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CRITERIA OF THERMAL CLASSIFICATIONS OF LAKES

Abstract. Since the early twentieth century limnological literature has presented numerous classifications of lakes. Most frequently these classifications refer to genetic systematization. In the latter half of the twentieth century new divisions of inland water bodies were introduced with respect to mictic, trophic and thermal properties. These proposals, however, make up a very diverse and scattered material, particularly due to the considered criteria. The author of this article decided to verify opinions and criteria of these systematisations to provide a better understanding of the problem.

Keywords: lake, classification, thermal

1. Introduction

Limnological typologies have always constituted one of the most fundamental issues, and also major research problems in limnology integrating and systematising knowledge developed in various branches related to the study of lakes. A very wide perspective of factors shaping up a thermal regime of a lake ecosystem is a consequence of many features which develop this unique territorial lake system (Lange 1986; Kubiak 2003). The diverse character of the ecosystem results from numerous processes which function there, and mainly the geographical location and the related climatic conditions, morphometric properties of the lake basins, the character of lake catchments, and a hydrological function of a particular lake during the recent years of human activity.

2. An overview of major thermal classifications of lakes

A wide view of thermal conditions determining lake ecosystems around the world has drawn the researchers to put forward classifications of lakes and systematize knowledge in this field. The first classification was presented by Geistbek in 1885 (after Kitajev 1978), and it distinguished warm and cold lakes. The boundary of division was the value of water temperature 6.5^{o}C near the bottom in the summer.

The most widespread classification based upon climatic zonality and the number of full circulations was the taxonomy put forward by Forel in 1892. It divided all the lakes in the world into three basic types: polar, moderate and tropical ones. Water temperature is always below 4^{o}C in polar lakes, higher than 4^{o}C in tropical lakes, and reaches 4^{o}C twice a year (in spring and autumn) in the lakes located in the moderate zone.

In 1925 Mołczanow (after Kitajev 1978) presented his thermal classification of water bodies considering the properties of the active warm layer (epilimnion). He differentiated warm and cold lakes. The former get warm throughout the entire year, the latter are the bodies with one minimum and one maximum.

Further systematisations in this field were only modifications of Forel's classification. Yoshimura (1936) adds subpolar and subtropical lakes into Forel's taxonomy. The former group comprises lakes with the temperature of over 4^{o}C with vertical gradients and a thermocline located near the surface. On the other hand, the latter group shows water temperature of over 4^{o}C near the bottom throughout the year, and homothermy in the winter with big amplitudes on the surface.

Findenegg (after Wiszniewski 1953) introduces the concept of mixis by differentiating holomictic lakes (mixed down to the bottom) from meromictic lakes (mixing does not occur in the entire water mass). Passowicz supplements this taxonomy in 1938 (after Wiszniewski 1953) by adding bradymictic lakes (poor water mixing) and tachymictic lakes (fast mixing of water). Then Olszewski (Wiszniewski 1953) adds eumictic lakes (a form of an intermediate pace of mixing, between brady- and tachy-mixis. Furthermore, Wiszniewski (1953) supplements Findenegg's classification by introducing the concept of polymixis (frequent mixing), and Paschalski (1961) adds the concept of pleomixis, i.e. excessive mixing.

In Poland, the first thermal classification of lakes was popularized by Wiszniewski (1953) who compiled several mictic classifications, presented earlier by various authors. In this classification Wiszniewski distinguished the following types of the lakes:

– meromictic – with clearly isolated layer of monimolimnion lying below and the dynamic surface layer of mixolimnion, separated by a chemocline,
– holomictic – with well developed summer stratification and total mixing of waters during circulation periods,
– polymictic – with multiple mixing of the entire water mass throughout the year. These are usually shallow lakes.

Other thermal classifications of lakes accounted for various criteria, however, most frequently they referred to the annual course of water temperature and heat resources of the water mass in the lakes. Zajkov (1955) distinguished five periods on the grounds of the changeability of heat resources and water temperature in the water mass of the lakes located in the moderate zone:

– spring warming which begins still under the ice, and ends when water temperature exceeds the value of 4°C,
– summer warming, which can be divided into a phase of early summer (from the formation of even stratification to the moment when heat inflows and losses stabilize), and a phase of late summer (with a considerable degree of temperature stability connected to the formation of epi-, meta- and hypolimnion),
– autumn cooling (starts when there is a negative balance of the water surface and finishes when there is homothermy of 4°C),
– winter cooling (begins with catothermal / reverse stratification and lasts until the formation of icing),
– winter warming (begins when the ice cover is formed).

One of the most widely applied limnological classifications, particularly in American literature, is the thermal taxonomy put forward by Hutchinson and Löffler (1956**.** They based their classification upon the number of complete homothermies. Additionally, they accounted for the zonality and the altitude of the location, so an aspect of a geographical location (Fig. 1). This systematization corresponds to many previous classifications. Hutchinson and Löffler distinguished the following types of lakes:

– amictic – practically sealed off permanently by ice, so there is no mixing,

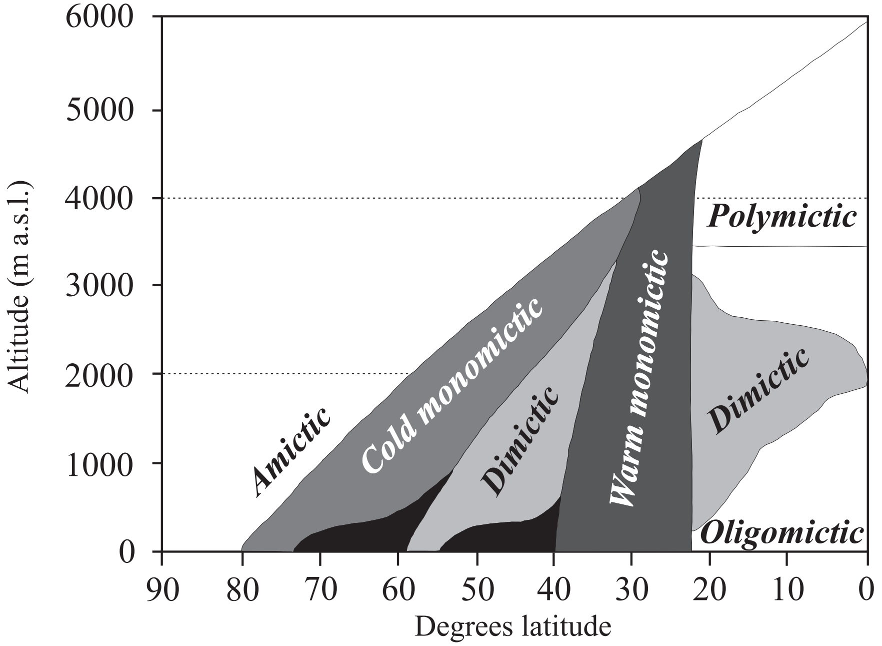

Fig. 1. The global distribution of thermal lake types in relation to latitude and altitude (after Wetzel 2001)

– cold monomictic – one circulation in the summer, and water temperature is never greater than 4°C,
– warm monomictic – water temperature sever goes below 4°C and circulation takes place in the winter; the lakes are stratified in the summer,
– dimictic – with two periods of mixing: one spring and one autumn,
– oligomictic – with rare circulation at irregular interval, and temperatures above 4°C,
– polymictic – shallow water bodies with frequent or continuous circulation.

Lewis states (1983) that the imperfections of Hutchinson and Löffler's classification (1956) result from the fact that they neglected shallow lakes, did not account for the relation between meromixis and the above mentioned lake types, or considered the complexity of tropical lakes and difficulties with the classification of cold lakes because of the set boundary of 4°C (Fig. 2).

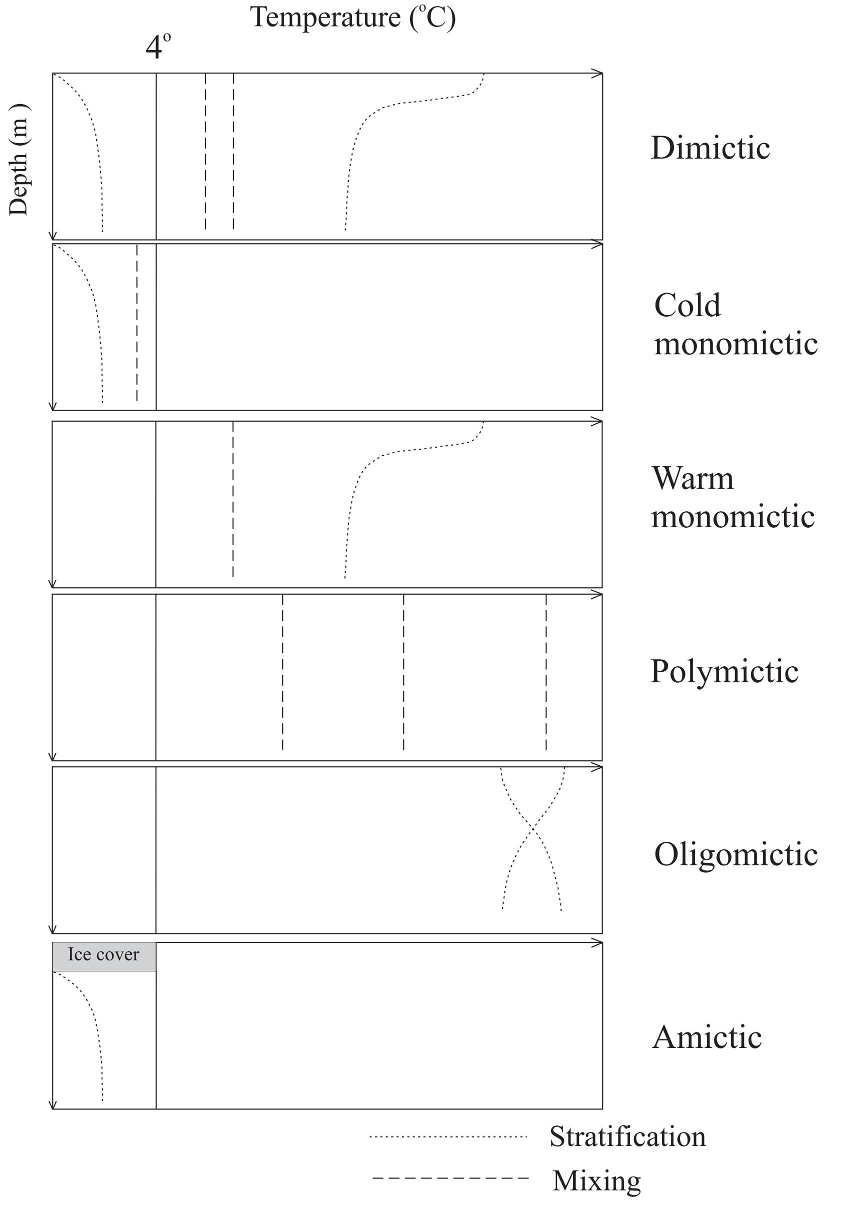

Fig. 2. Lake thermal structure and classification based on mixing characteristics (after Häkanson and Jansson 1983)

Lewis (1983) proposes to remove these imperfections, and introduce certain changes to the terminology and assumptions presented in the modified classification (Table 1).

Table 1. Thermal classification of lakes according to Hutchinson and Löffler (1956) and Hutchinson (1957) as modified by Lewis (1983)

Thermal type of a lake	Main properties
amictic	permanently ice-covered
monomictic	full circulation takes place only once a year
– warm monomictic	free circulation in the winter, a stable thermal stratification during the summer
– cold monomictic	temperature remains near 4°C throughout the year; circulation takes place only in the summer
dimictic	thermally stratified during the ice-free period, free circulation in the spring and autumn
polymictic	irregular thermal stratification throughout the year
– continuous cold polymictic	with a winter ice cover, and during the ice-free period, circulation is continuous or only interrupted by brief periods of stratification.
– discontinuous cold polymictic	with a winter ice cover, and during the ice-free season thermally stratified except for brief periods of circulation
– discontinuous warm polymictic	without any ice cover and thermally stratified but mixing occurs more than once a year
– continuous warm polymictic	without any ice cover but mixing occurs continuously throughout the year except for brief periods of stratification
meromictic	Lakes that do not undergo complete circulation due to a stable thermal or chemical layer near the bottom.

Zafar (1959) introduces a classification of lakes into three types: polar, moderate and tropical, and adds an element of vertical zonality, that is the height above the sea level (Table 2).

Table. 2. Thermal classification of lakes (after Zafar 1959)

Type	Subtype	Further division of the subtype
I. polar	Ia. subpolar (1 km < h < 2 km)	
II. moderate (h < 1km)	IIa. moderate subarctic 1 km < h < 2 km	
	IIb. moderate arctic h > 2 km	
III. tropical		subtropical h = 1–2 km
		moderate h = 2–4 km
		subarctic h = 4–6 km
		arctic h> 6 km
	IIIa. subtropical h < 1 km	moderate h = 1–2 km
		subarctic h = 2–4 km
		arctic h>4 km

As far as Lithuanian lakes are concerned, Chomskis (1969) distinguished four types of lakes on the grounds of the differences in the temperature of the water near the bottom in the deepest parts of the lake during the period of summer stagnation and the period with the ice cover. They were:

- very deep thermally stratified lakes (the difference of the temperature of the near-the-bottom layers amounts to approx. 4°C in the summer and winter, whereas the maximum depths may reach 10–50 m),
- deep thermally stratified lakes (the differences of the water temperatures range from 0.5 to 5°C, whereas all three thermal layers occur in the summer. During the summer the temperature of the near-the-bottom layers reaches 7°C),
- lakes of medium depth (the difference of the water temperatures ranges from 5 to 15°C, whereas the maximum depths may reach 30 m),
- shallow lakes (where there is practically no thermocline and the difference in temperatures is nearly 20°C).

The analysis of the annual course of water temperature and the character of thermal stratification in the summer leads Tikhomirov (1970, 1982) to propose a classification of lakes located in the moderate zone. He distinguishes epithermal (shallow water), metathermal (medium depth) and hypothermal (deep) lakes. He recognises two subtypes among the metathermal lakes: meta-epithermal lakes and meta-hypothermal lakes.

As for the lakes located in the Karelia region, having considered the form of the lake basin, the warming character of the water masses during the spring-summer season and the extent of water circulation and thermal stability, Friejndling (after Potachin 2006) differentiated three types of the lakes:

1 – shallow water bodies of an undisturbed bottom relief. These get warm in homothermal conditions, circulation occurs throughout the entire depth and there is unstable thermal balance,

2 – deep water bodies with a complex relief of the underwater part of the basin. These get warm in the conditions of stable thermal stratification; the maximum gradients are recorded in the thermocline,

3 – water bodies whose particular basins get warm in various conditions (Table 3).

The classification of the lakes located in the moderate zone presented by Abrosov (1971) accounts for the location of the thermocline and lists the following types of the lakes: 1 – warm homogenous – where the volume of epilimnion (V_E) equals the volume of the lake, 2 – warm homogenous – where the volume of epilimnion is several times as big as the volume of hypolimnion (V_H), 3 – moderately cold – where the ratio of the volume of pilimnion and hypolimnion is greater than 1, 4 – cold – where the ratio of the volume of epilimnion and hypolimnion is lower than 1 ($V_E/V_H < 1$), and 5 – very cold – where the ratio of the volume of epilimniom and hypolimnion is several times smaller than 1 ($V_E/V_H << 1$).

Table 3. Examples of thermal classifications of the lakes located in the moderate climatic zone (according to various authors)

Author, year. Distinguishing properties	Lake classes
Friejndling (after Potachin 2006). The form of the lake basin, the character of water mass heating during spring-summer periods, extent of water circulation, stability.	1. Shallow water bodies with an undisturbed bottom relief. They get warm in homothermal conditions; circulation occurs throughout the entire depth; unstable thermal balance. 2. Deep water bodies with a complex structure of the water part of the basin. They get warm in the conditions of stable thermal stratification; the maximum gradients are recorded in the thermocline. 3. Water bodies whose particular basins get warm in various conditions.
Tikhomirov (1970, 1982). The thermal structure in hydrological seasons, a yearly thermal cycle.	1. Epithermal: shallow water bodies, homothermy throughout the entire period without ice. Epilimnion makes up the entire water mass. 2. Hypothermal: large and deep water bodies, hypolimnion makes up the fundamental water mass. 3. Metathermal: the thermal regime is not homogenous. They can be divided into three groups: regular metathermal, meta-epithermal and mata-hypothermal.
Nesina, Ogneva (1975). The division of radiation balance into warming and evaporation.	1. Deep lakes: 70–80% for warming, 20–30% for evaporation. 2.Medium-depth lakes: 15–20% for warming, 75–80% for evaporation. 3. Shallow lakes: 5–10% for warming, 90–95% for evaporation.
Kitajev (1978, 1984). The mean integral temperature of water during the summer period (tśr), or the sum of temperature values during the period with water temperature over 10 °C (Σ t).	1. Very warm: tśr > 20°C; Σ t > 4 000°C. 2. Warm: tśr = 15–20°C; Σ t = 2 000–4 000°C. 3. Moderate: tśr = 10–15°C; Σ t = 1 000–2 000°C. 4. Cold: tśr = 5–10°C; Σ t = 500–1 000°C. 5. Very cold: tśr < 5°C; Σ t < 500°C.

By dividing radiation balance of the lake surface into the warming and evaporation periods, Nesina and Ogneva (1975) identify three types of the lakes: 1 – deep lakes: 70–80% for warming, 20–30% for evaporation, 2 – medium-depth lakes: 15–20% for warming, 75–80% for evaporation, and 3 – shallow lakes: 5–10% for warming, 90–95% for evaporation.

On the other hand, Kitajev (1978) created a new classification for hydrobiological purposes. This taxonomy accounted for benthos (littoral, sublittoral, profundal) and pelagial (epi-, meta- and hypolimnion). In hypothermal lakes (very deep) the area of littoral (F_L) is considerably smaller than the area of sublittoral (F_{SL}) and profundal (F_P): $F_L << (F_{SL} + F_P)$. The water mass volume of epilimnion (V_E) is significantly smaller than the sum of the volumes of metalimnion (V_M) and hypolimnion (V_H): $V_E << (V_M + V_H)$. In hypo- metathermal lakes (deep) the area of littoral is slightly smaller than the sum of the areas of sublittoral and profundal: $F_L < (F_{SL} + F_P)$, whereas the water mass volume of epilimnion is slightly smaller than the volumes of metalimnion and hypolimnion: $V_E < (V_M + V_H)$. On the other hand, in metathermal lakes (medium depth) the area of littoral (F_L) is the same as (close to) the sum of the areas of sublittoral (F_{SL}) and profundal (F_P): $F_L \approx (F_{SL} + F_P)$, and the volume of epilimnion is close to the volumes of metalimnion and hypolimnion: $V_E \approx (V_M + V_H)$. In metathermal lakes (shallow) the area of littoral is greater than the sum of the areas of sublittoral and profundal: $F_L > (F_{SL} + F_P)$, while the volume of epilimnion is greater than the sum of the volumes of metalimnion and hypolimnion: $V_E > (V_M + V_H)$. In epithermal lakes (very shallow) sublittoral, profundal, metalimnion and hypolimnion cannot actually be found: $(F_{SL} + F_P) = 0$, $V_M + V_H = 0)$.

The observations of water temperature conducted in 15 lakes located in northeast Poland in the years 1971–1978 lead Bernatowicz (1981) to distinguish three thermal types of the lakes:

- cold lakes – where the thermocline lies above the mean depth of the lake, thermal conditions change eight times throughout the year,
- moderate lakes- where the thermocline most frequently lies below the mean depth of the lake, thermal conditions of the water mass change twelve times throughout the year,
- warm lakes – most frequently without summer stratification, thermal conditions change as many as thirty-seven times throughout the year.

Wiszniewski and Koźmiński (after Wiszniewski 1953) accounted for optical properties and water temperature at the depth of 2 m below the ice in the lakes located near Suwałki, and distinguished warm lakes (> 3°C) and cold ones (< 3°C), transparent and non-transparent lakes. Gołębiewski and Lange (1976) do not agree with this classification as they claim water temperature below the ice should not be a criterion for the typology due to its big changeability in different years. Reviewing various limnological typologies they point out to the lack of universality and impossibility to apply them to all lakes. Numerous classifications show great individualism of the criteria. However, classifications should also account for local or regional conditionings of the natural environment.

Referring to the earlier proposals for the water surface layer in the Polish lakes (Chojnowski 1967; Bojanowicz 1970; Grześ 1978; Skowron 2001) distinguishes thermal seasons accounting for the defined values of water temperature (the minimum and maximum of temperature, 4°C and 15°C in the spring and autumn) and the ice-in dates.

Throughout the year the surface layer reveals a winter season with a phase of winter cooling and a phase of winter warming, a spring season with an early and late phase of spring warming, a summer season with a phase of summer warming and a phase of summer cooling, and an autumn season with the first and second phase of autumn cooling (Fig. 3). The distinguished seasons made it possible to differentiate accurately the lakes located in the Polish Lowland with respect to thermal conditions.

A similar character of the division of the year into seasons is defined for Estonian lakes by Järvet (2002). To distinguish climatic seasons in the lake waters he considers water temperature and such properties of the ice cover as: ice-in and ice-out dates (Table 4).

Table 4. Thermal seasons in Estonian lakes (according to Järvet 2002)

Climate seasons	Determining of climate seasons
Early spring	from the break up the ice cover up to the period of mean daily water temperature above +4°C
Spring	Period of mean daily water temperature from +10°C to +15°C
Summer	Permanent increase of diurnal mean water temperature above +15ºC
Autumn	Period of mean daily water temperature from +15°C to +4°C
Late autumn	Period from the end of daily water temperature above +4°C up to the beginning of ice phenomena
Early winter	from the beginning of ice phenomena up to the beginning of ice cover
Winter	Period with permanent ice cover

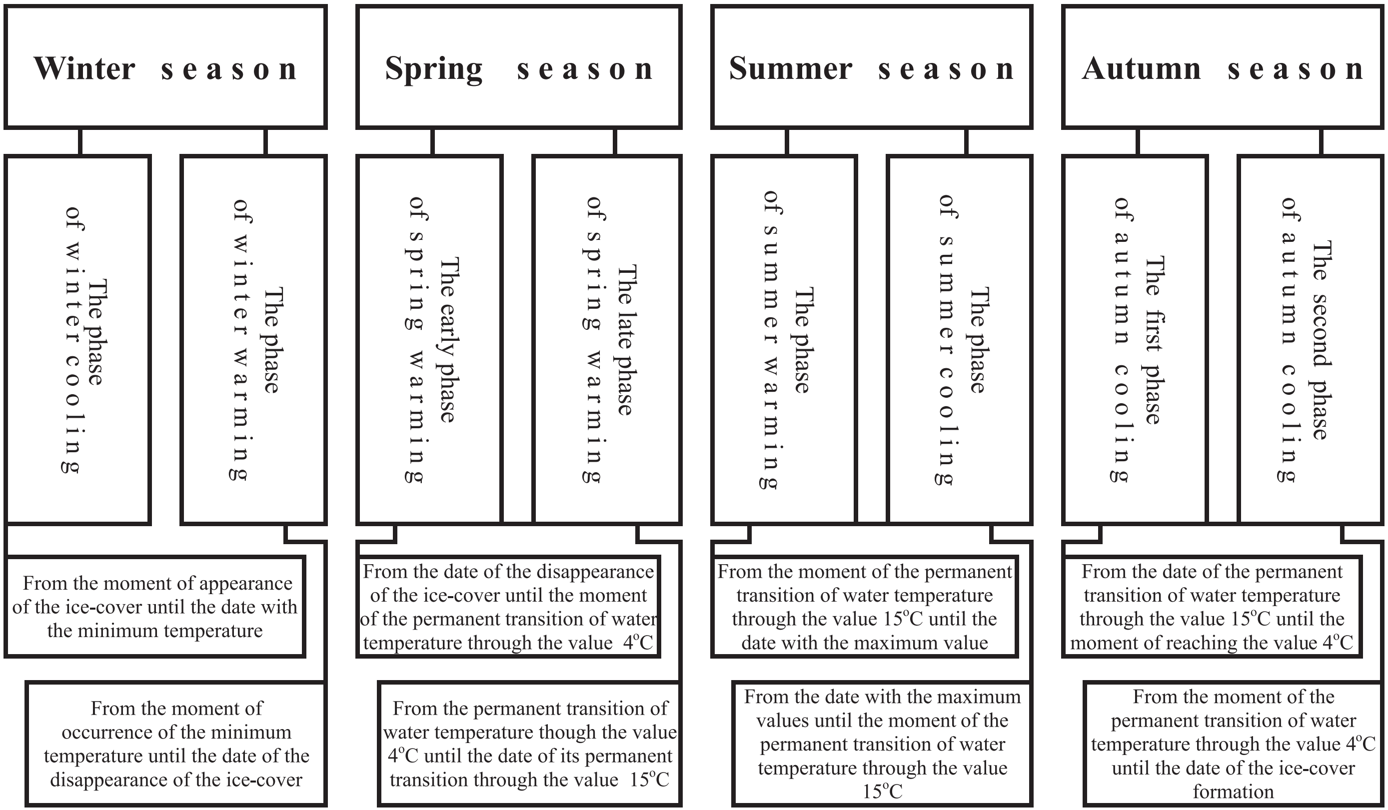

Fig. 3. The pattern of the division of the thermal year into periods and phases in the surface water layer in Polish lakes (after Skowron 2001)

Applied by Chomskis (after Kilkus 2000), the relative heat content in a volume unit ($J \cdot cm^{-3}$) in the water mass of the lake (T_v) and the temperature of the near-the-bottom water layer in the winter season (T_b) became criteria to differentiate the thermal types of the lakes located in Lithuania. The relative heat content is becoming a more frequently applied parameter defining the capacity to accumulate heat in the water mass of the lakes located in the moderate climatic zone, seen as the sum of the influences of climatic conditions and morphometry of the lake basin (Skowron 2009). According to these criteria the following lake types have been distinguished: cold lakes ($T_b < 3°C$), moderately warm lakes ($3°C < T_b < 4°C$), and evidently warm lakes ($T_b > 4°C$).

3. Conclusions

The classifications of the inland water bodies proposed by many researchers in recent eighty years mainly referred to the systematisation of knowledge in order to recognize the diversity and uniqueness of the lakes. They also aimed at integrating researching circles.

The review of the above typologies may lead to an assumption that the criteria of the lake classifications are varied, starting from special, which reflect a particular property of a lake, e.g. geographical, geological and genetic, thermal, oxygen, floral, fishing, optical and thermal, and finishing with more general criteria, which define e.g. a trophic state of a lake. These types may refer to many properties of the natural environment (Wiszniewski 1953). The Naumann-Thienemann typology based on these assumptions was developed and complemented with time by Findenegg; Wiszniewski and Koźmiński; and Stangenberg (after Wiszniewski 1953).

All the pioneering thermal classifications of lakes arise from the typology proposed by Forel and constitute its development in a sense. Depending upon the leading factor, we can clearly distinguish three fundamental groups. The first group comprises the classifications based upon physical and geographical zonality, accounting for the lake's geographical location and its height above the sea level. The second group of the lake classifications refers to the character of water mass mixing and mictic condition of the water bodies. This typology can also be applied to all the lakes in the world, though in most cases it refers to the water bodies located in the moderate zone. The third group of the classifications considers properties of water thermal structure with a different degree of detail.

In the 1980s the classifications whose criteria were based upon the selected properties of the thermal structure of the water throughout the year were developed. The most fundamental properties were:

- the annual changeability of heat resources accumulated in the lake water mass,
- the temperature of the near-the-bottom water layers in the summer,
- the mean temperature of the water column near the maximum depth or the mean temperature of the water in the summer season,
- the sum of water temperatures (degree-day) in the season with the temperature value of over 10^{o}C,
- the character of water mass warming in the spring-summer season,
- the difference of temperatures of the near-the-bottom water layers in the summer and in the winter,
- the ratio of the depth of epilimnion to the maximum depth of the lake, or the other way around,
- the annual fluctuations of water temperature and the character of thermal stratification,
- the character of the summer mixing of water masses depending upon the lake's area and depth as well as the run-up of the wind,
- the decline of water temperature with the depth in the summer, releasing heat by bottom deposits in the winter, and the changeability of the temperature of the near-the bottom- water layer in the summer and in the winter,
- the ratio of the zones of benthos and pelagial during the summer stagnation,
- the percentage share of the volume of the epi-, meta- and hypolimnion during the summer stagnation.

Therefore, the thermal classification of the lakes must be based upon the elements characterising the changeability of the selected features of the thermal regime of the lakes throughout the year. Otherwise, it may become rather non-objective and unrepresentative. It should account for thermal variations between the lakes and local or regional conditionings of the natural environment..

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