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WATER TEMPERATURE AND ITS DIVERSITY IN THE DEEPEST LAKES OF THE TUCHOLA FOREST AND THE KASHUBIAN AND BRODNICKIE LAKELANDS

Abstract: This study presents the results of monthly examinations of the vertical distribution of water thermal structure (2008–2011) carried out over a four-year period in the deepest lakes located in the Kashubian and Brodnickie Lakelands and the Tuchola Forest[1]. Three lakes were selected for examination (Raduńskie Górne, Zbiczno and Ostrowite). Their maximum depths slightly exceed 40 m, and their surface areas range from 121 to 362.5 ha. The results of the measurements show that, despite only minor differences in depth, water temperature varied significantly between the studied lakes. These differences were mainly apparent in the extent of the epilimnion, water thermal stratification, and in the water temperature in the bottom-most layers in summer and winter. The diversity in thermal stratification of the lakes is mainly determined by their morphometric properties, their location above sea level, and the dynamic influences of winds.

Key words: water temperature, lakes, NW Poland

[1] Measurements of water temperature in the selected lakes were partially conducted within the ministerial grant N306 354836 entitled *Forming oxygen regime in postglacial lowland lakes.*

Introduction

Air temperature is the main factor determining the course of all biotic and abiotic processes in the aquatic environment. Seasonal changeability of water temperature can be observed in lakes in the temperate climatic zone, regardless of their surface areas, depth relations and hydrological character. The sinusoidal course of water temperature is recorded in the entire lake mass over the year. However, it is observed most clearly in the surface layer, whose thickness may be up to several metres (Chomskis 1969; Skowron 1999, 2011; Jefremova and Palshin 2003; Choiński 2007). The surface layer is the element of the lake system which is most susceptible to changes in meteorological conditioning. It is here that the basic processes and mechanisms shaping the dynamics and regime of the entire lake system take place (Lange 1977; Skowron 2009).

It is generally known that an increase in the extent of the euphotic zone improves conditions for the penetration of solar radiation into deeper parts of lakes. However, heat accumulation in the layers underlying the euphotic zone is mainly due to wind mixing or currents and internal circulation (Langmuir circulation, seiches) in bigger and deeper lakes (Wetzel 2001; Lampert and Sommer 1996; Kilkus 1985).

The depth of mixing is most frequently associated with the depth of the epilimnion (Patalas 1960; Chomskis 1969; Okulanis 1976, 1981; Skowron 1990; Ambrosetti and Barbanti 2001). Below the epilimnion, there is a layer with a rapid change in temperature (the metalimnion, or thermocline), which forms a boundary above which water circulation movements predominate, and below which convection and molecular exchanges of heat take place (Chomskis and Żukajte 1970). Therefore, the extent of the epilimnion in the thermal structure of water at the beginning of August is usually identified as being the result of the maximum extent of the influence of climatic factors.

Study materials and methods

This study presents the results of the monthly measurements of vertical distribution of water temperature in three lakes (in the places of maximum depth) over the period 2008–2011. The analysed lakes represent the deepest water bodies in the Kashubian and Brodnickie Lakelands and the Tuchola

Forest. Three lakes were selected for the study: Raduńskie Górne (the Kashubian Lakeland), Zbiczno (the Brodnickie Lakeland) and Ostrowite (the Tuchola Forest). Their maximum depths slightly exceed 40 m (Fig. 1). In total, 108 measurements of the vertical distribution of water temperature were carried out, mostly during the summer months (43%). The WTW OXI 197 temperature and oxygen meter was used to measure water temperature every 1 m of depth.

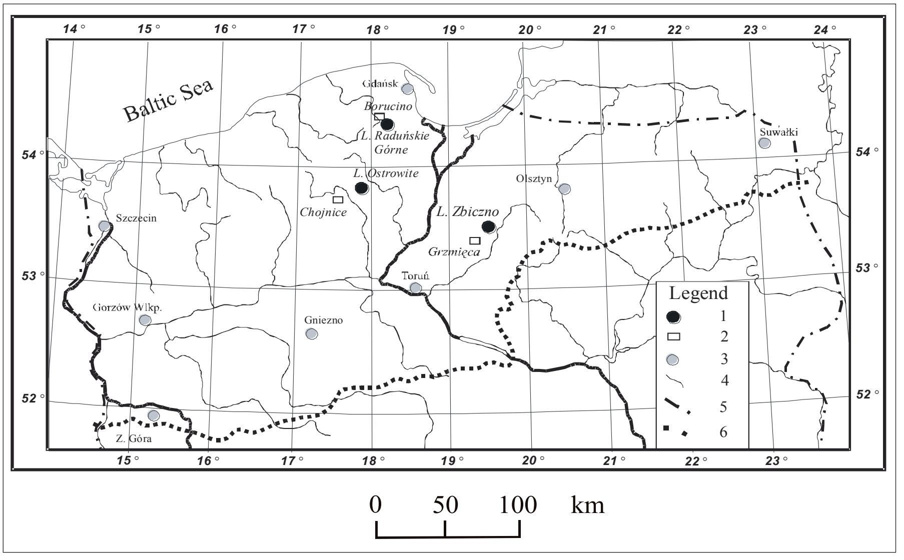

Fig. 1. Location of observation stations: 1 – Lakes; 2 – Meteorological stations; 3 – Towns; 4 – Rivers; 5 – The Polish border; 6 – The maximum extent of the Weischelian Glaciation

Moreover, the study takes into account the mean monthly values of air temperature recorded at the meteorological stations located in the close vicinity of the lakes over the years 2001–2011, and the mean monthly values of surface water temperature in Lake Raduńskie Górne and two lakes (Charzykowskie and Bachotek) located in the neighbourhood of the analysed water bodies. In order to determine the theoretical mixing depth, the values of an effective lake length along the central line of the lake was applied (Skowron 1990; Choiński 2006).

The study aims to present differences in the main properties of the thermal regimes of lakes of similar maximum depths, but differing surface areas and volumes.

Discussion

The analysed lakes are typical postglacial water bodies with varied morphometric properties of their basins (Table 1). From a hydrological point of view, they are flow-through lakes, except for Lake Ostrowite; full water exchange occurs every 2–4 years (every 50 years for Lake Ostrowite.) These lakes are characterised by small (30- to 40-cm) annual amplitudes of water stages. Their areas range from 121 to over 362 ha. Their mean depths equal from 10.7 to 15.5 m, and their maximum depths range from 41.6 to 43 m. That they have the character of a clearly indented basin is illustrated by the relative depth indices and the mean inclinations of the lake bottoms. Moreover, the low proportion of depth up to 2.5 m (below 25% of volume) and water transparency indicate slight differences between the particular lakes.

Table 1. Hydrological and morphometric properties of the studied lakes

Parameter	Raduńskie Górne	Zbiczno	Ostrowite
Numbers according to the Catalogue of Lake of Poland after Choiński (2006)	I-19-36	II-49-47	I-36-81
The nature of the hydrological	flow-through lake	flow-through lake	outflow lake
The annual outflow (thousand m^3)	26,535.4	3,763.7	599.8
Indicator horizontal the exchange of water	0.44	0.25	0.02
The exchange horizontal of the water in the years	2.27	4.0	50.0
Mean annual water level amplitude (cm)	30	35	40
Surface (ha.)	362.5	121.0	259.0
Mean position of lake water level above the sea level	161.6	71.2	124.2
Volume (thousand m^3)	60,158.7	15,054.9	29,989.8

Table 1 (Continued)

Parameter	Raduńskie Górne	Zbiczno	Ostrowite
Maximal depth (m)	43.0	41.6	43.0
Mean depth (m)	15.5	11.7	10.7
Mean width (m)	656	490	720
% of lake volume of depth up to 2.5 m	15.1	20.2	20.4
Relative depth index	23.6	23.9	14.9
Mean bottom inclination	5.9	5.85	5.42
% of lake volume of depth up to 10 m	47.4	34.8	34.4
Theoretical depth of the epilimnion according to Skowron (2011)	6.4	5.1	5.6
Transparency of water in summer after 2005 (m)	2.6	2.4	6.8
Water purity class by A. Choińskiego (2006)	II	II	I

Despite the small distances between the lakes, the regions where they are located are characterised by diverse climatic conditions. This diversity can be documented by the mean monthly values of air temperature recorded at the stations located in the direct neighbourhood of the analysed lakes (Table 2).

Table 2. Mean monthly values of air temperature (°C) in the years 2001–2011

Meteorological stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year	Amplitude
Grzmięca	-1.1	-1.1	3.1	9.4	15.3	18.1	20.6	19.5	14.5	8.9	4.3	-0.2	9.3	26.3
Chojnice	-2.1	-1.0	2.1	7.9	12.7	15.6	18.5	17.6	13.4	7.8	3.6	-0.5	8.0	22.5
Borucino	-4.1	-3.3	1.1	8.1	11.5	15.4	18.6	17.4	13.2	6.8	4.2	-1.8	7.2	24.1

The region of the Brodnickie Lakeland (Grzmięca) has distinctly the highest mean yearly air temperature (9.3°C). In contrast, the lowest value was recorded in the Kashubian Lakeland (Borucino), and was a mere 7.2°C. During the winter season the lowest temperature values by some margin are recorded in the Kashubian Lakeland (< -3.3°C) and were more than 2.2°C lower than in the other regions. Furthermore, in the period from April to November the region of the Brodnickie Lakeland was noticeably warmer than the other regions (> 2–3°C).

These thermal differences in the lakes are confirmed by the courses of surface water temperature values (Table 3). The highest mean yearly surface water temperature is observed in Lake Bachotek (10.4°C), and the lowest is observed in Lake Raduńskie Górne (9.1°C).

Table 3. Mean monthly values of surface water temperature (°C, TWP) over the years 1971–2010 (based on data obtained from the Institute of Meteorology and Water Management-PIB)

Lake/Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Bachotek	6.0	2.3	1.2	1.3	2.8	7.4	14.6	18.9	20.9	20.8	16.5	11.5	10.4
Charzykowskie	6.2	2.8	1.2	1.1	2.1	5.5	12.4	17.1	19.4	19.3	15.5	11.0	9.5
Raduńskie Górne	6.1	3.1	1.6	1.4	2.3	5.2	10.9	16.1	18.5	18.6	15.0	10.5	9.1

It is generally known that the annual thermal cycle of water in lakes located in the temperate climatic zone starts the moment ice phenomena disappear completely. Such a viewpoint has been expressed with respect to big lakes of a dimictic character (Tikhomirov 1982; Wetzel 2001; Palshin and Jefremova 2003). However, some authors assume that the thermal cycle in lakes starts the moment snow vanishes on ice or traces of water circulation can still be seen under ice (Niesina 1970; Jędrasik 1975; Skowron 2001). When ice phenomena occur, heat resources accumulated in the water mass and in a thermally active layer of bottom deposits, as well as heat exchange between deposits and surface layers, mainly define the thermal conditions of water in lakes (Grześ 1978).

In summer seasons the character of water thermal stratification in lakes in the temperate zone is clearly differentiated by: the thickness and gradients of the epilimnion, the position of the thermocline, temperature differences between surface water and bottom-most layers (Skowron 1990), the degree of thermal vertical lamination (Niesina 1970), the absolute differences in water temperature in the lake (Kilkus 2000), and the percentage share of the epi-, meta- and hypolimnion in the lake volume (Tikhomirov 1982; Kitajev 1978; Skowron 2011).

The location and extent of the particular thermal layers depends upon numerous factors, the most important of which include the morphometric properties of the lake, and particularly its area and depth (Hutchinson 1957; Tikhomirov 1982). Many researchers claim that the thickness of the epilimnion is influenced mainly by wind and effective lake lengths (Patalas 1960; Chomskis 1969; Okulanis 1981; Skowron 1990, 2011; Jańczak and Maślanka 2006; Maślanka and Nowiński 2006).

Table 4. Mean values of water temperature (°C) at selected depths in winter (January and February) and in summer (July and August) in the years 2008–2011

Depth (m)	Lakes					
	Raduńskie Górne		Zbiczno		Ostrowite	
	winter	summer	winter	summer	winter	summer
1	1.8	20.5	2.9	21.5	2.4	20.8
5	2.2	19.4	3.2	20.3	2.8	20.4
10	2.4	11.6	3.2	6.7	3.0	10.8
20	2.9	6.5	3.2	5.1	3.4	5.6
30	3.3	5.8	3.3	4.9	3.5	5.1
40	3.5	5.7	3.7	4.8	3.7	5.0

The course of water temperature recorded at various depths is presented in Table 4 and Figure 2. The data indicate that during winter months (Dec–Feb) reverse (cathothermal) stratification can be observed. The lowest temperature values at a depth of 1 m were recorded in Lake Raduńskie Górne (1.8°C), whereas the highest were noted in the smallest lake, namely Zbiczno (2.9°C). This character is confirmed by the mean values of water temperature (Table 6). During summer months (Jun–Aug) normal (anothermal) stratification forms in a varied way. In this case, the temperature of the layers below 10 m (below the metalimnion) is determined by the lake's area. At a depth of 30 m, the highest mean water temperature was 5.8°C (Lake Raduńskie Górne), while the lowest was 4.9°C (Lake Zbiczno) (Table 4). The lowest values of water temperature observed below 10 m in summer (from March to November) are recorded in Lake Zbiczno and Ostrowite, and they are lower than in Lake Raduńskie Górne by approx. 1.5–2.0°C (Fig. 2).

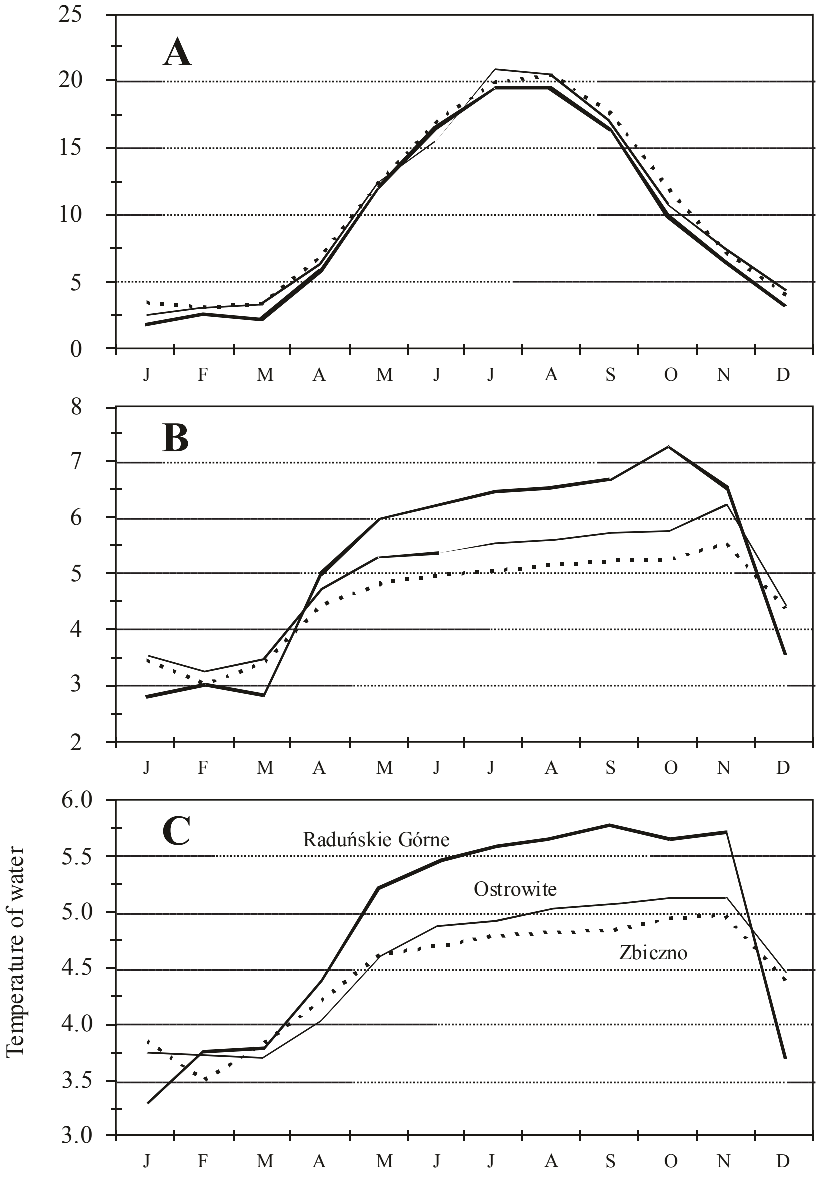

Fig. 2. Mean monthly course of water temperature (°C) over the years 2008–2012 at various depths: A – 5 m; B – 20 m; C – 40 m

The analysed lakes show diverse annual courses of water temperature and its parameters. From April to December the highest values of temperature below 10 m were recorded in Lake Raduńskie Górne, while the lowest were observed in Lake Zbiczno. The same distribution is upheld for the bottoms of all three lakes. During the summer the thermal structure of the lakes comprises several distinct layers. The distribution of the epi-, meta- and hypolimnion layers varied in the analysed lakes. The extent of those particular layers is presented in Table 5. The thickest epilimnion was found in Lake Raduńskie Górne (6.6 m), while the thinnest was observed in Lake Zbiczno. Lake Ostrowite was found to have average properties most frequently, despite certain differences (Choiński et al. 2012). Despite this, in many cases this lake showed properties more similar to those of Lake Zbiczno.

Table 5. Real and theoretical depth of the epilimnion in the studied lakes

According to the authors	Formula	Depth of epilimnion (m)		
		Raduńskie Górne	Ostrowite	Zbiczno
Measured mean depth of epilimnion	-	6.6	6.2	5.0
Patalas (1960)	$4.4\ F^{0,5}$	7.0	6.8	5.3
Okulanis (1981)	$7.3\ F^{0,5}$	5.9	6.2	5.1
Skowron (1990)	$7.7F_L^{0,5}$	6.4	5.6	5.1

Many researchers have drawn attention to the fact that, regardless of the geographical location and the influence of meteorological factors upon the thermal regime of lakes, the character of the metalimnion is determined by the shape and form of the lake basin. Relatively good dependencies have been found between the mixing depth and the lake's size expressed as effective lengths, thus confirming the findings of Patalas (1960), Okulanis (1981) and Skowron (1990, 2011). In all cases the formulas describing these dependencies (Table 4) have a fairly significant range of deviations (±15 %), although they show differences between the lakes well.

The thickness of the metalimnion showed a slight diversity. Its top limit stayed at the depth of 5.0 m in Lake Zbiczno, and 6.6 m in Lake Raduńskie. On the other hand, the bottom limit was 11.5 m on average in Lake Raduńskie Górne, 11.0 m in Lake Ostrowite, and 10.2 m in Lake

Zbiczno. Therefore, the thickness of the metalimnion was 4.9, 4.8 and 5.2 m respectively. The resulting mean value of the gradient in the metalimnion was typical of deep lakes in Poland, and equalled 2.4, 2.3 and 2.8°C.

At the turn of July and August the hypolimnion stayed below 10.5–11.5 m on average, and covered approx. 30–41% of the lake's volume. The percentage share of the different thermal layers in the lake's volume made it possible to classify the lakes as water bodies of hypothermal character (Skowron 2011). However, according to Skowron's classification (2010), all the lakes were classified as moderately cold lakes with the lake's thermal index (I_T) ranging from 1.01–1.22, which proves certain thermal differences between the lakes.

The distribution of thermal layers in lakes is well characterised by their thermal stratification coefficient during summer seasons (Niesina 1970). The highest such value is noted in Lake Zbiczno (0.380) and it is characteristic of the deepest lakes in Poland (Skowron 2009). In Lake Raduńskie Górne, which is a considerably bigger water body, the index reaches 0.467 due to stronger wind mixing.

Heat resources in the water of the analysed lakes provide significant information on the characteristics of the thermal regime. The biggest heat resources both in summer and winter are accumulated in Lake Raduńskie Górne, whereas the lowest are in Lake Zbiczno. Primarily, this results from the diverse volumes of the lakes. Their courses during the year also vary (Tables 7 and 8). Heat flux density per unit surface area (kcal · cm^{-2}) and density of per unit volume (J · cm^{-3}) are the key parameters for showing the essential difference in heat resources between one lake and another. Heat resources by volume is a good parameter for differentiating lakes which belong to the same thermal type.

Table 6. Course of mean monthly and yearly heat resources and its parameters in the selected lakes over the years 2008–2011

Lake	Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Raduńskie Górne	tj (°C)	6.5	3.5	2.1	2.7	2.4	5.5	8.8	11.1	12.9	13.1	12.2	8.9	7.6
	MJ	1640.7	878.3	538.7	676.3	615.5	1377.9	2203.1	2797.7	3271.6	3056.4	3062.4	2240.5	1887.7
	$kcal \cdot cm^{-2}$	10.8	5.8	3.6	4.5	4.1	9.1	14.5	18.4	21.6	21.8	20.2	14.8	12.6
	$J \cdot cm^{-3}$	27.3	14.6	9.0	11.2	10.2	22.9	36.6	46.5	54.4	54.9	50.9	37.2	31.7
Zbiczno	tj (°C)	6.8	4.2	3.3	2.9	3.3	6.3	9.8	12.0	13.5	13.4	12.3	9.6	8.1
	MJ	429.0	263.0	207.8	181.0	210.5	394.9	615.9	754.8	854.5	846.6	777.5	606.9	511.9
	$kcal \cdot cm^{-2}$	8.5	5.2	4.1	3.6	4.2	7.8	12.1	14.9	16.9	16.7	15.3	12.0	10.1
	$J \cdot cm^{-3}$	28.5	17.4	13.8	12.0	14.0	26.2	40.9	50.1	56.8	56.3	51.6	40.3	34.0
Ostrowite	tj (°C)	7.3	4.4	2.8	3.0	3.3	6.1	9.7	12.2	14.2	14.4	13.2	9.7	8.3
	MJ	911.7	553.1	347.2	371.5	408.8	761.4	1214.6	1530.2	1782.9	1812.6	1657.7	1222.3	1047.8
	$kcal \cdot cm^{-2}$	8.4	5.1	3.2	3.4	3.8	7.0	11.2	14.1	16.4	16.7	15.3	11.3	9.7
	$J \cdot cm^{-3}$	30.4	18.4	11.6	12.4	13.6	25.4	40.5	51.0	59.5	60.4	55.3	40.8	34.9

Explanations: tj = mean temperature water in lake; MJ = heat resources in $MJ \cdot 10^6$; $kcal \cdot cm^{-2}$ = heat content in $kcal \cdot cm^{-2}$; $J \cdot cm^{-3}$ = heat content in $J \cdot cm^{-3}$.

Table 7. Average heat resources, thermal stratification and thermal typology of the analysed lakes during summer stagnation (from 20th July to 20th August) in the years 2008–2011

Lakes	Heat resources (MJ)	Mean water temperature (°C)	Heat content		Thermal stratification index μ)	% volume of epilimnion	Thermical type
			kcal·cm^{-2}	J·cm^{-3}			
Raduńskie Górne	3,164.0	13.00	21.70	54.7	0.467	37.2	H/M
Zbiczno	850.6	13.48	16.78	56.5	0.360	37.9	H/M
Ostrowite	1,797.7	14.32	16.59	59.9	0.416	44.7	H/M

Explanation: H/M = metahypothermal lakes

Table 8. Average heat resources in the selected lakes during winter stagnation (from 15th January to 15th February) over the years 2008–2011

Lakes	Heat resources (MJ)	Mean water temp. (°C)	Heat content		Water temperature at 1 m depth (°C)	Thermal stratification index (μ)
			kcal·cm^{-2}	J·cm^{-3}		
Raduńskie Górne	636.2	2.53	4.19	10.57	2.0	1.89
Zbiczno	192.5	3.05	3.80	12.79	2.7	1.68
Ostrowite	369.0	2.94	3.40	12.30	2.4	2.04

Conclusions

The results of the synchronous measurements of water temperature conducted at monthly intervals in three selected lakes over the years 2008–2011 show that the course of the vertical distribution of temperature remained closely related to the areas and properties of the lake's bottom relief. These lakes have approximate maximum depths of 41–43 m, and a relatively small ratio of their volume to a depth of 2.5 metres (15.1–20.4%). Despite the lakes' smaller variation in depth, several significant differences in the course of their thermal regime features can be observed:

– In the yearly course the lowest values of surface water temperature are recorded in the period from April to November in Lake Raduńskie Górne (located highest, at 161.6 m a.s.l.), whereas the highest values are recorded in Lake Bachotek. The differences in temperature in this period exceeded 2°C most frequently, with the biggest difference in May (3.7°C). On the other hand, in the period from November to February a reverse trend was observed with the differences not usually exceeding 0.6–0.8°C.

– Relatively low summer water temperatures in Lake Raduńskie Górne and Ostrowite also resulted from the distance of these lakes' water tables above sea level. The height of the water table was 161.6 m a.s.l. in Lake Raduńskie Górne, 124.2 m a.s.l. in Lake Ostrowite, and 71.2 m a.s.l. in Lake Zbiczno (Table 1).
– The investigations conducted in three lakes confirmed the results of the previous observations (1973–2006) of other lakes (approx. 90 lakes of the Polish Lowland) that the wind mixing depth is determined not only by the lake's area and the orientation of the lake's longer axis with respect to prevailing winds but also by the sheltering of the shoreline with large trees.
– Various depths of the location of the upper and lower limits of the thermal spike in the lakes are determined by their areas and their effective lengths which determine the intensity of wind mixing.
– Investigations of the thermal structure of waters should be based upon one constant point on a lake which shows average mixing conditions.

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