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RESEARCH ARTICLE

EVALUATION OF THE PHYSICAL, CHEMICAL, AND BIOLOGICAL NATURE OF LAKES IN NORTHERN SIBERIA

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ABSTRACT

This article presents the results of research at selected lakes located on the border of northern Siberia beyond the Polar Circle conducted during the summer of 2016, and covers physical, chemical, and biological methods. This article also highlights the differences between glacial lakes in that part of Siberia and those of Europe and North America. These differences affect not only water quality, but more importantly the age of the lakes, their exact origin, and their hydrogeological conditions. In the water of the studied lakes, physical and biological properties match oligotrophic and mesotrophic class, while chemical parameters classify them mainly as eutrophic and hypertrophic lakes with no anthropogenic sources of contamination.

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INTRODUCTION

Lakes dominate the landscape of many regions of the northern part of Siberia; their numbers are exorbitant considering the vastness of the region. Larger lakes located closer to areas inhabited by people have names, yet the vast majority do not, which results in difficulties regarding the determination of their number and total surface. In regions such as Surgut (Western Siberia), lake density amounts to 20% of the region, while in Chukotka (Eastern Siberia) it reaches as high as 70%. Yet, the clear majority of lakes are small thermokarst lakes characterized by a relatively short period of existence; moreover, they are shallow, often frozen at the bottom, and are often deprived of ichthyofauna. Their surfaces undergo vast changes throughout the year; research in the central part of Siberia indicates that changes in their surface depend on the precipitation (Kravtsova, 2011). Interest in these lakes has grown in recent years, making them a subject of numerous studies. These studies focus mainly on the issue of their greenhouse gas emissions, yet they also provide valuable information on their content of macro and microelements (Langer, 2015; Walter, 2006; Boike et al., 2015). Typically, limnologic research of both thermokarst and post-glacial lakes has been carried out only occasionally in this region. Lakes located in northern Siberia, which are generally classified as post-glacial, are particularly interesting from a limnological point of view. This is due to the following features distinguishing these lakes compared to post-glacial lakes of Europe and North America:

Origin: Post-glacial lakes were given this term because they formed as a result of glacial retreat, mainly northwards. In the northern part of northern central Siberia, as many as three factors have contributed to shaping the landscape in the Pleistocene period: influence of glaciers, tectonic phenomena, and marine transgression (Sheinkman, 2015). The listed factors, along with the location of the studied lakes in this article is presented in Figure 1. As far as the formation of lakes is concerned, we should add to the mentioned factors the thermokarst process, which already in this period initiated the formation of the first lakes of this kind. As it has been mentioned, all these phenomena took place in the Pleistocene; therefore, these lakes are significantly older than the typical post-glacial lakes from the early Holocene period in North America and Europe. Until recently, it was thought that the southern boundary of maximum glaciation in this area of Siberia was along a range of hills called the Siberian Uvals, also presented in Figure 1. However, the most recent studies do not confirm this fact (Sheinkman, 2015 and Velichko, 2011) and state that during the glaciation periods there were two centers from where glaciers spread out in this region: one in

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the northern part of the Ural Mountains, and second on the Putorana Plateau. Their range, especially during the last glaciation, was limited only to foothills. These facts mean that the majority of lakes in this area are not post-glacial. On the other hand, if we assume that the studied lakes, due to their proximity to the Putorana Plateau, formed as a result of glacial influence, it means that they had to be formed during the period of their maximum extent which could cover this area. The greatest glacial extent in this area was attributed to the Zyrianian glaciation, which comprised two glacial periods: ca. 70 - 60 thousand and 30 - 20 thousand years ago. Additionally, it is assumed that the extent of the second glaciation period was very short. Hence, lakes of this area may be approximately 60 thousand years old. This means that they may be as much as 6 times older than typical lakes formed in Europe and North America from the early Holocene period.

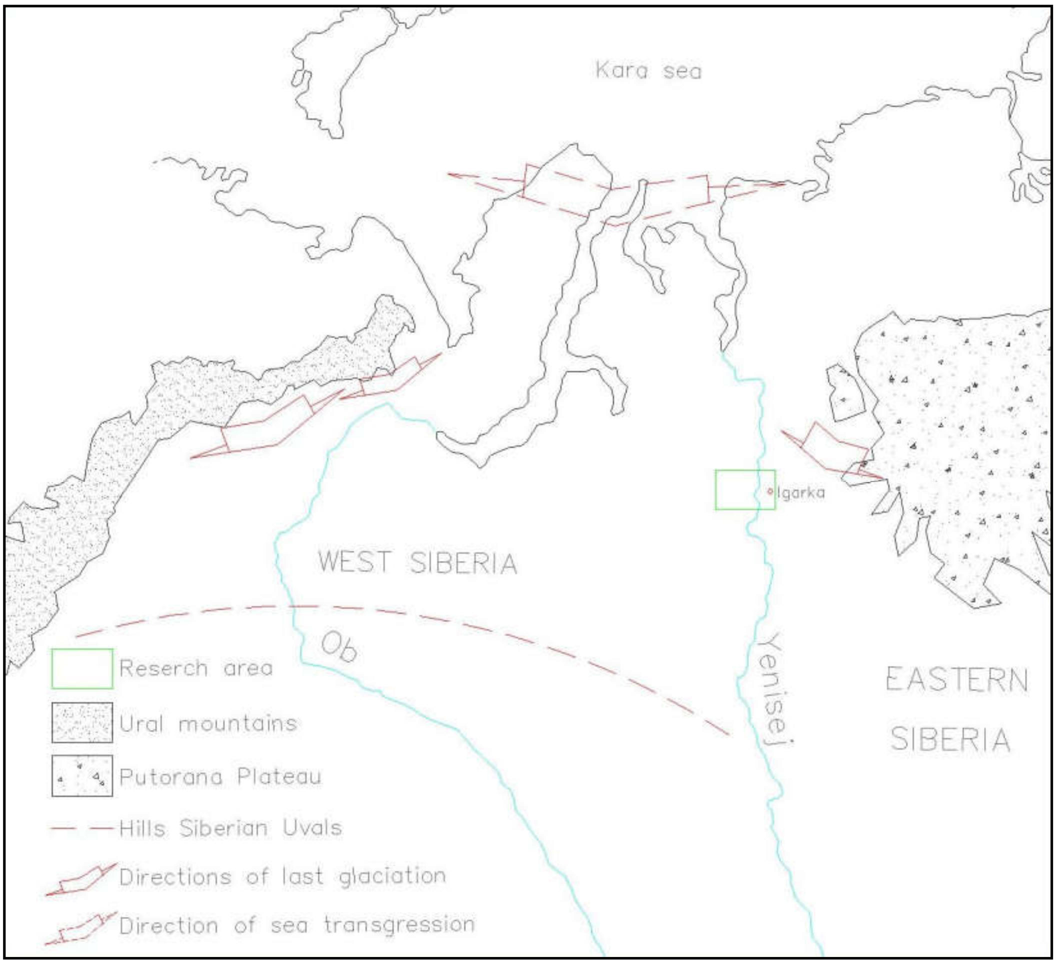

Figure 1. Sampling locations and glacier movement directions during the Pleistocene

The issue of the origin of the lakes in western an central Siberia is still an unsolved academic problem (Lyubomirov, 1990). Many detailed studies on the origin of certain lakes in the river valleys of Jana and Kołyma carried out in the 20th century demonstrated that it is unlikely that the origin of these lakes is thermokarst (Vtyurin, 1977). Hence, for the lakes studied in this study it is assumed that they are post-glacial; however, there are no credible data confirming this. These lakes may be of tectonic origin as such phenomena have been documented in this region during the Pleistocene. The thermokarst process may also cause their formation; however, this is not likely considering their depth. Moreover, they may be a result of the last marine transgression which took place approximately 135 – 140 thousand years ago (Arkhipov, 1999).

Hydrogeological conditions: Owing to the continental climate prevailing in northern Siberia during the Pleistocene, the creation of glaciers was very limited there due to dry air and low precipitation; it resulted in the formation of permafrost, which as a relic of the Pleistocene, is preserved until the present day within Siberia and covers as much as 9 million square kilometers, which constitutes approximately 2/3 of the surface area of the Russian Federation (Alekseev, 2016). The whole northern part of Siberia is covered with permafrost, in some places reaching a depth of 1,500 m below ground surface. This has a huge impact on water circulation in the local lithosphere. This, in turn, changes the function of lakes in that region, in particular their water regime. For the shallow thermokarst lakes formed as a result of the ice thaw from the ground, their water source is most often precipitation and surface runoffs from melting snow. Additionally, their water source may include groundwater runoffs in the season when the upper layer of permafrost thaws. On the other hand, post-glacial lakes usually occupy deeper land depressions and may be, depending on permafrost depth, more connected to groundwater; however, it is generally assumed that in these areas ground sources of water for lakes constitute only 10% of all water supply and is similar to water source conditions of lakes located in the steppe part of Siberia (Rakovskaya, 2001). The limited water supply in these lakes increases retention time, which, in turn, results in an increased concentration of organic and mineral substances in lakes. This also differentiates the studied lakes from European and American lakes. When permafrost is present beneath lakes, water reservoirs are formed and are referred to in Russian literature as "taliki". These reservoirs constitute a certain water reserve and separate lake water from permafrost. Examples of such reservoirs are presented in Figure 2. At places where permafrost does not exceed 100 m in depth and where the average temperature of permafrost does not exceed -2 °C, such reservoirs are formed under all non-freezing lakes with a diameter of more than 200 m (Fotiev, 1978). In extremely harsh conditions where permafrost reaches a few hundred meters, these pools are created under lakes that have a diameter larger than 2,000 m. In many cases, as shown in Figure 2, through these pools many lakes are connected with groundwater located on the surface of permafrost in the area of summer thawing (Fig. 2a and Fig. 2b) and groundwater laying under the layer of permafrost (Fig. 2c). Mutual impact of lakes with surrounding permafrost is a complex process and is still poorly understood. It is generally known that permafrost with negative ground temperature decreases the temperature of water in lakes, thereby impeding the pace of biological processes. Another significant effect is the fact that between early autumn and late spring, when the surface layer of permafrost freezes after summer thawing, the flow of groundwater that forms permafrost on the surface in the summer is hampered (Figure 2). In this long winter period, lakes are practically deprived of water and form a closed system (Anisimova, 2000). Except for deep lakes with runoff that is connected with sub-permafrost water, water may flow in during the winter. Moreover, as presented in Figure 2, permafrost surrounding the lake with a water reservoir under the lake acts as a tight impermeable layer, enclosing water of a lake in its depression and separating it from the surrounding geological environment (Shepelev, 2011).

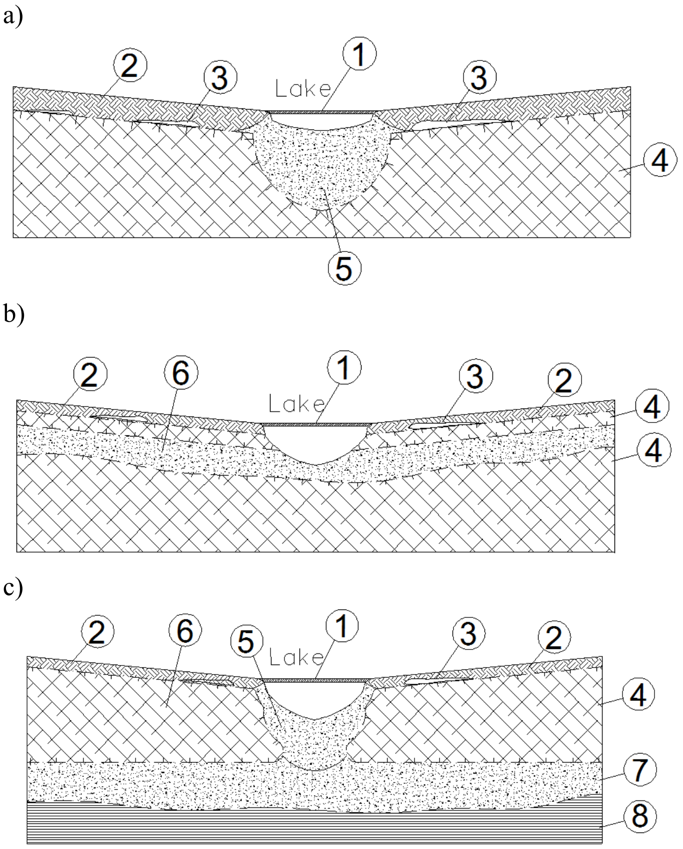

Fig. 2. Hydrochemical conditions associated with lakes located in the permafrost zone, 1 - ice cover in winter, 2 – summer permafrost thaw layer, 3 - groundwater over the permanent permafrost, 4 – permanent permafrost, 5 - water layer under lake, 6 - groundwater in permanent permafrost layer, 7 - groundwater under permanent permafrost layer, 8 - impermeable layer

The two features of lakes mentioned above (origin and hydrogeological conditions) are the reason why the lakes located in the northern part of Siberia are extremely interesting from a scientific point of view since:

- They underwent many periods of climate warming and cooling, yet preserved many features of oligotrophic lakes. Today, as we observe another dynamic warming, these lakes are where an answer can be found to many current questions concerning changes in water ecosystems caused by climatic changes;
- In spite of ice crust being present since October to June, these lakes, even with high organic matter content, maintained oxygen conditions allowing for full biological life in such a long period of night;
- These lakes have been the least studied and contain many unsolved scientific mysteries requiring a broad interdisciplinary approach;
- They are a unique source of knowledge about natural water ecosystems and their evolution since the Pleistocene because of their long distance from impacts of anthropogenic disturbances such as air pollution and to their long existence.

As this research results indicate, surface water quality and its relationship to particular parameters does not match lakes standards. This fact proves that lakes from northern Siberia are widely different to lakes located in Europe or North America.

Location, climate and permafrost conditions in research area

This research was carried out near Igarka city, 163 km north of the Arctic Circle, to the east of the Yenisey River (Fig. 1.) and covered three lakes: Yuratskoye Lake, of approx. 12 km^2, Muram Lake, of approx. 9 km^2 (both located on the left bank of the Yenisey River, 25 km west of Igarka.), and Piesciane Lake, approx. 0.5 km^2, located 5 km north of Igarka. Lake locations and density around that region are shown in Fig. 3. Climate conditions around the study area are shown in Table 1; this is an area where subarctic continental climate is characterized by long, cold winters and short and hot summers (Shumilova, 1962).

Table 1.Climate conditions of Igarka Lake region. (Modified from (Grigoriev, 1992)

Climate elements	Results
The average yearly temperature	- 9.3 ºC
The average temperature in July	+ 14 ºC
The average temperature in January	- 26.5 ºC
Number of days with temperatures below zero	225
The amount of atmospheric precipitation, including:	460 mm/year
XI - III	130 mm
IV - X	320 mm
Average time of snow cover	210 days
Snow depth:	
Minimal value	0.2 m
Maximum value	3.5 m

For the permafrost in the studied area, a boundary between the left-bank and the right-bank permafrost zone coincides with the Yenisei River. The left-bank portion, where Yuratskoye Lake and Muram Lake are located, is characterized by considerably more severe condition of permafrost, the thickness of which in some places may reach 540 m and with temperatures reaching -7 ºC at the depth of 10 m. On the other hand, in the right-bank portion where the city of Igarka and Piesciane Lake are located, permafrost occurs in a non-continuous manner and its maximum thickness is 30 m and the average temperature ranges from -0.2 to -0.3 ºC. The thaw depth of permafrost in the summer season is different and depends on the type of permafrost soil. For sandy soils the thaw depth ranges between 1.6 to 1.8 m, for clay soils it ranges between 1.2 to 1.4 m, and for organic soils between 0.3 to 0.6 m (Grigoriev, 1992). For the studied lakes, organic soils are present in their drainage areas.

Place and methods of research

Research was carried out the last two weeks of July in 2016. Sampling locations are shown in Figure 1 and Figure 3. Lake water samples were collected at a depth of 0.3 m. Furthermore, physical tests, pH, conductivity, and chlorophyll α content determinations were carried out at different depths.

According to the methodology used in the analytical determination of the quality of water, filtered water was only used for the determining magnesium, calcium, and potassium (Chapman, 1996). For other analyses water was not filtered. Measurements for physical properties, acidity, and conductivity were carried out in situ, and chemical analyses were carried out in the laboratory with frozen water after sampling. To determine chlorophyll α, water samples were filtered with a frozen filter and results were recorded until 30 days. BOD_5 analyses were performed in Winkler bottles two hours after sampling; the bottle was placed in an incubator for a 5-day incubation period.

Analyses of the mineral forms of nitrogen, phosphorus, calcium, potassium, iron, manganese, magnesium and sulfide were carried out using a spectrophotometer photo lab 6600 UV-VIS. Analysis of the content of the general form of nitrogen and phosphorus, chemical oxygen demand (COD), and total organic carbon (TOC) were carried out using the same spectrophotometer, but based on the Spectroquant Cell Test. Tests of pH, conductivity, temperature, oxygen concentration, and oxygen saturation were obtained using a multifunctional instrument Multi 340i made by WTW. Turbidity tests were carried out using a portable turbidimeter TURB 355 IR made by WTW.

Fig. 3. Lake locations around Igarka City

Table 2. Physical properties, acidity, and salinity of studied waters measured at the 0.3 m depth below the water surface

Lake name	Temperature	Transparency	Turbidity	pH	Redox	Conductivity
	ºC	m	NTU	-	mV	µS
Yuratskoye	24	2.5	0.66	8.3	- 92	70
Muram	22	1.2	1.23	8.0	- 85	45
Piesciane	20	4.1	1.47	8.1	- 82	68

Table 3. Content of oxygen, organic substances, and chlorophyll α in the studied lakes, measured at 0.3 m depth below the water surface

Lake name	O_2	O_2	BOD_5	COD	TOC	Chlorofil a
	mg/dm^3	%	mg/dm^3	mg/dm^3	mg/dm^3	µg/dm^3
Yuratskoye	8	92	2.4	51	95	3.2
Muram	8.3	94	2.9	61	116	3.4
Piesciane	9.3	103	1.9	47	120	3.7

Tests results: The results of all the indicators in the water samples of studied lakes are presented in tables 2, 3, 4 and 5.

Table 6 shows changes in lake water quality at different depths in the Pieciane lake. In other lakes values are similar and indicate similar dependence.

Table 4. Content of biogenic substances in the studied lakes, measured at 0.3 m depth below the surface of the water

Lake name	NH$_4$-N	NO$_3$-N	NO$_2$-N	TN	PO$_4$-P	TP
	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3	mg/dm^3
Yuratskoye	0.18	0.22	< 0.02	0.5	0.35	0.5
Muram	0.12	0.3	< 0.02	0.4	0.06	2.8
Piesciane	0.08	0.1	< 0.02	0.2	0.01	0.27

Table 5. Content of main cations and anions in the studied lakes, measured at 0.3 m depth below the water surface

Lake name	*Ca*	*Mg*	*Fe*	*Mn*	*K*	*Cl*	*SO$_4$*
	mg Ca /dm^3	mg Mg /dm^3	mg Fe/dm^3	mg Mn /dm^3	mg K /dm^3	mg Cl /dm^3	mgSO$_4$/dm^3
Yuratskoye	2	2.8	0.23	0.02	70	76	920
Muram	1.2	0.2	0.05	0.01	11.7	75	780
Piesciane	5.4	4.1	0.06	0.01	3.8	11	18

Table 6. Changes in temperature, pH, conductivity and chlorophyll α along the vertical profile of the lake Pisciane

Measuring depth in meters below the surface of the lake	Temperature	Redox	Conductivity	Oxygen	Oxygen	Chlorophyll α
	ºC	mV	µS	mg O$_2$	%	µg/dm^3
0.3	20	- 82	68	9.3	103	3.7
2	19.6	- 78	68	8.2	92	2.0
4	15.0	- 82	86	7.3	72	1
6	12.5	- 65	72	6.1	58	0.5
8	7.8	- 81	78	5.5	52	0.0
10	4.6	- 111	70	4.8	44	0.0

Temperature: As shown in Table 2, lake surface water temperatures vary from 20 to 24ºC. These temperatures are relatively high considering these lakes are in arctic Siberia. This confirms the subarctic type of climate characterized by a short, yet warm summer. Temperature ranges are slightly higher compared to small thermokarst lakes in Alaska, where average daily temperature of surface water in July is several degrees lower (Hobbe, 1980). As compared to the similar-sized shallow thermokarst lakes located a few hundred kilometers to the west of the studied area, it is 3-8 degrees higher (Halicki,, 2015). These differences may be caused by the depth of the lake since in shallow lakes water can cool faster by the presence of permafrost at the bottom. In deep lakes, like those studied, the surface water can be isolated from the bottom at an average 10 m in depth. As indicated by the vertical profile results, temperature rapidly decreases with increasing depth, which explicitly indicates the impact of permafrost on water temperature. High differences in temperature in the studied lakes impede water mixing and thus temperature levelling.

As it seems from Table 6, water from the surface layer to a depth of 2 m under the surface of the lakes has a constant temperature, which indicates uniform density of water and facilitated mixing. However, at the depth of 4 m the temperature of water differs by 5 ºC, which may completely eliminate water mixing. With increasing depth, the temperature of water drops to 4 ºC at the bottom layer. Figure 4 presents a vertical temperature profile which was delimited for three studied lakes. This chart also presents an example of temperature pattern of the stratified lake in Europe. As it seems from the comparison of curves, their pattern is significantly different, which probably differentiates the lake of the northern part of Siberia from classic post-glacial lakes of Europe or North America. The chart shows two layers: the first is present at 2 m near the surface layer where water is warmed by the sun and under the influence of wind mixes, making the water temperature leveled. This layer corresponds to the epilimnion layer present in classic stratified lakes.

It can be said that in the second layer a linear drop in water temperature occurs from the near-surface layer to the bottom of lake, which resembles the second layer and is referred to as metalimnion. A vertical gradient of water temperature presented on the chart clearly indicates that a certain water stratification takes place in the studied lakes; however, the difference from the classic lakes lies in the lack of constant water temperature in the bottom layer known as the hypolimnion (Lampert, 1999). Stratification fosters faster warming of the surface layer of water, since it is a shallow layer of approximately 2 m. for the studied lakes. Moreover, this layer is isolated from the bottom permafrost with a water layer with a temperature much higher, even by more than 10 ºC, than the bottom temperature. The results of water temperature tests allow the following conclusions:

- The lakes analyzed in this part of Siberia are subject to stratification due to permafrost; in spite of being relatively shallow, their depth in the studied region is approximately 10 m. In moderate climate, the stratification does not take place in lakes which are less than 10 m deep.
- Considering the fact that these lakes are located in the sub-polar climate zone, according to the thermal classification of lakes they should classify as cold monomictic lakes. However, because of the stratification of lakes in the summer season, they should be classified as dimictic lakes. These, however, are present in the cold temperate climate zone, which is likely due to the presence of permafrost.
- An epilimnion of the studied lakes (approximately 2 m in depth) is characterized by small thickness compared to the epilimnion of stratified lakes in the cold temperate climate zone, where it reaches at least 10 m below the surface of lake. The reason for this is also the presence of permafrost, which affects the stratification of shallow lakes, which automatically makes the epilimnion layer less thick.

Table 7. Basic criteria for the lakes classification (University of Florida, 1983)

Type of lake	Chlorophyll α	P (total)	N (total)	Transparency
	μg / dm3	mg / dm3	mg /d m3	m
Oligotrophic	3	0.015	0.4	>4
Mesotrophic	3 - 7	0.015 – 0.025	0.4 – 0.6	2.4 - 4
Eutrophic	7 - 40	0.025 - 0.1	0.6 – 1.5	0.9 – 2.4
Hypereutrophic	>40	>0.1	>1.5	< 0.9

- The epilimnion of small thickness results in a significantly shorter residence time in the summer period since an outflow from lakes takes place only from the epilimnion. Because of the stratification, water layers located below are not involved in the water exchange taking place at that time (Meybeck, 1995).

In addition, obtained results show a direct correlation between the temperature of water in the near-surface layer and lake size. The highest temperature (24 ºC) was measured in Yurackoye Lake, which is the largest, and the lowest temperature (20 ºC) was that recorded in Piesciane Lake, which is the smallest. However, it is difficult to explain this relationship based on research on three lakes. As proven by the presented results, the impact of permafrost on lakes is probably most evident in the vertical distribution of temperature. This, in turn, has a decisive effect on the pace of biological processes taking place in the water and the bottom layer. In addition, the existence of such temperature regimes determines that only psychrophilic bacteria find their short temperature optimum (from +10 to +20 ºC) during the year (Rheinheimer, 1991). On the other hand, as indicated by data on the content of chlorophyll α in the vertical profile (see Table 6), the impact of the water temperature in the studied period on the development of phytoplankton was not great. Despite a similar temperature present in the near-surface layer at the depth of 2 m and good water transparency, the concentration of chlorophyll α exhibits considerable differences. This means that the temperature of the studied lakes was not a factor limiting the primary production of phytoplankton.

Water transparency and turbidity: As it seems from Table 2, the water transparency of the studied lakes varies considerably and can range from 1.2 to 4.1 m. The specified scope falls within values observed in similar lakes in Alaska, where the scope of transparency ranged from 0.6 m to 14.6 m and the average value was 7.1 m (LaPerriere, 2003). The water transparency observed in the studied lakes is much smaller compared to the lakes studied in Alaska, which proves differences in the studied water samples in relation to the Alaskan lakes, which are significantly younger. A few factors have an impact on the water transparency. The first one is the water turbidity, the average value of which, for the studied lakes, amounts to 1.12 NTU and 0.48 NTU for most of the lakes studied in Alaska, given that the maximum value recorded there was as much as 18 NTU (LaPerriere, 2003). The main reason for higher turbidity was the development of phytoplankton expressed by chlorophyll α concentration. Its average value for the studied Siberian lakes (see Table 3) amounts to 3.43 μg/dm^3 and for the Alaskan lakes is 1.45 μg/dm^3. The reason for the higher chlorophyll α content is an excessive concentration of biogenic substances, which directly affects the intensity of phytoplankton development in surface waters and indirectly affects the value of water transparency. Another important factor limiting the transparency of water is its color, especially color caused by large amounts of humic substances. Although not tested, the color of water in the lakes was slightly brown, likely due to humic compounds diluted in water. The presence of these compounds is confirmed by a high content of TOC (see Table 3), significantly exceeding concentrations typical of clean lakes. On the other hand, if we compare obtained water transparency results with lake classification requirements, it can be stated that, in terms of water transparency, Piesciane Lake is an oligotrophic lake, Yuratskoye Lake is a mesotrophic lake, and Muram Lake is a eutrophic lake.

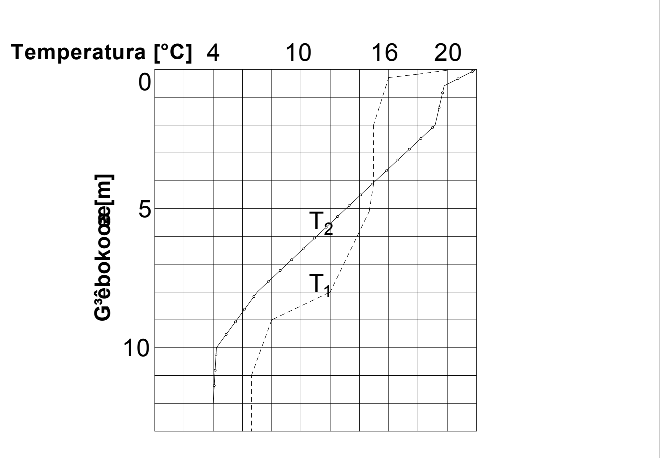

Fig. 4. Temperature dependence of lake water depth, T_2 – studied lakes, T_1 – exemplary European lake (Lampert, 2001)

Conductivity and pH: There is a correlation between conductivity and pH; there are high fluctuations of pH in water with low conductivity and lower fluctuation in water with high conductivity. The reason is poor buffering of water with low conductivity, and increased buffering of water with high conductivity (Allanm 1998). In the studied lakes, the average pH is 8.2 and the average conductivity is 61 μS. In the natural surface water, which is non- polluted with the exception of steppe and desert areas conductivity of water ranges from 10 to 1000 μS and pH value ranges from 6 to 8.5 (Chapman, 2000). A comparison of the results from the studied lakes to the above limits of pH and conductivity of natural water samples, and the results published for other lakes of termokarst origin, the northern part of Western Siberia (Halicki, 2015; Besch, 1992; Klee, 1991) shows:

- The conductivity of the studied water samples is low and its value is convergent with large thermokarst lakes stocked with fish. As compared to small and large thermokarst lakes not stocked with fish (shallow and freezing), the value of conductivity is, on average three times higher. This fact confirms that the water source of thermokarst lakes is almost exclusively from precipitation which is characterized by low conductivity.

- The low value of conductivity translates into poor buffer conditions in lakes concerning the neutralization of substances acidifying waters, which results in the possibility of seasonal and even daily change in the water acidity. This fact is confirmed by the results of an analysis of the calcium and magnesium content in the studied lakes, which is very low (see Table 5).
- pH of the studied lakes is higher than that of small thermokarst lakes, which generally have acidic reaction; on the other hand, it is comparable to water samples of larger lakes measured in the late summer period. The reason for increased pH of water may be the activity of phytoplankton confirmed by the chlorophyll α analysis (see Table 3). Although its concentration is within the range typical of mesotrophic lakes, such intensity of photosynthesis may result in pH increase at low water conductivity and very small concentrations of calcium and magnesium ions.

Generally, it can be stated that, due to their chemical composition, the studied lakes are susceptible to acidification. In addition, they are even more susceptible to acidification due to their drainage areas being dominated by organic soils, which are sources of humic acids. This is confirmed in the studied lakes by a high TOC value. Despite these adverse conditions these lake waters do not exhibit features of acidic waters in the summer period, on the contrary they are slightly alkaline. This fact confirmed a relationship observable in natural lakes. Increasing water alkaline occurs in lakes with increasing water fertility and eutrophication (an example of which are the studied lakes).

Chemical parameters

Organic substances: Assessment of the content and the quality of organic matter was carried out based on three different analyses. The first type is TOC, which determines the exact quantity of carbon compounds in water. The second parameter is COD, which determines a quantity of chemical oxidant required for oxidation of all organic and inorganic compounds contained in water. The third is biochemical oxygen demand (BOD_5), which determines a quantity of oxygen required for biochemical oxidation of approximately 70% of organic matter readily degradable in water during a five-day incubation.

Table 8. Summary of the limit values of organic matter concentration in standing surface water for different trophic classes (Besch, 1992 and Klee, 1991)

Parameter	Unit	Trophic Class			
		Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
BOD5	mgO_2/dm^3	3	3 – 5.5	5.5 – 14	> 14
COD	mgO_2/dm^3	1 - 2	8 - 9	20 - 65	-

In clean, non-contaminated surface water, values of these parameters are lower than: COD 20 mgO_2/dm^3, TOC 10, and BOD_5 3 mg/dm^3 (Chapman, 1996). However, for polluted and waters with runoff from peatland, COD may be 200 and TOC may be more than 100. Values of BOD_5 and COD for different trophic classes are shown in Table 8.

By comparing the results shown in Table 3 with quality criteria from Table 8, the following conclusions can be drawn:

- BOD_5 of water samples for the studied lakes falls under the category of oligotrophic lakes. This translates into a very small internal production in lakes, which is confirmed also by the chlorophyll α results. This likewise corresponds to the category of oligotrophic lakes. Low productivity occurs despite excessive concentration of phosphorus compounds (see Table 4).
- COD values of the studied lakes are classified as eutrophic. Considering the BOD_5/COD ratio in the studied lakes which, on average, amounts to 1:22, it seems that the organic matter of lakes is difficult to degrade. This is confirmed also by the TOC results, the average value of which is 110 mg /dm^3 for the studied lakes.
- Due to a very high concentration of COD and TOC in the results, the studied lakes are highly contaminated, mainly with humic substances coming from the drainage basin. Their very low susceptibility to biochemical degradation (small values of BOD_5) does not adversely affect the oxygen conditions in the lakes since, as indicated by the results from Table 3, oxygen saturation in the top layer of lakes reaches 100%. Lower layers, which are not subject to mixing, also have a relatively large oxygen stock (see Table 6).

Similar relationships between BOD, COD and TOC exist in other lakes in northern Siberia, and they affect both the summer and winter (Halicki, 2016). The reason for this condition is peat bogs present in this area, which, as a result of climate warming particularly observable in northern areas, dehydrate. This leads to increased mineralization of peat and the release of humic compounds. As proved by these results, an excessive concentration of COD and TOC in the form of humic substances does not affect oxygen conditions or primary production in lakes, which is at the minimum level. Humic substances, on the other hand, affect the change in the color of water, which becomes brown. This fact may contribute to faster increase in water temperature, which may result in higher primary production. However, for studied lakes with a minimum primary production (low chlorophyll α), it is difficult to see the direct impact of water temperature on the phytoplankton production.

Biogenic substances: Biogenic compounds are important factors limiting the size of primary production and the trophic status. Table 4 demonstrates results and the concentration levels in the studied lakes, and Table 7 demonstrates biogenic content for different trophic classes. A comparison of the data from both tables allows the following conclusions:

- Concentration of total phosphorus classifies tested lakes as hypertrophic; these lakes many times exceed the minimum concentration required for this class.

  A comparison of the concentration of phosphorus to phosphate shows that for Muran Lake and Piesciane Lake, only 2% to 3% of total phosphorus was available for phytoplankton in the form of phosphates. These available phosphorus concentrations were at levels which occur in oligotrophic lakes for Piseciane Lake and eutrophic for Muran Lake. However, in Yuratskoye Lake, phosphate concentration was at the hypertrophic lake level.

- Regardless of the level of phosphorus available in the studied lakes, in all cases the intensity of primary production (chlorophyll α) was at a similar level. This means that for studied lakes, phosphorus compounds were not a factor limiting the size of production, as is mostly the case with European or North American lakes. As it results from the phosphorus/nitrogen ratio, which is 1:1.2 for Yuratskoye Lake, 1:0.1 for Muran Lake and 1:0.7 for Piesciane Lake, nitrogen availability is a factor limiting the production volume. Similar relationships were observed in other lakes of northern Siberia (Halicki, 2016).
- According to concentration of general nitrogen of Muran and Piesciane lakes, they are classified as oligotrophic, while Yuratskoye lake is mesotrophic. As opposed to phosphorus compounds, general nitrogen in the studied lakes is available for algae in the form of nitrates and ammonia in 80 % of Yuratskoye Lake, 100% of Muran Lake and 90 % of Piesciane Lake. Differences between the availability of phosphorus and nitrogen result from a greater capacity of phosphorus to form fixed chemical compounds from ions like iron, calcium and magnesium. In environments rich in humus, this chemical compound hardly formed soluble connections. For nitrogen, only ammonia nitrogen creates a hardly soluble connection with humic compounds, while nitrates and nitrites do not. In addition, as demonstrated in Table 4, the difference between the sum of ammonia, nitrate, and nitrite nitrogen is not much smaller than the values of general nitrogen. This means that in the studied lakes only a small part of nitrogen was chemically bound with humic compounds.

A very high concentration of phosphorus compounds and humic compounds in the studied lakes clearly indicates that these lakes are intensively supplied with these compounds from the drainage basin. It also indicates that nitrogen compounds must be supplied to lakes in large quantities. However, their small concentration indicates an intensive nitrogen removal process by way of nitrification and denitrification. Successful denitrification may not be confirmed unless temperature and oxygen conditions observed in waters of lakes, but good conditions for the nitrification process are demonstrated. Anoxic conditions are required for denitrification, which are probably present in the bottom layer. Another significant condition for denitrification is the availability of easily degradable organic matter. This is usually supplied in lakes through the primary production of plankton. For the studied lakes, it is extremely low, therefore, the actual source of easily degradable organic matter in lakes is not clear.

Cations and anions ions: Cation and anion concentration are shown in Table 5. Main cations present in natural water samples include calcium, magnesium and potassium; chemical composition of the drainage area primarily determines their concentration. If soil material and bed rock are low in calcium and magnesium, their concentration in natural water does not exceed 10 mg Ca/dm^3 and several milligrams of magnesium and potassium per liter. For the drainage area where soil material and bed rock is rich in calcium, magnesium, and potassium compounds, their concentration in natural water often exceeds 100 mg/dm^3 for calcium. This value is lower for magnesium and potassium. In the studied lakes, the average concentration of calcium, magnesium and potassium amounts to 2.8 mg/dm^3, 2.3 mg/dm^3 and as much as 28 mg/dm^3, respectively. For calcium and magnesium, these are present in very low concentrations, while the concentration of potassium is very high.

The main reason may be the presence of permafrost rich with organic soils, which surrounds the lakes. These soils thaw in the summer by a few dozen centimeters, and though they are usually rich in calcium and magnesium and poor in potassium, the runoff of waters from these soils into lakes is low. On the other hand, mineral formations located below organic soils, are not involved in supplying waters to lakes, nor in delivering mineral substances to them since they remain frozen all year round. Table 9 demonstrates the percentage of the chemical composition of typical peat soils.

Table 9. Chemical composition in top layers of peat (in percent dried matter). (Buckman 1969)

Peat component	Content in dry matter (%)
Organic matter	80
Nitrogen	2.5
Phosphorus	0.09
Potassium	0.08
Calcium	2.8
Magnesium	0.3
Sulfur	0.6

Furthermore, a high content of calcium and magnesium compounds in peats surrounding the lakes results from the fact that peat soils have a natural and exceptionally high capacity for sorbing these cations. This fact may result in the limiting of calcium mobility; namely they stay in peats because only small amounts of them penetrate to the lakes. However, high concentration of potassium in water, in spite of the fact that its content in peats is the lowest of all cations, is a very interesting phenomenon. Perhaps this may result from a lower capacity of peats to the absorption potassium compounds. In peat soils the most intensively absorbed cations are calcium cations, then magnesium cations, and potassium. The situation is similar for nitrogen and phosphorus. The nitrogen content in peats is approximately 15 times higher than the phosphorus content, while in the studied lakes the average phosphorus content was 1.3 mg/dm^3 and only 0.34 mg/dm^3 for nitrogen. Therefore, it may be asserted that the circulation of basic elements in drainage areas of lakes located on permafrost differs from classic examples. In this case. we are dealing with drainage areas abundant in these elements; however, their concentration in lakes is exceptionally low.

For anions, the content of chlorides and sulfates was tested. In natural water the chloride concentration is less than 10 mg/dm^3 while the sulfate ranges from 2 to 80 mg/ dm^3. Obtained results are set out in Table 5 and are more difficult to explain than the content of cations in tested water samples. For Youratskoe and Muran lakes, sulfate concentrations are at a very similar high level while in Piesciane Lake the value is similar to the results for natural water samples. An explanation for such a high concentration of sulfates on the basis of the carried analysis and studied literature is not possible. Also, the concentration of chloride is not typical for lakes. In Youratskoe and Muran lakes it is relatively high and close to seven times exceed their concentration in the Pieciane lake. In the studied lakes, the content of cations and anions is far from typical levels of these compounds in natural water. Their exact origin and circulation in the basin is not sufficiently understood and requires further research.

Biological properties

This research also covered biological analysis as a content of chlorophyll α, biochemical oxygen demand in the studied lakes. Furthermore, this research determined the species composition of zooplankton at different depths and its quantity and dominant ichthyofauna. This article presents only the results of chlorophyll α and biochemical oxygen demand, which were presented during the physical and chemical parameters discussion. Both parameters indicate oligotrophic and mesotrophic characteristics of the studied lakes. Results for species composition of zooplankton and dominant ichthyofauna will be the subject of another publication.

Summary

The conducted research of lakes in the northern part of Siberia and analysis of obtained results allowed the following conclusions to be drawn:

- The analyzed lakes, in spite of being relatively shallow with depths of approximately 10 m due to the presence of permafrost, are subject to stratification in the summer period without the development of the hypolimnion layer.
- According to the thermal classification of the studied lakes, due to their location, they should classify as cold monomictic lakes. However, because of the stratification of lakes in the summer season, they are classified as dimictic lakes; these, however, are present in the cold temperate climate zone.
- Despite a similar level of chlorophyll α concentration in the studied lakes and the similar color of water, transparency was different in each lake, classifying one of them as oligotrophic, one as mesotrophic, and one as eutrophic.
- Despite the fact that the chemical composition of the studied lakes indicates sensitivity to acidification, water samples of every lake had a slightly alkaline reaction, typical of eutrophic water.
- The studied lakes are highly contaminated with humic substances coming from the drainage basin based on a very high concentration of COD and TOC. Their very low sensitivity to biochemical distribution (small BOD_5 values) means that their excessive concentration has no negative impact on oxygen conditions in the lakes.
- Despite a very large concentration of phosphorus compounds in the studied water samples classifying them as hypertrophic lakes; their primary production is low, characteristic of oligotrophic and mesotrophic lakes.
- A factor limiting the primary production in the lakes is nitrogen compounds; the concentrations of which are at the level normally recorded in oligotrophic and mesotrophic lakes.
- Concentrations of major cations in water samples of the studied lakes exhibit a slight inconsistency compared to the surrounding drainage areas. Despite calcium-rich peats, the calcium content in the studied water samples is minimal. On the other hand, potassium, observed in small quantities in peats, is present in large quantities in the water.

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