EARTH'S CRYOSPHERE
SCIENTIFIC JOURNAL

Kriosfera Zemli, 2021, vol. XXV, No. 3, pp. 19–29

GEOLOGICAL CRYOGENIC PROCESSES AND FORMATIONS

GEOCRYOLOGICAL FACTORS OF DYNAMICS OF THE THERMOKARST LAKE AREA IN CENTRAL YAKUTIA

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The analysis of Landsat satellite images revealed a significant increase in the area of thermokarst lakes in Central Yakutia over the period 2000–2019. The lake area increased twice in the Suola and Taatta River basins and by 25 % in the Tanda River basin. It has been established that, despite the presence of a general linear trend, the increase in the area of lakes occurs abruptly. Qualitative relationship between the changes in the state of the upper layer of permafrost and the dramatical increase in the area of thermokarst lakes has been revealed. The main factor leading to disruption of a stable state of thermokarst forms are short-term (1–3 years) periods of sudden changes in temperature of seasonally thawed layer from below-average to anomalously high values. These periods can be caused by a rare combination of hydrometeorological conditions, such as anomalously high values of snow water equivalent, increased annual precipitation, and an increased water content of soils of the seasonally thawed layer.

Key words: *thermokarst lakes, permafrost, Landsat images, Central Yakutia, temperature and water content of a seasonally thawed layer, precipitation, snow cover, Spasskaya Pad'.*

INTRODUCTION

Central Yakutia is characterized by the widespread occurrence of thermokarst formations [*Soloviev, 1959; Bosikov, 1991*]. Their most evident manifestation is thermokarst lakes, which occupy 80 % of the total number of lakes in Yakutia [*Nestereva, 2012*]. Such lakes have a significant influence on the formation of the water balance of the territory [*Karlsson et al., 2012; Fedorov et al., 2014; Swanson, 2019*] and the development of economic activity [*Crate et al., 2017*]. The study of the conditions, under which thermokarst processes are activated, is extremely relevant against the background of the forecasted significant climate warming in Central Yakutia [*Streletskiy et al., 2019*].

Changes in the number and the area of thermokarst lakes in different Russian regions and worldwide have been observed under the conditions of modern climate warming. For example, a significant decrease in the area of thermokarst lakes in the northwestern part of Alaska has been noted due to an increase in the intensity of thermoerosion processes [*Jones, Arp, 2015; Swanson, 2019*]. In the Northwestern Territories of Canada, the total area of thermokarst lakes generally increased between 1978 and 1992 and decreased between 1992 and 2001 [*Plug et al., 2008*]. In Russia, multidirectional changes in the area of thermokarst lakes have been revealed only in 8 out of 20 reference areas located in different parts of the cryolithozone; however, no unambiguous relationship between the dynamics of lakes and geocryological conditions has been derived [*Kravtsova, Bystrova, 2009*]. In the work of S.N. Kirpotin [*Kirpotin et al., 2008*], it was established that the total area of lakes in the zone of the continuous permafrost increases, while in the zone of the discontinuous permafrost, on the contrary, it decreases. The modern estimates of changes in the area and number of thermokarst lakes in Central Yakutia are presented in many works. For example, J. Boike [*Boike et al., 2016*], I. Nitze [*Nitze et al., 2017*], and M. Ulrich [*Ulrich et al., 2017*] point to a growth in the area of lakes in this region. According to T.V. Rodionova, V.I. Kravtsova, and T.V. Tarasenko, the total area and number of thermokarst lakes expanded by two to three times for different sites over the period from 1980 to 2009 [*Kravtsova, Tarasenko, 2011; Rodionova, 2013*].

The purpose of this work is to study the conditions leading to the nonlinear dynamics of the increase in the number and the area of thermokarst lakes in Central Yakutia on the basis of the remote sensing data and observations of a state of a seasonally thawed layer. The study accomplished two basic tasks: 1) the changes in the area of thermokarst lakes in the basins of three rivers of Central Yakutia have been assessed on the basis of the Landsat satellite images in period 2000–2019; 2) the qualitative relationship between the state of the seasonally thawed layer of permafrost deposits, climatic factors, and the increase in the area of thermokarst lakes in Central Yakutia has been revealed.

THE STUDY AREA

The study area is located within the Lena–Amga interfluve in the southeastern part of the Central Yakutia lowland. Geocryological studies of this region were previously conducted by many authors, e.g., V.G. Zolnikov [*1954*], P.A. Soloviev [*1959*], M.S. Ivanov [*1984*], and N.P. Bosikov [*1991*].

The average absolute elevation of the lowland is 250 m with the maximum values up to 400 m. The Paleozoic, Mesozoic, and Cenozoic rocks form the geological structure of the territory. Deep faults played an important role in the history of its development. During the Cenozoic, tectonic activity in such zones had an influence on the formation of main geomorphological levels, structure, thickness, ice content of permafrost deposits and on the development of thermokarst [*Ivanov, 1984*].

The region has a severely continental climate. Over the period 1966–2018, the mean annual air temperature at the Yakutsk weather station was –8.8 °C. The maximum mean monthly temperature is observed in July and reaches +19.5 °C, the minimum mean monthly temperature is recorded in January and drops down to –38.6 °C. The mean annual amount of precipitation is 237 mm, 75–85 % of precipitation falls in summer [*Bosikov, 1991*]. The snow cover forms in October, breaks up in the first days of May; by the beginning of snowmelt, its depth is 36 cm on average (w/s Yakutsk, 1966–2018).

Central Yakutia belongs to the area of the continuous permafrost. The permafrost thickness varies from 10 to 50 m in a low floodplain, from 50 to 300 m in middle and high floodplains; it increases on terraces, exceeding 400 m in some areas [*Ivanov, 1984*]. The depth of seasonal thawing varies from 0.5 m in waterlogged areas to 4 m in pine forests [*Ivanov, 1984*]. The study area is located in the zone, where there are the Late Pleistocene deposits of the ice complex, the high ice content of which is a factor of thermokarst development both in the past and in the modern climatic conditions. Taliks are common in river valleys and under large thermokarst lakes.

The predominant landscape of the area is herb-cowberry larch forest on permafrost-taiga pale, sod-forest, and alluvial meadow soils [*Ivanov, 1984*].

One of the main features of the region is the poorly developed river network and the widespread erosion-thermokarst depressions [*Zolnikov, 1954*]. The most mature thermokarst forms, alas depressions with the flattened and sodded sides are covered with meadow-steppe vegetation on saline soils.

The study area involves the basins of three rivers (Suola, Tanda, and Taatta) with areas from 1270 to 8290 km^2 with the widespread alas depressions (Table 1, Fig. 1). The basins of these rivers were chosen as the objects of the study due to the availability of hydrological gauges with data on the river discharge observations in the period 1960–2017. These data are necessary for the next stage of the work related to the assessment and modeling of the role of thermokarst lakes in the hydrological regime of the Central Yakutia rivers. The alas area percentage of the watershed area was estimated on the basis of the works of J.I. Torgovkin and A.A. Shestakova [*Torgovkin et al., 2018; Torgovkin, Shestakova, 2018*]. It varies from 4.9 % within the Tanda River watershed to 9.7 % in the Suola River watershed, upstream the hydrological gauge (h/g) of Bedeme village.

Table 1. **The distribution of alases and thermokarst lakes in the river basins (2000–2019)**

Name of the basin	Code of the hydrological gauge	Watershed area, km^2	Alas area		Number of images	The minimum area of lakes			The maximum area of lakes			The changes in the area of lakes		The area of lakes, 09.06.2019	
			km^2	%		km^2	%	year	km^2	%	year	km^2	% of the initial value	km^2	%
Suola River–Byuteidakh settlement	3217	1270	81.7	6.4	58	8.9	0.7	2003	19.4	1.5	2018	10.5	117	17.9	1.4
Tanda River–Byariya village	3306	2000	97.9	4.9	11	23.4	1.2	2001	29.4	1.4	2018	6.0	25	27.7	1.4
Taatta River–Uolba village	3628	8290	776.0	9.4	7	118.0	1.4	2001	225.0	2.7	2018	107.0	90	213.3	2.6
Suola River–Bedeme village	3659	3380	326.0	9.7	27	34.0	1.0	2004	70.8	2.0	2008	36.8	108	66.1	1.9

Note: Relative values of the area are given as a percentage of the watershed area.

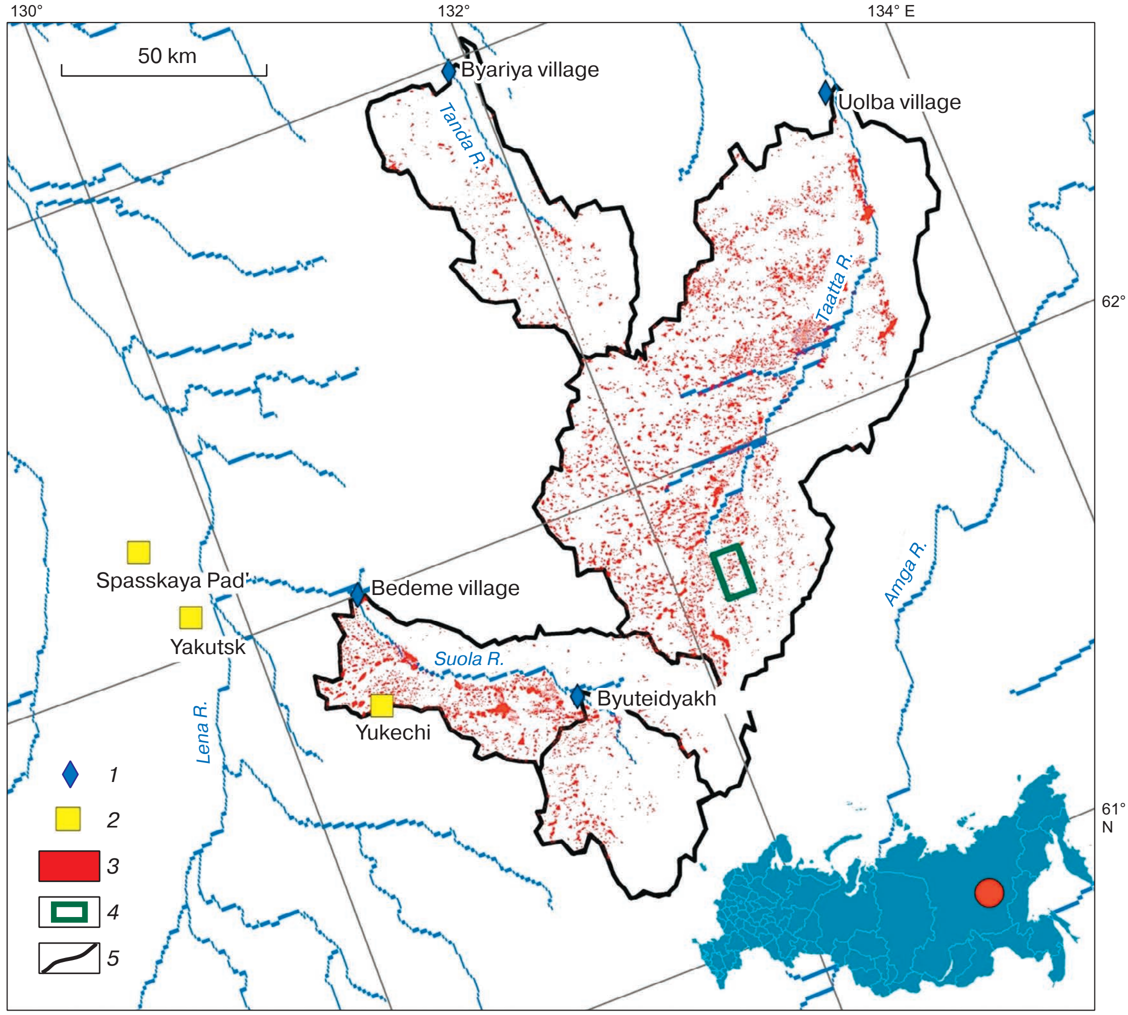

Fig. 1. The map of the study area.

1 – hydrological gauge, *2* – monitoring site/weather station, *3* – alases, *4* – reference site, *5* – boundary of watershed.

MATERIALS OF THE STUDY

Remote sensing data. Different types of the remote sensing data are used to study the long-term dynamics of thermokarst lakes. The aerial survey data or ultrahigh resolution (1 m and more) satellite images were used in some works [*Sannel, Brown, 2010; Jones et al., 2011*]. Until recently, their disadvantage has been rare repeatability of survey. As a result, anomalous meteorological conditions (e.g., heavy precipitation), that might occur shortly before the survey, could lead to improper conclusions about the changes in the area of thermokarst lakes [*Olthof et al., 2015*]. Only in 2017, after the launch of nanosatellite from the Planet Labs, it became possible to monitor the area of thermokarst lakes with a high spatial resolution (3 m) in the daily mode [*Cooley et al., 2017*].

The Landsat satellite images (TM, ETM+ and OLI sensors) with a spatial resolution of 30 m remain the main data source for estimating the changes in the area of thermokarst lakes over long periods of time (more than 10 years). Estimation of the areas of lakes using these data is less accurate than estimation on the basis of super-resolution images. However, the most important advantage is the availability of the homogeneous series of observations for the period since 1984 (since 1999 for some regions of Russia, including Central Yakutia). In addition to the spatial resolution, the Landsat data is limited by a high share of cloudy images. The frequency of cloud-free images turns out to be several times lower than the nominal temporal resolution (16 days).

To distinguish the water surface from satellite data, the mid-infrared (SWIR) spectral range [*Frazier, Page, 2000*] or spectral indices, based on it, are used. The most effective of the indices is considered to be the normalized difference water index mNDWI [*Xu, 2006*]. When identifying thermokarst lakes, there is the problem related to the fact that the area of most of the lakes is comparable with the area of one pixel of Landsat image (0.09 ha). Thus, more than 50 % of the pixels, falling within the limits of thermokarst lakes, are not fully occupied by water. To estimate accurately the area of thermokarst lakes, it is recommended to determine the percentage of water area in each pixel on the basis of the spectral mixture analysis [*Olthof et al., 2015*], or consider only relatively large lakes (with the area over 0.5–1.0 ha), which will give a lesser error.

In this study, 54 Landsat images (sensors TM, ETM+, OLI) for the period from 2000 to 2019, were used. They were obtained from the web-service of the USGS [*USGS..., 2020*] to determine the area of thermokarst lakes in Central Yakutia. We considered the images of the summer season (from June to September). The choice of images for the entire summer season (and not only for its second half, when the lake area reaches the seasonal minimum) was due to the scarcity of cloud-free data. It is also important to note that in most cases, the intra-annual variability of the water surface area is less than the interannual variability. To minimize the errors in determining the area of lakes, the cutoff threshold for the minimum area was taken to be 1 ha (which corresponds to 11 pixels of the Landsat imaging system). To reduce the estimation errors for each particular lake, we chose the threshold equal to 1 ha for the assessment of the minimum area of lakes. When the threshold value equal to 0.4 ha is chosen, such errors can be very significant, because image pixels do not fall completely within the limits of the water surface of a lake.

The methodology of identification of the lakes included the following stages:

1) the recalculation of values of brightness in spectral channels from initial values (Digital Numbers, DN) into reflectance and the atmospheric correction by Dark Object Subtraction (DOS). This operation was performed using the “Semi-automated image classifier” software module of the QGIS geoinformation system [*Congedo, 2016*], which is used for loading, preprocessing, and classification of images from the satellites of Landsat series, Sentinel-2, and Terra/Aqua MODIS;

2) the water surface distinguishing by the threshold value of the Modified Normalized Difference Water Index (MNDWI), which is assumed to be 0.3. The author of this index [*Xu, 2006*] proposed the lower threshold (0.09). In this work, an increase in the threshold value allowed us to separate partially the water surfaces and the shadows from clouds;

3) the conversion data to a vector format, calculation of areas, and removal of the objects smaller than 1 ha in area. The capabilities of the ArcGis Model Builder were used to automate calculations at 2–3 stages. The area of the lakes was calculated for each image separately, with subsequent removal of duplicate objects in overlapping areas of the images.

In addition to removal of lakes with a small area, the data are basically restricted by the presence of shadows from clouds in most of the images. Shaded areas also have low brightness in the SWIR range and can be mistakenly attributed to water objects. Most of the obtained images contained the cumulus clouds and shadows from them, which occupied 1–5 % of the area. In this regard, we have been able to estimate the area of thermokarst lakes on all 54 images only for the basin of the Suola River–Byuteidyakh settlement, which has the minimum area, but is representative for the selected territory. The total area of the lakes in the basin of the Suola River–Byuteidyakh settlement has the significant correlation with the total area of the lakes in the neighboring watersheds, obtained for the same dates with the use of the images without cloud cover. The coefficient of determination of the total area of thermokarst lakes in the upper and lower parts of the Suola River basin is 0.79. For the other basins, the number of completely cloudless scenes ranged from 7 to 25.

Additionally, in this work, we have studied dynamics of thermokarst lakes in the territory of Yukechi monitoring site on the area of 113 ha (similar to the area presented in [*Fedorov et al., 2014; Ulrich et al., 2017*]) over the period 2000–2019. Using the abovementioned method, 44 images were analyzed, from which 27 images were taken in the same dates as the images of the watershed of the Suola River–Byuteidyakh settlement. In doing so, we considered a lake area of less than 1 ha as an area of a whole pixel, in which the lake was included.

Ground-based observation data. To assess the relationship between the characteristics of the seasonally thawed layer and snow cover and dynamics of the development of thermokarst lakes, we used the data of observations from the Spasskaya Pad’ monitoring site, which is located on the flat inter-alas plain with the indigenous larch forest growing on fine-grained sands. Materials included daily data on the soil water content at depths of 0.1, 0.2, 0.4, 0.6, and 0.8 m and the temperature at a depth of 1.2 m over the period 1998–2010 [*GAME–Siberia..., 2003; Iijima et al., 2010*], as well as the data on the soil water content (up to 1.5 m) and the soil temperature (up to 3.2 m), which were measured 1–2 times a month over the period 1998–2018 (data provided by A.N. Fedorov, Melnikov Permafrost Institute, SB RAS). In the work [*Iijima et al., 2010*], it was demonstrated that the data from Spasskaya Pad’ site are representative of the typical landscape conditions of Central Yakutia. The data on the snow cover (1996–2018) and the soil temperature (1964–2017) at a depth of 1.6 m at the Yakutsk weather station were also used for the analysis (Fig. 1).

RESULTS OF THE DATA ANALYSIS

Dynamics of thermokarst lake area. In the basins of the Suola and Taatta rivers, the area of thermokarst lakes doubled in the period 2000–2019. In the basin of the Tanda River–Byariya village, the area of the lakes increased only by 25 % (6 km^2) (Table 1). Its basin is characterized by the smallest area of the distribution of alas depressions (4.9 %, Table 1). This is most likely related to the sporadic (more limited compared to other considered basins) distribution of the Ice Complex on the Emil terrace of the Lena–Amga interfluve [*Soloviev, 1959; Zakharova et al., 2018*]. Despite the fact that this part of the ancient terrace of the Lena River represents the widespread surface with small lakes (0.018–0.075 km^2) [*Zakharova et al., 2018*], the threshold of the minimum area of lakes (1 ha), used in this study, allows us to trace their dynamics.

Figure 2 demonstrates the increase in the total area (both residual and primary) of thermokarst lakes from 2001 to 2019 at the most representative site (Fig. 1) in the western part of the Taatta River basin. On July 17, 2001 (Fig. 2, *a*), there were 20 lakes with the total area of 93 ha at the site. Over 18 years, the total number of lakes and their area have almost increased fourfold (76 lakes with the total area of 323 ha were recorded on July 27, 2019) (Fig. 2, *b*).

Figure 3 represents a plot of the changes and a diagram of the range of changes in the area of lakes in the basin of the Suola River–Byuteidyakh settlement in the period 2000–2019. The maximum area of the lakes was observed in 2008 and 2018, and the minimum area – in the period 2001–2004. There is a proportional increase in the area of both residual and primary thermokarst lakes. For the watershed of the Suola River–Byuteidyakh settlement, the area of primary thermokarst lakes, not intersected by alases, was 1.1 km^2 (or 11.8 % of the total area of lakes of 9.3 km^2) on 17.07.2001, and 3.0 km^2 (or 17.0 % of the total area of lakes of 17.9 km^2) on 07.08.2020. A similar situation is observed in the basin of the Tanda River–Bariya village: the area of primary thermokarst lakes increased by 1.8 km^2 from 2001 to 2019 (4.6 km^2 or 19.7 % of the total area of lakes of 23.3 km^2 and 6.4 km^2 or 22.7 % of the total area of lakes of 28.2 km^2, respectively).

The increase in the number of primary thermokarst lakes is confirmed by the observations at Yukechi site [*Ulrich et al., 2017*]. Between 1944 and 2014, 15 new primary thermokarst lakes with the total area

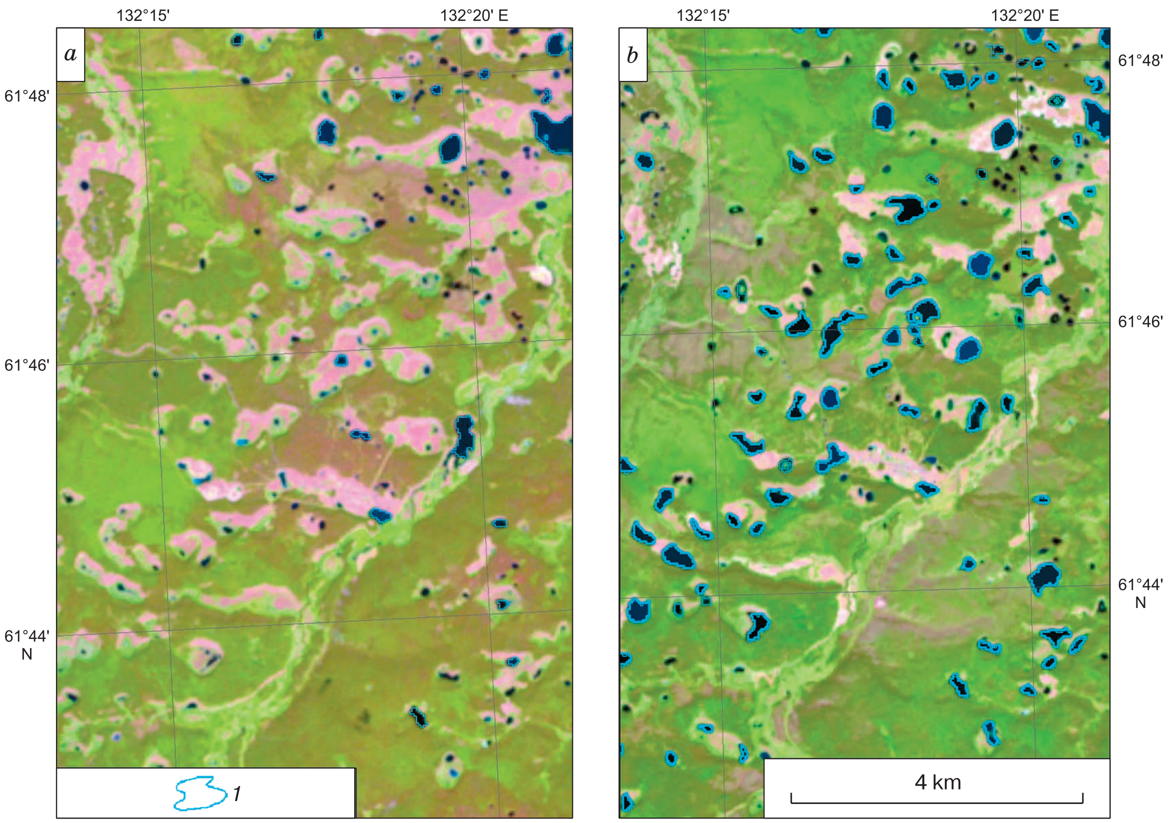

Fig. 2. Increase in quantity and the area of the residual thermokarst lakes by the example of the western part of the Taatta River basin, revealed on the basis the Landsat images taken at different times:

a – 17.07.2001, *b* – 27.07.2019. *1* – thermokarst lakes.

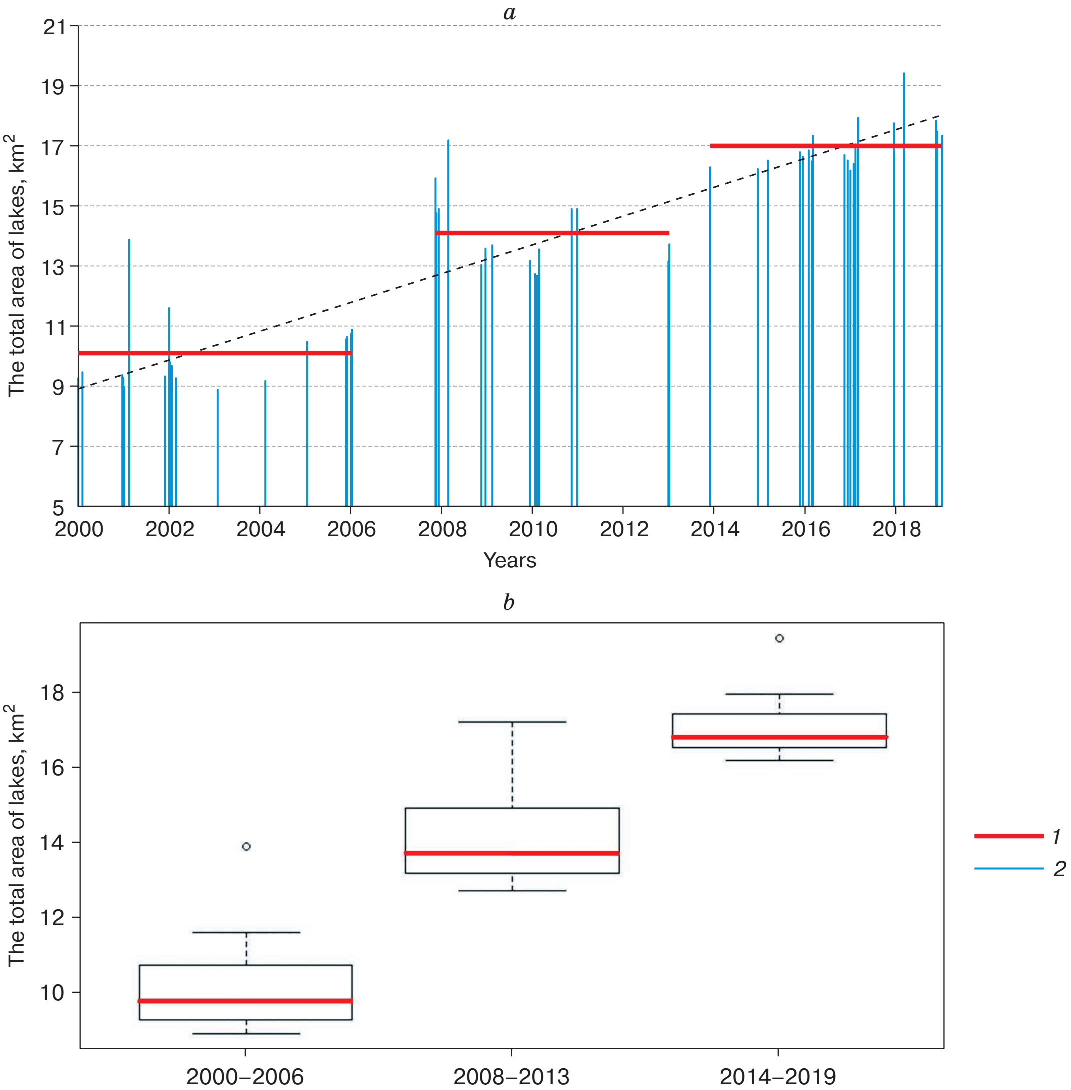

Fig. 3. The trend of changes (*a*) and the diagram of the spread of the area (*b*) of thermokarst lakes in the watershed of the Suola River–Byuteidyakh settlement over the period 2000–2019.

1 – the average area of lakes over the periods 2000–2006, 2008–2013, and 2014–2019; *2* – the area of lakes on specific dates. Data with omissions in 2007 and 2012.

of 0.7 ha (an increase from 0.04 to 0.6 % of the site area) were formed at the site. During the same period of time the area of residual lakes increased from 0.4 to 1.4 ha (from 0.4 to 1.2 %). In total, the area of residual and primary thermokarst lakes of Yukechi site increased more than fourfold (from 0.5 ha to 2.1 ha or from 0.4 to 1.9 %) over the period 1944–2014.

The comparison of the area of lakes at the watershed of the Suola River–Byuteidyakh settlement and the total area of the lakes at Yukechi site points to the unidirectional tendency of their increase with the *R*-squared value of 0.79 (Fig. 4). Thus, we can assume that the observations at Yukechi site are representative for the study area. On the basis of the established relationship (Fig. 4) and historical data on the area of lakes at Yukechi site, which have been recorded since 1944 [*Ulrich et al., 2017*], we assumed that the total lake area increased more than 2.5-fold (from 6.8 km^2 in 1944 to 17.6 km^2 in 2019) in the watershed basin of the Suola River–Byuteidyakh settlement over the period 1944–2019; the main increase occurred between 2000 and 2019 (2-fold).

Despite the presence of the general linear trend of increase in the area of lakes, the changes occur abruptly. For example, in 2007 and 2014 there was dramatical expansion in the area of lakes, determining its dynamics in subsequent years (Fig. 3). An average area of the lakes in the Suola River basin–Byuteidyakh settlement was 10.1 km^2 in the period 2000–2006, 14.1 km^2 in the period 2008–2013, and 17.0 km^2 in the period 2014–2019.

This is proved by the work [*Ulrich et al., 2017*], in which the authors identified the trend of significant short-term increases in the lake areas over short periods of time, e.g., 1965–1967, 1992–2010 (with the largest increase between 2007–2008), and 2012–2014. The authors point to both the increase in the residual lakes and the active appearance of new primary thermokarst lakes in recent years. The rates of expansion of the residual and primary thermokarst lakes reach, on average, 1.6 and 1.2 m/year for the period 1944–2014, respectively.

Geocryological factors affecting thermokarst processes in Central Yakutia. To identify the relationship between the changes in a thickness of a seasonally thawed layer and the increase in the area of thermokarst lakes in Central Yakutia, we analyzed data of the ground-based observations.

In the work [*Rodionova, 2013*], dynamics of the thermokarst processes in Central Yakutia is associated with changes in the precipitation regime. Indeed, the dramatical increase in the lake area in 2007–2008 was preceded by the period 2005–2008 with anomalously snowy winters and with the total annual precipitation exceeding the norm by 20–43 %. While the average value of snow water equivalent was 59 mm by the beginning of snowmelt according to the snow survey at the Yakutsk weather station (1966–2018), in 2005–2007 this value was 88, 86 and 78 mm exceeding the norm by 49, 46 and 32 %, respectively [*Bulygina et al., 2020*]. The average annual amount of precipitation for the period 2005–2008 was 303 mm (while the norm was 237 mm). However, there is no direct functional relationship between the area of thermokarst lakes and the amount of solid or total precipitation.

In the work [*Iijima et al., 2010*], the geocryological consequences of heavy precipitation in the study period were considered in detail. Anomalously high values of snow water equivalent and liquid precipitation in the pre-winter period resulted in a prolonged period of the increased soil water content in the seasonally thawed layer in Central Yakutia. Thus, in 2006, according to the data from Spasskaya Pad' site, the average soil water content of the upper 80-cm layer was 24 % during the warm period (May–September) compared to 11 % in 2003. On October 1, 2006, before the beginning of freezing, soil was in a state of complete water saturation (the soil moisture content was 50 % in the upper 10-cm layer and 46 % in the 80-cm layer). Thus, by the beginning of snowmelt in 2007, the soil was frozen and, probably, the ice content was even higher due to water migration to the freezing front. The maximum measured soil water content in the 1-meter layer was up to 34 % in 2006, and only 14 % in 2003.

Figure 5 demonstrates, that the maximum area of thermokarst lakes in the basin of the Suola River–Byuteidyakh settlement is related to the average (for the warm period) and the maximum daily soil water content for the layer of 1 m and 0.8 m thick in the previous year. The correlation coefficient is 0.63 and 0.80, respectively. Obviously, the identified dependences have the qualitative nature, because they can be built only for a short period of time, characterized by a dramatical change in the study values. In the future, in dry years, when the soil water content will be minimal, the area of lakes most likely will not decrease to the level of the 2000s.

As a result of the combined effect of two interrelated factors – the significant soil water and ab-

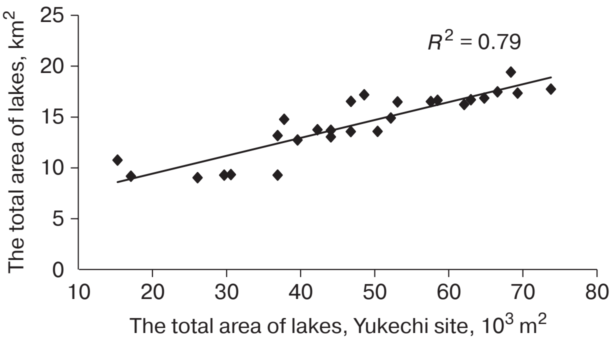

Fig. 4. Dependence of the total area of lakes in the watershed of the Suola River–Byuteidyakh settlement on the total area of lakes at Yukechi site lakes on the basis of the Landsat images for the same dates, 2000–2019.

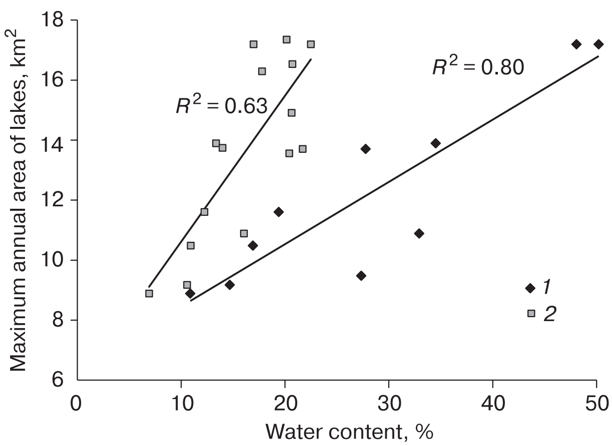

Fig. 5. Dependence of the maximum total area of lakes in the watershed of the Suola River–Byuteidyakh settlement of soil water content at Spasskaya Pad' site in the preceding year.

1 – maximum for the year daily soil water content of the top layer 0.8 m thick (1999–2008); *2* – mean annual soil water content of the layer 1 m thick during the warm period (2000–2015).

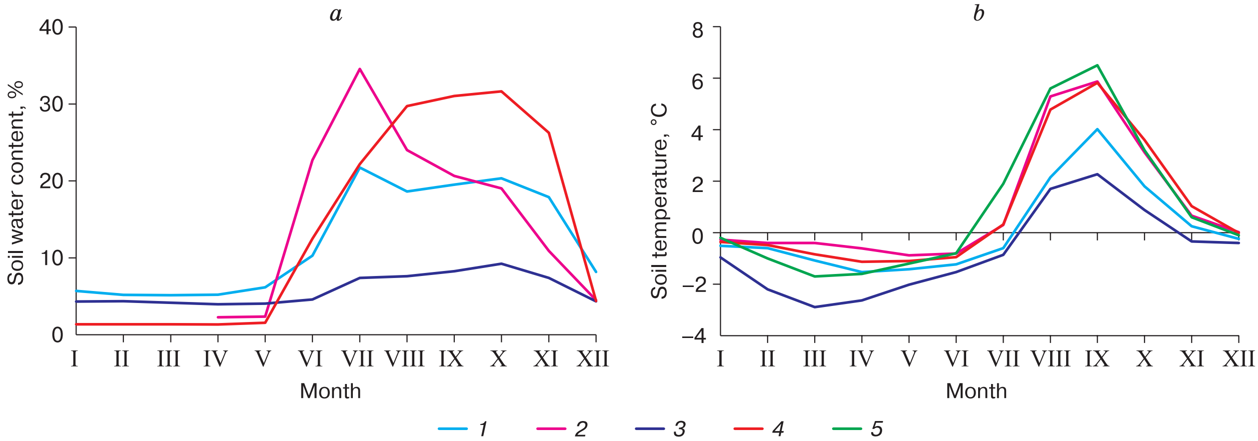

Fig. 6. Mean monthly values of the soil water content at a depth of 0.8 m at Spasskaya Pad' site (*a*) and the soil temperature at a depth of 1.6 m according to data from Yakutsk weather station (*b*).

1 – 1998–1999; *2* – 2000; *3* – 2003–2004; *4* – 2005–2007; *5* – 2014.

normally high values of snow water equivalent – the thermal regime of soil changes. Figure 6 represents the plots of changes in the mean monthly values of the soil water content of the 0.8-m layer and the soil temperature at a depth of 1.6 m. It is seen that the periods of increased soil temperature correspond to the periods of increased soil water. For example, the increased soil water content in 2005 due to high values of snow water equivalent in winter and heavy precipitation in summer, as well as the snow cover depth in the next winter season, prevented soil freezing, which resulted in the increase in soil temperature at a depth of 1.6 m in 2006. The winter period between 2006 and 2007 was also characterized by the snow cover with the above normal thickness, which again resulted in the increase in the soil temperature in 2007. The maximum depth of thawing before 2004 varied from 1.37 to 1.57 cm; in 2007 it was 1.67 cm [*Iijima et al., 2010*]. The periods, when the considered values changed, also coincide with the main periods of abrupt change in the area of lakes.

We plotted changes in the average total area of lakes in the basin of the Suola River–Byuteidyakh settlement and the mean monthly minimum (March–April) and maximum (September) soil temperatures at a depth of 1.6 m at the Yakutsk weather station (Fig. 7). Comparison of the data of the lake area with the data from w/s Yakutsk is due to the fact that, unlike Spasskaya Pad' site, where data are available only for the individual, not always comparable, dates, at the weather station, the daily data are available for the entire year. Nevertheless, the relationship between the values of the soil temperature at the two sites has a high correlation (0.77).

The coefficient of determination between the total area of lakes and the soil temperature at a depth of 1.6 m with a shift of 1 year is 0.12, but Fig. 7 clearly illustrates that the tendency of changes in the area of lakes repeats the variations of the soil temperature with a 1-year delay. The increase in the soil temperature in 2005–2007 is followed by the dramatical expansion in the area of lakes from 8.9 to 15.7 km^2 in 2007–2008. A similar situation is observed in 1999–2000: the dramatical increase in the soil temperature by 0.8 °C in March–April and by 1.9 °C in September in 1999–2000 is followed by a jump in the area of lakes from 9.4 to 10.4 km^2 in 2000–2001. In 2014, the high values of the maximum temperature (6.5 °C in September) were also accompanied by an increase in the area of lakes (Fig. 7).

According to the data from Yukechi site [*Ulrich et al., 2017*], the maximum change in the lake area occurred in 1966–1967, when the total lake area dramatically increased from 0.5 ha (1965) to 1.2 ha (1967). In August 1966–1967, mean monthly values of the maximum soil temperatures at 1.6-m depth were 4.1 °C in 1966 and 5.0 °C in 1967, significantly exceeding the mean annual temperature of 3.2 °C (1964–1980).

One of the possible mechanisms for the fast expansion in the area of primary thermokarst lakes may be cryogenic landslides on the shores of lake depressions, which indicate the activation of thermokarst processes [*Leibman, 2005; Pelletier, 2005; Smith et al., 2005; Sannel, Kuhry, 2011*]. Small thermokarst forms – byllars – are often formed along the lakeshores [*Brouchkov et al., 2004; Séjourné et al., 2015*].

When the soil temperature increases, the depth of thawing increases, the soil is saturated with thawed ice and the soil blocks move down the slope. As a result, these blocks are accumulated and the process attenuates until the time of a new onset of a certain combination of extreme hydrometeorological conditions. An example is the coastal retreat in 2011–2013,

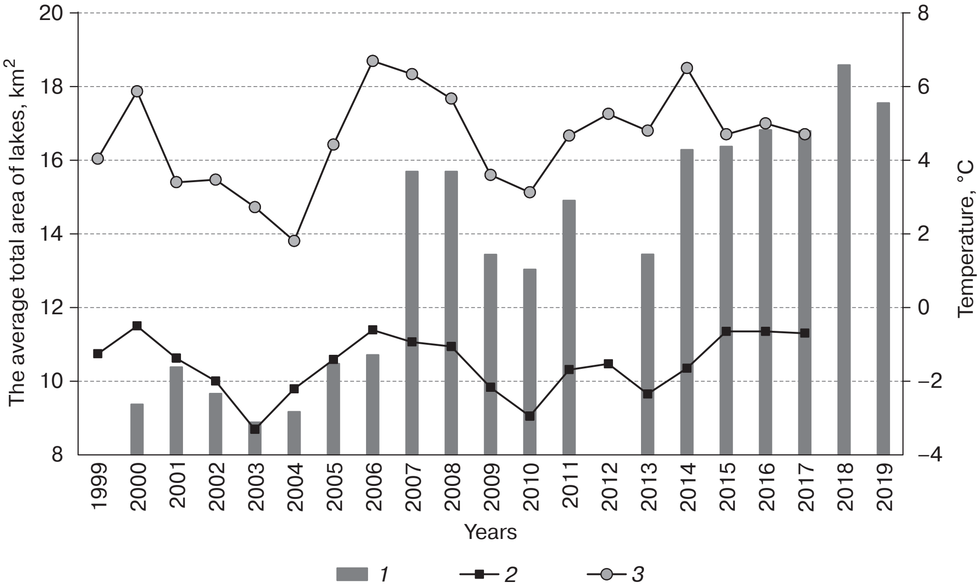

Fig. 7. Changes in the average total area of lakes and the mean soil temperature in March–April and in September at a depth of 1.6 m at Yakutsk weather station.

1 – mean area of lakes, Suola River–Byuteydyakh settlement; *2* – the mean soil temperature at a depth of 1.6 m for March–April; *3* – the mean soil temperature at a depth of 1.6 m for September. Assuming that the area of lakes in 2007 is not less than the area of lakes in 2008.

demonstrated in the work of A. Sejourné et al. [*Séjourné et al., 2015*], the rate of which varied from 0.5 to 3.16 m/year.

When the amount of atmospheric precipitation increases and, as a consequence, the level of lakes rises, additional erosion of the shores takes place. Under conditions of highwater levels, maintaining for 1–2 years, and due to the impact of new thermal impulse, the thawed sediments are oversaturated with water and collapse, thus increasing the area of the lake basin [*Leibman, 2005; Séjourné et al., 2015*].

In spite of the leading role of rainfall or snowmelt, which form the short-lived maximums of the lake areas, the lakes do not return to their initial state after their abrupt increase in area. This is confirmed by the data of [*Zakharova et al., 2018*], satellite altimetry pointing to the initial rise in the water levels of thermokarst lakes in 2006 with the maximum areas of lakes in 2007 and 2008. The average level rise between 2006 and 2009 was 130 cm with the maximum values up to 230 cm. After 2009, the water level began to drop and, over the period 2013–2016, decreased only by 70 cm on average with the maximum decrease of 120 cm [*Zakharova et al., 2018*].

Geocryological conditions have a direct impact on the development and the increase in the area of thermokarst lakes in Central Yakutia in the long term. It is evident, that the local conditions significantly determine dynamics of the temperature and the soil water content of the seasonally thawed layer. The limited point data of observations, which we are forced to use as indicators for large areas, allows us to establish only qualitative relations between the area of lakes and changes in the characteristics of permafrost deposits. The trend of the changes in these values (observed or forecasted) may serve as the indicator of the tendencies in the development of thermokarst processes in Central Yakutia.

CONCLUSIONS

On the basis of the Landsat satellite images, it has been revealed that the total area of the lakes in the basins of the Suola, Tanda, and Taatta rivers in the eastern part of Central Yakutia increased over the period 2000–2019. The development of the lakes occurs at different rates in different areas, with proportional growth for both the residual lakes and the primary thermokarst lakes. In the basins of the Suola and Taatta rivers, the area of the lakes doubled over the 20-year period; in one of the sites of the Taatta River basin, the number of lakes and their area increased almost 4 times over 18 years, and in the basin of the Tanda River – by 25 %, which is most likely due to the more limited distribution of the Ice Complex compared to other considered basins.

Using the identified relationship between the area of the lakes in the Suola River basin and dynamics of the area of the lakes at Yukechi site, we assumed that the total area of the lakes during the period 1944–2019 in the basin of the watershed of the Suola River–Byuteidyakh settlement increased more than

2.5-fold, with the main increase between 2000 and 2019 (2-fold).

It has been established that despite the presence of the general linear trend of increase in the area of the lakes, it occurs abruptly. The periods 1965–1967, 1999–2001, 2006–2008, and 2014–2015 are the examples, when there were dramatical expansion in the lake area, which caused the development of the lakes in subsequent periods. This is proved by the work of other authors [*Brouchkov et al., 2004; Ulrich et al., 2017*]. Some authors point to the short duration of the active phase of the thermokarst development and even consider it as a catastrophic event [*Brouchkov et al., 2004*].

The correlation between the characteristics of the seasonally thawed layer and the dramatical increase in the area of thermokarst lakes in Central Yakutia has been revealed. The main factor leading to disturbance of the stable state of the thermokarst lakes is the short-term (1–3 years) periods of the anomalous increase in the temperature of the seasonally thawed layer. These periods may be caused by a combination of hydrometeorological conditions, such as anomalous high values of snow water equivalent and annual precipitation, and the increased water content of the seasonally thawed layer.

In the work [*Kravtsova, Bystrova, 2009*], it is emphasized that a joint analysis of the remote sensing data and materials of hydrometeorological and geocryological observations is necessary for understanding the reasons of the nonlinear development of thermokarst lakes. The results of our study demonstrate that the combination of hydrometeorological factors (e.g., a high-water period) may lead to the nonlinear changes in the thickness of the seasonally thawed layer and the "explosive" development of thermokarst lakes. The established relationship may be used to forecast the development of thermokarst lakes in the future, both on the basis of the observational data on the state of permafrost and the model calculations.

Acknowledgements. *The research was supported by the Russian Foundation for Basic Research within the framework of scientific projects No. 19-35-50030 mol_nr, No. 19-35-90090_aspirants and with the support of St. Petersburg State University (Action 6, Project ID: 38360634).*

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Received January 9, 2020
Revised version received February 7, 2021
Accepted February 10, 2021