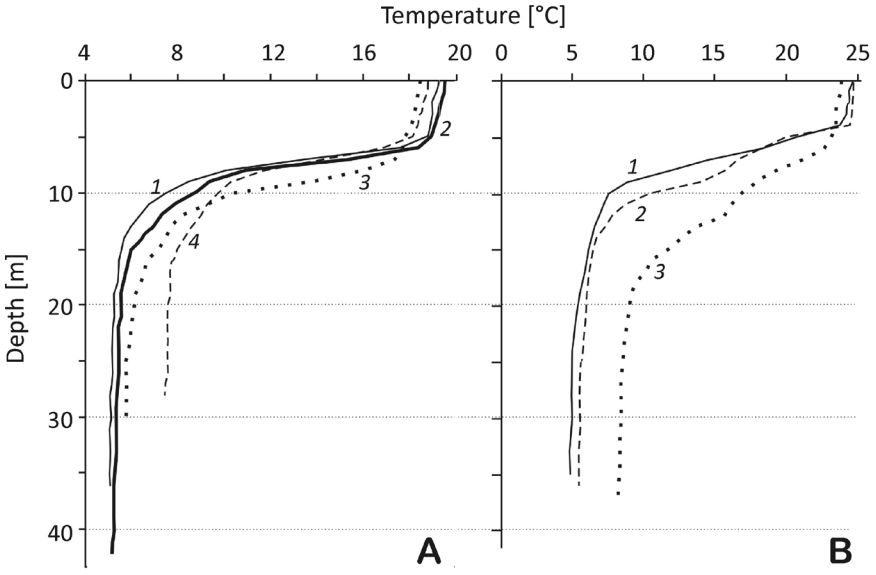

Fig. 2. Vertical profiles of water temperature in selected Polish lakes. A – on August 17, 1998: 1 – Garbaś, 2 – Dobskie, 3 – Mausz Duży, 4 – Krzywe; B – on August 7, 2018: 1 – Jeleń, 2 – Jagodne, 3 – Niegocin

yond doubt that the range of epilimnion during the summer stagnation (July-August) was in the range of 2.6-6.6 m, heat content from 60.24 to 86.23 J cm^{-3}, and average water temperatures at the depth of 10 m from 5.8 to 10.5°C. Such varied water temperatures at this depth may be caused by the influence of groundwater supply.

The analysis covered 141 lakes located in northern Poland, in the area of the last glaciation. They are located unevenly over this region and their selection resulted from the available and collected data on the vertical distribution of water temperature and morphometric data. There are 63 lakes in the Pomeranian and Greater Poland Lakelands (west of the Vistula), and 78 lakes in the Masurian Lakeland (east of the Vistula).

This paper presents materials on thermal stratification during the summer collected by the author and morphometric data gathered by the Inland Fisheries Institute in Olsztyn. Water temperature measurements during the summer (August) were taken in the deepest place (at least in three seasons), although for some lakes there are at least 30 measurement series (Bachotek 56, Raduńskie Górne 43, Morzycko and Tarnowskie Duże after 30). Measurements in thermal risers were made in a layer to the depth of 15 m every 0.5 m, and deeper every 1 m (Skowron 2011). This made it possible to calculate the values for 10 parameters of the water thermal structure.

Excel and Corel Quattro Pro 8 spreadsheets were used to calculate all the parameters of the water thermal structure, their mean, extreme values, and standard deviation and trends. Corel Draw 9 helped in graphic processing.

Study area description

The analysed lakes present a wide spectrum of morphometric, hydrological and mixing properties. Their areas range from over 11,000 ha (Śniardwy – 11,487.5 ha) to just over 5 ha (Czarne – 5.5 ha). There are 20 lakes above 1,000 ha and they constitute as much as 66.7% of the area of all the analysed lakes, while there are 39 below 100 ha. In terms of volume, the biggest lakes are: Miedwie (681,672 dam^3), Śniardwy (660,212 dam^3), Wigry (336.727 dam^3) and Drawsko (331.443 thousand m^3). For the next 15 lakes, the volume is greater than 100,000 (dam^3). The lakes with the smallest volume are: Czarne (151,000 m^3), Główka (300,000 m^3) and Wielkie Gacno (444,000 m^3). In terms of their depth, the maximum values range from 2.0 (Ruteckie) to 106.1 m (Hańcza). However, mean lake depth, which is a reliable indicator of depth relations, ranges from 0.9 m (Ruteckie) to 38.7 m (Hańcza). For 16 lakes, the mean depth is greater than 15.0 m, while for 31 lakes it is less than 5.0 m. The nature between the horizontal and vertical lake sizes is well represented by the relative depth index (C_R), which is the quotient of the mean depth to mean width (Skowron 2004). Its value for the analysed lakes ranges from 0.01 (Brzeźno) to 66.55 (Łagowskie). For 40 lakes the value of this parameter is greater than 20, while for 46 shallow ones it is less than 10.

In addition, most lakes in the Polish Lowlands have a clearly varied shoreline and basin shape. This is primarily due to the genesis of their basins, as well as the processes that have occurred since the beginning of their formation up to modern times. These conditions are well characterized by the shoreline development indicator (Choiński 2007). The average values are in the range of 2.09-2.12, and the largest values are characterized by multi-reservoir water bodies (Jeziorak – 5.85, Gopło – 5.55, Wigry – 4.43, Rajgrodzkie – 4.07). The well-divided shoreline and the multi-reservoir nature of the lake basin are of great importance for the formation of a diversified thermal water regime.

Results and discussion

An important issue raised in this work is the relationship between the basic morphometric parameters and thermal parameters during mid-summer (August). Eight morphometric parameters and 10 parameters referring to the thermal structure of water in lakes during the summer stagnation were taken into account. These relationships can be best seen between the lake depth, represented by the lake volume up to a depth of 5 m ($V_{(5)}$), the mean slope of the bottom of lake basin (γ_{mean}), the lake maximum (z_{max}) and mean (z_{mean}) depth, and the relative depth index (C_R) and thermal stratification parameters such as the sum of meta- and hypolimnion volume (V_{M+H}), thermal stratification coefficient (mean temperature in the water column to surface water temperature ratio), μ, heat content in the volume unit, Q, (J cm^{-3}), water temperature difference between the surface and bottom layers (Δt), and the mean water tem-

perature in the water column (tj). The values of correlation coefficients between them are above 0.650 with a statistical significance of p <0.001. In turn, the weakest correlation relationships were found between the effective lake lengths (fetch, mean width) and all thermal stratification parameters (beyond the epilimnion range) rarely exceed 0.200, with a statistical significance of p >0.01 (Table 1).

Differences in the course of surface water temperature between the lakes were also found in the dates of the appearance of specific temperature values (Skowron 2011). During the summer months, the surface temperature of the water was usually higher in lakes with small depths, than in deep lakes (Skowron 2009). Such examples were observed in lakes regardless of their location.

It was established beyond any doubt that the average bottom water temperature and the mean temperature gradient in the metalimnion ($\Delta t/\Delta z$) in the summer were strongly correlated with the lake depth indicators (with maximum, mean and relative depths). A similar tendency was observed in relation to the lake compactness index. High correlation was obtained especially between the relative depth index (C_R) and heat content indexes (Q) in the lake (Skowron 2009, 2011).

The research based on the heat balance method conducted on 20 lakes of the Kashubian Lakeland shows that the overall heat content in the lakes has a significant relationship with climatic conditions and with morphometric and hydrological properties (Lange 1978).

Parameters that significantly affect the thermal structure of water in lakes during the summer include the mean depth of the lake and the mean slope of the bottom of the lake between which there is a very high correlation (Fig. 3). A very strong relationship was found for the mean lake depth and the percentage share of the hypolimnion layer in the lake volume (Fig. 4).

The impact of the shape of the lake basin on the parameters determining the internal thermal structure of water is interesting (Fig. 5). It had an influence on the lake volume up to a depth of 5 m ($V_{(5)}$) and the thermal stratification factor (μ) and between mean slope of the lake bottom γ_{mean} (degree) and the heat content Q (J cm^{-3}). In the first case, an increase in the water thermal stratification index can be recorded with a percentage increase in the lake volume share to a depth of 5 m. In turn, in the second case, the increase in the slope of the bottom of the lake basin is accompanied by a decrease in the heat content in a unit of volume. Both relationships have statistical significance $p < 0.001$.

Table 1. Correlation coefficients between selected morphometrical and thermal parameters in August in the years 1971-2010 (bolded statistical significance below 0.001). Symbols: $V_{(5)}$ – volume up to 5 m depth, γ_{mean} – mean slope of lake bottom (degrees), z_{max} – maximum depth (m), z_{mean} – mean depth (m), C_R – relative depth index (mean depth to mean width ratio, dimensionless), K – shape factor (dimensionless), F – fetch (m), B_{mean} – mean width (m)

Thermal parameter	Morphometric parameter							
	$V_{(5)}$	γ_{mean}	z_{max}	z_{mean}	C_R	K	F	B_{mean}
Volume (metalimnion + hypolimnin), V_{M+H} [%]	**0.866**	**0.797**	**0.773**	**0.794**	**0.572**	**0.481**	0.295	0.199
Thermal stratification index, μ [dimensionless]	**0.868**	**0.721**	**0.797**	**0.733**	**0.515**	**0.496**	0.303	0.172
Heat content in lake, Q [J cm^{-3}]	**0.863**	**0.808**	**0.824**	**0.833**	**0.555**	**0.413**	0.134	0.088
Maximum temperature difference, Δt [°C]	**0.778**	**0.652**	**0.631**	**0.621**	**0.527**	**0.519**	**0.459**	0.271
Mean lake's water temperature, tj [°C]	**0.856**	**0.791**	**0.816**	**0.824**	**0.543**	**0.394**	0.112	0.077
Mean water temperature at the bottom, t_{bot} [°C]	**0.814**	**0.634**	**0.671**	**0.643**	**0.495**	**0.514**	**0.342**	0.211
Mean hypolimnion temperature, t_{hyp} [°C]	**0.697**	**0.620**	**0.605**	**0.570**	**0.498**	**0.396**	0.252	0.208
Epilimnion thickness, z_{epi} [m]	0.283	0.162	0.252	0.166	0.185	0.035	**0.753**	**0.697**
Mean thermal gradient in metalimn. $\Delta t/\Delta z$, [°C m^{-1}]	0.116	0.162	0.081	0.006	0.298	0.014	**0.394**	**0.320**
Mean temperature at a 5 m depth, t_5 [°C]	0.205	0.187	0.180	0.182	0.02	0.039	0.078	0.124

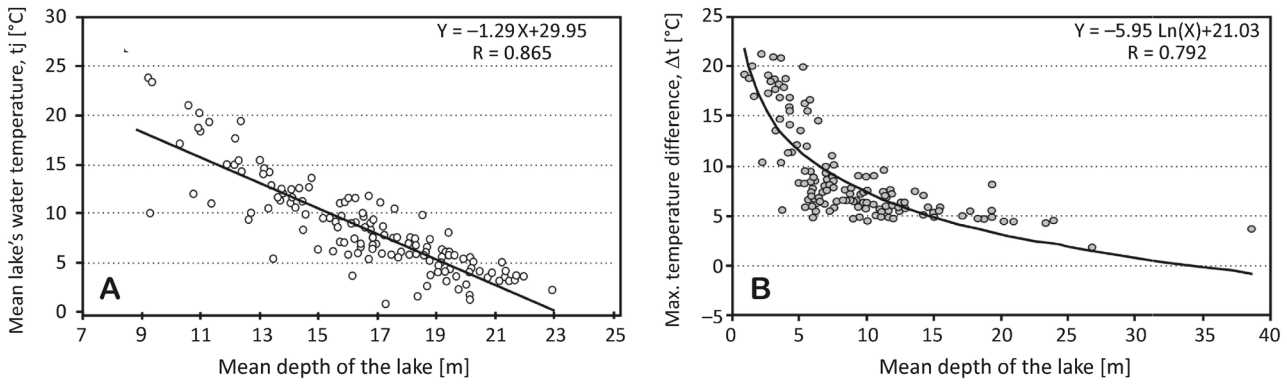

Fig. 3. Relationships between mean lake depth (m) and: A – mean lake water temperature (tj, °C); B – maximum difference of water temperature (surface temperature minus near bottom temperature) (Δt, °C)

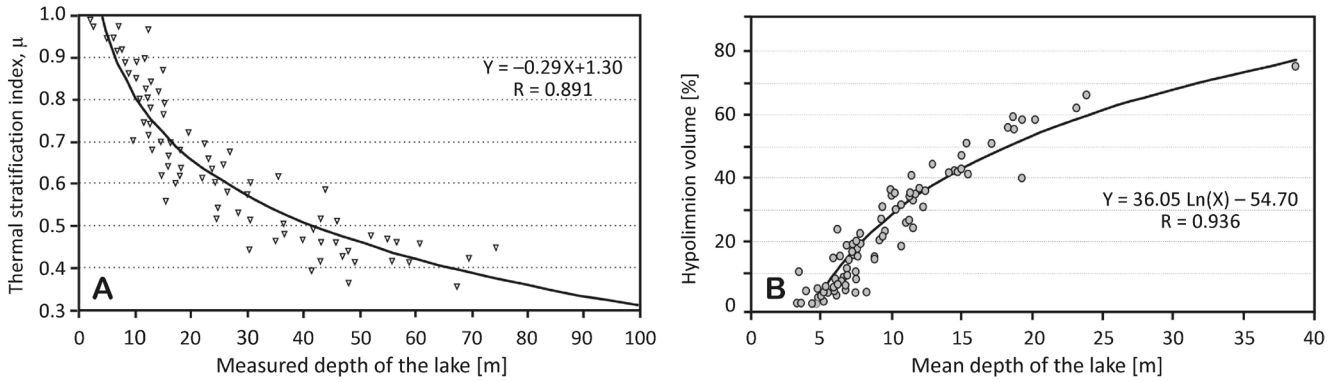

Fig. 4. Relationships between: A – measured lake depth and thermal stratification index (μ, dimensionless), and B – mean lake depth and percentage of hypolimnion in the volume of lake (%)

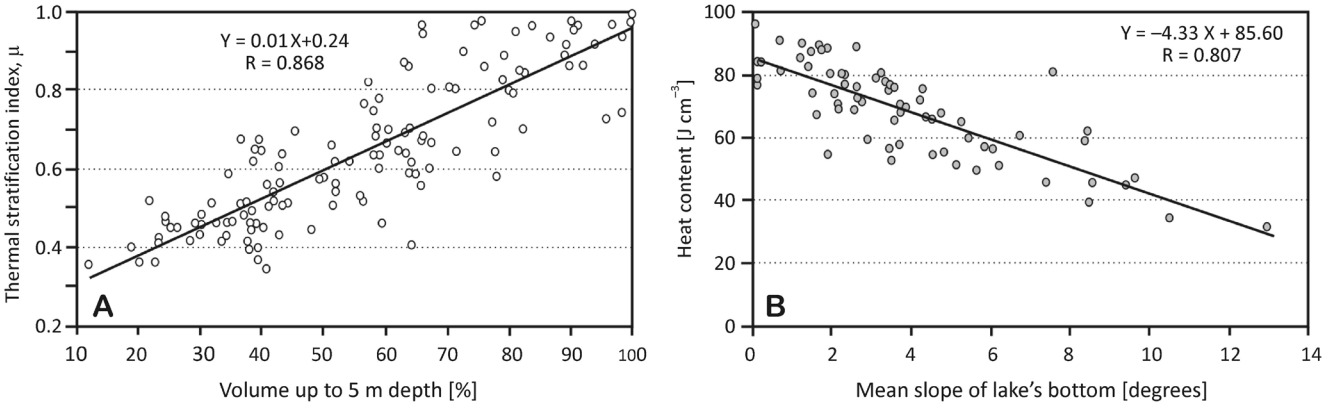

Fig. 5. Relationships between: A – lake volume up to 5 metre depth and thermal stratification index (μ), and B – mean slope of lake bottom (degrees) and heat content in lake (J cm^{-3})

Conclusions

The influence of lake basin morphometry on the vertical thermal structure of water has also been the subject of the analysis of lakes located in various latitudes (Efremova and Pal'shin 2003). Taking into account the Karelia lakes, their surface, depth at the place of measurement, water exchange rate, water temperature at any depth and the thermal classification of the lakes were determined by means of the empirical equations. Studies of the selected properties of the thermal regime and the impact on their morphometry were carried out in Lithuanian lakes (Chomskis 1969; Kilkus 1985). It was noticed that the temperature of surface and bottom layers as well as the thickness of the epilimnion reflected relationships with the average depth of lakes, wind incidence and thermal typology of lakes. For lakes from the Kashubian Lakeland, a clear relationship between the lake surface and the maximum depth was obtained, determining their mycelicity (Jędrasik 1985).

The research on the relationship between morphometric and thermal parameters showed that the thermal structure of the water in the lakes is mainly determined by the lake depth and related parameters. The linear parameters, including the surface have only a minor influence. However, it should be remembered that the lake surface is also a parameter not covered by this analysis, nor are: the basin compactness index, the lake exposure (openness) index, the development of the shoreline or the relative depth.

The existing relationships are confirmed by the thermal types of the studied lakes as a function of the mean lake depth and the relative depth index. Clear boundaries between the particular thermal types indicate the decisive role of depth in the shaping of the thermal and mixing regime of the lakes (Fig. 6).

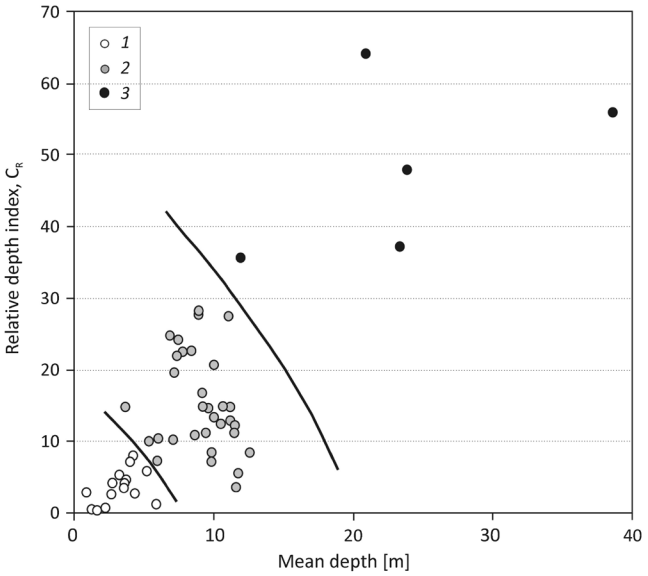

Fig. 6. Thermal types of Polish lakes as a function of their mean depth and relative depth index (C_R): 1 – epithermal lakes, 2 – metathermal lakes, 3 – hypothermal lakes

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