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CATASTROPHIC OUTBURST-FLOOD OF THE SPARTAKOVSKOYE GLACIER-DAMMED LAKE ON THE BOLSHEVIK ISLAND (SEVERNAYA ZEMLYA)

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The changes in the level of the Spartakovskoye glacier-dammed lake during the period of 2016 to 2019 have been studied. In the summer of 2016, the lake level reached its maximum, and during the period from August 16 to August 25, a catastrophic outburst-flood occurred due to the floating-up of a glacier dam formed by the outlet glacier of the Semenov-Tyan-Shansky dome. Estimation of the lake area has been obtained as a result of interpretation of satellite images. The volume of the lake and the height of the glacier dam have been determined according to the data of processing of the multi-temporal digital relief models. The maximum water level in Spartakovskoye Lake was 122.9 m, while its area and volume were (6.63 ± 0.42) km^2 and (404.3 ± 21.9) million m^3, respectively. The minimum height of the iceshed of the dam before the lake drainage was about 137 m, which ensured its ascent with an average ice density of 0.875 g/cm^3. The calculations based on the data of snow surveys and the amount of summer melting have revealed that the melting of seasonal snow cover, perennial snowfields and ice on the surface of glaciers in the catchment area of the lake gives a runoff value of 37.1 to 48.2 million m^3 of water annually depending on average summer temperatures and precipitation. The lake basin is completely filled in about 10 years. The previous outburst-flood of the lake had occurred in the summer of 2006, and until 2016 the level of the lake was continuously raising. At the end of August 2019, the lake's level reached 80 m, which was consistent with the calculations of runoff into the lake. While maintaining the pace of the lake's filling, its next outburst-flood may occur in 2024–2025.

Glacier-dammed lake, outlet glacier, snow cover, melting, maximum level, flood-outburst of lake, Severnaya Zemlya

INTRODUCTION

Glacier-dammed lakes are numerous in Iceland and Greenland [*Grinsted et al., 2017; Carrivick, Fiona, 2019*], often found on Svalbard, Novaya Zemlya, Franz Josef Land, Canadian Arctic Archipelago. The regime and outburst-floods of some of them have been described earlier in [*Walder, Costa, 1996; O'Connor, Costa, 2004; Carrivick, Rushmer, 2006*]. The most large-scale events have been noted in Iceland during the outburst-flood of glacial lakes (jokulhlaup) located in the area of active volcanism [*Clague, Mathews, 1973; Björnsson, 1992; Ng, Liu, 2009*]. On the Severnaya Zemlya archipelago there are only two large glacial-dammed lakes – the Figurnoye and Spartakovskoye ones [*Bolshiyanov, Makeev, 1995*].

As a rule, methods for determining the volume of floods during the outburst-floods of ice-dammed lakes were developed for mountainous areas on the basis of physical and mathematical modeling [*Glazyrin, Sokolov, 1976; Kidyaeva et al., 2018; Popov et al., 2019*] or by analyzing meteorological information [*Konovalov, 1990; Ng, Liu, 2009*]. Quantitative information on the nature of individual events formed the basis for successful modeling. In the absence or inability to obtain reliable field data on the regime of outburst lakes, the results of analysis of Earth remote sensing data with accurate spatial resolution [*Furuya, Wahr, 2005*] are recently used. That method is the most promising for identifying objects in remote areas. The information received by remote methods is completely enough to detect interannual changes in water level in the lakes and to estimate the volume of their basins. In addition, to predict the outburst-floods of lake, information is needed on the state of the glacial dam and the characteristics of the glacial drainage system through which the lake can be drained [*Macheret, Glazovsky, 2011*].

Although the forecasting of the outburst-floods of glacier-dammed lakes, the calculations of discharge volume and construction of flood hydrographs are more relevant for territories where economic activity is carried out, the study of such events in the Arctic region is important in the scientific and practical respect. The catastrophic outburst-floods of lakes in the Arctic are more widespread than in the mountainous regions of temperate latitudes. Discharge volumes and maximum water discharge are ten times greater;

therefore the degree of environmental impact is more significant. The penetration of large masses of water into the glacial ice mass is of great importance for the thermodynamic state and dynamics of glaciers [*Glazovsky, Macheret, 2014*].

Spartakovskoye Lake, dammed with a discharge glacier of the Semenov-Tyan-Shansky dome, is located relatively close to the Ice Base "Baranov's Cape" research station, which gives an unique opportunity to study the regime of the lake, the state of the glacier and the characteristics of the catchment basin.

Currently, mass balance studies of the Mushketov and Semenov-Tyan-Shansky ice domes, observations of snowmelt and runoff of the Amba, Mushketovka and Bazovaya rivers are being carried out on Bolshevik Island as part of the North expedition research program led by AARI [*Makshtas, Sokolov, 2014*]. Based on field measurements, information has been obtained on the distribution of snow reserves and the structure of the snow cover in the northern part of Bolshevik Island [*Vasilevich, Chernov, 2018*]. To date, the information about Spartakovskoye Lake is fragmentary and does not give an idea of its regime. According to the results of helicopter photography in August 2017, the drainage of the lake and many icebergs lying in the lake basin has been fixed. Its regime has become clear only after analyzing the Earth remote sensing data, carried out in different time.

In this work, we study the change in the state of Spartakovskoye Lake after the 2016 outburst, which is probably the largest outburst glacier-dammed lake in Russia.

DESCRIPTION OF THE AREA

Bolshevik Island is the second largest island of the Severnaya Zemlya archipelago, and is located in its southern part. In the west, it is separated by the Shokalsky Strait from October Revolution Island. In the south, the Vilkitsky Strait separates the island from the mainland. In the central and northern parts of the island, on elevated plateaus there are the Leningradsky, Semenov-Tyan-Shansky, Wojciechowski, Kropotkin and Mushketov glacial domes. The hydrological network on the island is represented by small rivers and lakes, alimentated in the summer period due to the melting of glaciers and snow cover. The most full-flowing and longest rivers are located in the northern part of the island. The Bazovaya, Razyezzhaya, Slozhnaya rivers originate from the Semenov-Tyan-Shansky and Leningradsky domes and flow into the Gulf of Akhmatov. Of greatest interest is Spartakovskoye Lake, formed by the ice dam of the outlet glacier of the Semenov-Tyan-Shansky dome (Fig. 1). At the maximum water level, the lake has an efflux in Laptev Sea. In case of an outburst-flood, the lake's water is discharged into Kara Sea. On topographic maps of the second half of the 20th century, it is displayed that Bazovaya River flows out of Spartakovskoye Lake.

About 40 % of the catchment basin of Spartakovskoye Lake is occupied by glaciers and perennial snowfields. The ice-free territory of the basin is characterized by the gentle-sloped hills covered with rock streams. Their surface is dissected by erosion incisions, which form canyons in the lower parts of the slopes. The northern slopes of the Semenov-Tyan-Shansky and Wojciechowski glacial domes belong to the basin of Spartakovskoye Lake. The outlet glacier of the Semenov-Tyan-Shansky dome overlaps the Spartak Fjord, forming an ice dam about 3 km wide.

The climate of Severnaya Zemlya is characterized by long and frosty winters and short cold summers. Mean annual air temperatures make up about −14 °C, the period of positive temperatures lasts 70–80 days, approximately from mid-June to the end of August. In summer, air temperature at sea level often drops below 0 °C [*Bryazgin, Yunak, 1988*]. According to meteorological observations at the Ice Base "Baranov's Cape" research station, the mean temperatures of summer months at sea level vary within the range of from 0 to 4 °C [*Makshtas, Sokolov, 2014*]. Annual precipitation on Bolshevik Island is relatively small: from 200 mm (at sea level) to 300–400 mm (in the glacial reservoirs of ice domes) [*Kotlyakov, 1997*]. In the summer months, 75 to 100 mm of liquid precipitation falls on the coast. Above the altitude of 100 m, the precipitation of mixed-type falls, and its amount increases with height [*Bryazgin, Yunak, 1988*]. The snow cover goes off by mid-June, but on glacial domes at altitudes above 500 m it remains until the end of summer [*Bolshiyanov et al., 2016*]. The snow surveys performed in the spring of 2017 on the northern part of the island, has demonstrated that the distribution of snow reserves in gently-sloping areas has linear altitudinal

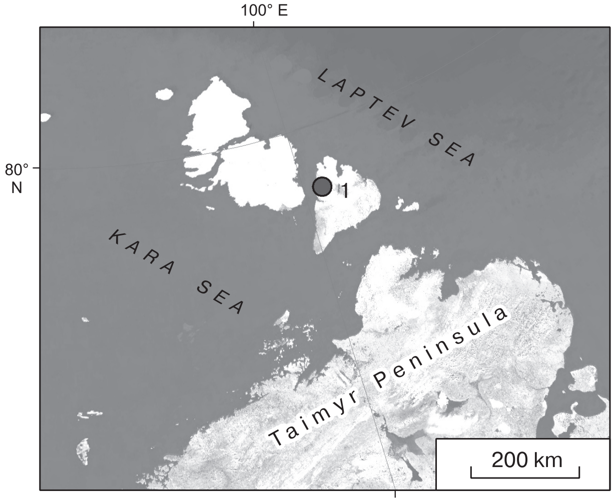

Fig. 1. Research Area.

1 – position of Lake Spartakovskoye on Bolshevik Island.

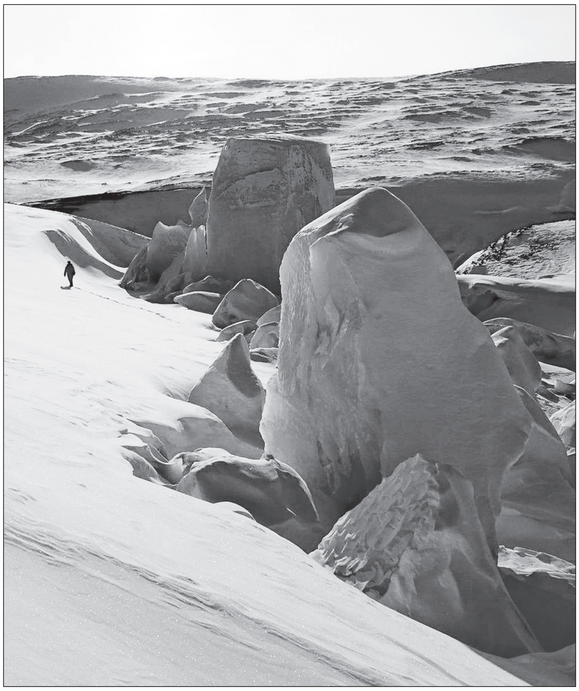

Fig. 2. Icebergs at the bay's bottom of Spartakovskoye Lake (Photo by R.A. Chernov).

dependence. The maximum values of snow reserves have been fixed on the slopes of the glacial domes, and the minimum values of those are typical for coastal areas. At the foot of the glaciers, perennial snowfields form due to the snowstorm snow drift. Increased snow accumulation has been noted in the erosive incisions, where snow reserves are 7–8 times higher than background values [*Vasilevich, Chernov, 2018*]. After the snow cover has gone off, the melting of snowfields during the summer is the main source of alimentation for rivers and lakes of the island.

Lake Spartakovskoye is one of the largest among the glacier-dammed lakes on the islands in the eastern sector of the Arctic. The filling of the lake occurs in the summer due to snow-melting and melting of ice on the surface of the glacial domes. In the northeastern part of the lake there is a long and narrow bay, which in the upper reaches is connected by a pass with the valley of Bazovaya River. As a result of that the maximum level of the lake is defined by the height of the overflow point in the valley. In May 2017, during the route studies, the consequences of the lake's drainage in 2016 have been discovered. The entrance into the bay proved to be blocked by a pile of numerous icebergs lying at the bottom of the canyon (Fig. 2).

RESEARCH METHODS

The following materials have been used in the work: 1) Sentinel-2 satellite images of the L1C processing level (08/01/2016, 08/27/2016, 09/09/2016, 08/26/2018, 09/01/2019) with a spatial resolution of 10 m; 2) the digital elevation model (DEM) ArcticDEM v3.0 [*Porter et al., 2018*] – mosaic with spatial resolution of 2 m and individual fragments ("strip"); 3) data of field observations in May 2017; 4) meteorological observations on the Ice Base "Baranov's Cape" research station; 5) topographic maps in a scale of 1:200,000 edited in 1955 (state of the terrain in 1952).

All the Earth remote sensing data, used in the work, have been recorded in the UTM projection (zone 47N) on the WGS-84 ellipsoid. The processing of satellite images and DEM has been carried out in the software packages QGIS and ESRI ArcGIS.

Deciphering of the lake's boundaries on the Sentinel-2 satellite images has been performed manually. The spatial reference accuracy of the Sentinel-2 images, according to ESA (European Space Agency), is within 11 m with a confidence level of 95.5 % [*SENTINEL 2..., 2019*].

ArcticDEM v3.0 has been used to determine the highest possible water level in the lake, the volume of the lake basin, the surface level of the lake dammed by the outlet glacier, the boundaries of the catchment basin and the areas of its altitudinal zones. In the documentation for that DEM, provided on the developers' website [https://www.pgc.umn.edu], it has been noted that the horizontal and vertical characteristics of its accuracy had not been verified. The mosaic coverage of the Spartakovskoye Lake region has been formed by the results of processing of the WorldView-1, WorldView-2 and WorldView-3 satellite images of 2012–2017, adjusted by using the ICESat survey data (exact collection and coverage of fragments is unknown) – the accuracy of their spatial reference without the using of ground control points is within 4, 3.5 and 3.5 m, respectively. Mosaic ArcticDEM v3.0 with spatial resolution of 2 m is the most accurate and detailed of the available materials containing information on the relief and heights of stable surfaces (surface of land, with the exception of glaciers, snowfields and large erosive incisions).

The maximum water level in the lake (122.9 m) has been measured at the watershed of the catchment basins of Spartakovskoye Lake and Bazovaya River. Measurement has been performed by the ArcticDEM v3.0 mosaic raster. The satellite image of Sentinel-2 (08/01/2016) displays that, a stream outflows from the northeastern end of the lake to the Bazovaya River valley. The base flows out by a stream (an overflow point in Fig. 3). That implies, that on 08/01/2016, the water level in the lake was as highest as possible. Obviously, it remained to be maximal, at least until 08/16/2016, when the overflow of water from the lake to the Bazovaya River valley was being observed by I.S. Yozhikov, the employee of the hydrological unit of AARI.

The volume of the lake has been calculated as the volume enclosed between the maximum possible water level in the lake (122.9 m) and the DEM of its bottom surface. To obtain DEM of the bottom of the lake, two fragments of DEM ("strip") of 04/11/2017 and 08/08/2017 have been selected, included in the ArcticDEM database v3.0 and available separately for download, completely covering the lake basin. A fragment of 04/11/2017 covers more than 80 % of the lake area on 08/01/2016. A fragment of 08/08/2017 covers the western end of the lake (0.78 ± 0.04 km^2, or 11.8 % of the area), not covered by the fragment of 04/11/2017. Those DEM fragments are the freshest out of those created after the drainage of the lake at the end of August 2016. The lowest elevations, recorded on small flat areas in the western part of the DEM fragment of 04/11/2017, were in the range of 20–21 m above sea level.

Verification and correction of the altitudinal reference for the "strip" fragments of ArcticDEM v3.0 have been carried out relative to the mosaic of the indicated DEM. To do that, the regular grid of points with a step of 100 m has been created (Fig. 3), from which all points located on unstable surfaces – glaciers, snowfields, water surfaces and erosive incisions – have been excluded. The latter have been excluded due to the accumulation of a large amount of snow in them as a result of snowstorm redistribution, which is a significant factor, since, firstly: the "strip" fragments of ArcticDEM v3.0 were created in different seasons, secondly: the mosaic of that DEM created with their use may not contain information about the bottom elevations of the erosive incisions, but may indicate the surface elevations of the snow accumulated in them (a difference of up to several meters).

Next, the points located on stable surfaces were assigned mosaic elevations and corresponding "strip" fragments of ArcticDEM v3.0. The surface of the DEM "strip" fragment of 04/11/2017 was systematically increased by 1.62 m – the median deviation for 2322 points from the mosaic surface. The surface of the DEM "strip" fragment of 08/08/2017 was systematically increased by 3.33 m – the median deviation for 870 points from the mosaic surface. The elevation error of the "strip" fragments of ArcticDEM v3.0 relative to the mosaic data is estimated by the authors as ±3 m. That confidence interval includes the deviation values of 92.6 % of 2322 points of the "strip" fragment of 04/11/2017 and those 97.2 % of 870 points of the "strip" fragment of 08/08/2017 from the ArcticDEM v3.0 mosaic values located on stable surfaces.

Since the drainage of Spartakovskoye Lake had occurred at the end of August 2016, i.e., almost at the end of the melting period on the glaciers and snowfields of the region, the DEM fragment of 04/11/2017 most closely has reflected the bottom surface of the lake after its drainage. The DEM fragment of 08/08/2017 has referred to the next warm season after the drainage of the lake. Measurement of the elevation difference between the adjusted DEM fragments of 04/11/2017 and 08/08/2017 has displayed a water level difference of 10.09 m. That value has been taken into account when calculating the volume of the lake basin.

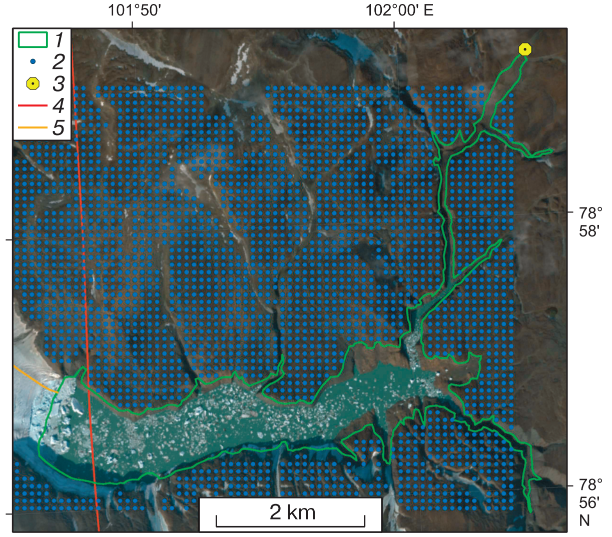

Fig. 3. The boundaries and co-registration points of the DEM used in the work.

1 – shoreline of the lake on 08/01/2016; *2* – points of co-registration of the DEM; *3* – a watershed of the lake and Bazovaya River basins; *4* – the border between the "strip" fragments on 04/11/2017 (eastern) and 08/08/2017 (western) DTM ArcticDEM v3.0; *5* – profile (data for which see in Fig. 6). A Sentinel-2 satellite image of 09/01/2019 is in the background.

The adjusted fragments of the DEM of 04/11/2017 and 08/08/2017 were combined, as a result of which the DEM of the bottom of the lake after its drainage has been obtained. That have made it possible to calculate the volume enclosed between the level of 122.9 m (the watershed of the lake and Basovaya River drainage basins) and the surface DEM of the lake's bottom, amounting to (404.3 ± 21.9) million m^3.

The boundaries of the catchment area have been deciphered manually on a Sentinel-2 satellite image of 08/27/2016. As an auxiliary material, a raster image of the surface exposure created out of the ArcticDEM v3.0 mosaic has been used.

To calculate the runoff values in a catchment basin of the lake, the data on the snow reserves distribution in the central part of Bolshevik Island, obtained by the first author during the snow survey in the spring of 2017, have been used. The work has been carried out according to the program of hydrological studies of the Ice Base "Baranov's Cape" research station. The snow thickness measurements on gently-sloped surfaces (plateau, glacier) were being carried out on linear profiles and test sites in the traditional way – with a probe; in riverbeds, the snow cover radar method was being applied [*Vasilevich, Chernov, 2018*]. According to the snow measurements, it has been found that the average thickness and density of snow cover increases with the increasing of the terrain elevations. According to measurements of the snow cover thickness at elevations of 100–200 m, its average thickness was 25 cm with an average snow density of 0.30 g/cm^3, which corresponds to a snow reserve of 75 mm water equivalent (WE). At elevations of 200–400 m, the average snow cover is 50 cm with an average snow density of 0.40 g/cm^3, which corresponds to a snow reserve of 200 mm WE. According to our measurements in 2017, the average snow cover density varied from 0.38 to 0.45 g/cm^3 on the northern slope of the Mushketov dome.

The thickness of seasonal snow in river beds and canyons varied widely, during the period of maximum snow accumulation, the average snow thickness on flat plateaus, as well as in the channels of the Mushketov and Amba rivers, was 0.37, 1.80 and 1.86 m, respectively [*Vasilevich, Chernov, 2018*]. Our estimates have demonstrated that the snow deposits in river beds accumulate up to 20 % of snow reserves on a plateau.

THE RESEARCH RESULTS

The maximum lake area (6.63 ± 0.42 km^2) was recorded in the summer of 2016 (Fig. 4, *a*). The volume of the lake had amounted to (404.3 ± 21.9) million m^3 at the maximum level in 2016. The lake was held by an ice dam about 3 km wide, up to 13 m high in the northern part. When comparing the lake level and dam height, the hydrostatic condition of ice ascent is performed at an average density of glacial ice of 0.875 g/cm^3, which is quite consistent with real values. If the base of the glacial dam lies several meters below sea level, the hydrostatic ascent condition will also be fulfilled.

The catastrophic drainage of Lake Spartakovskoye has occurred from August 16 to 26, 2016. On the Landsat-8 satellite image of 08/25/2016, the water surface is visible, and also it is visible that the water level in the lake is significantly lower than the maximum possible value. An almost drained lake basin dotted with ice fragments is observed in the Sentinel-2 image of 08/27/2016 (Fig. 4, *b*). A small amount of water has remained near the ice dam in the west of the lake basin. In the northeastern part of the basin, the accumulation of icebergs was the largest – the narrow and deep bay had been cluttered with icebergs up to 25 m high (Fig. 2). An ice dam from the lake side had been broken by cracks. In its eastern part, a surface sink was clearly distinguishable, where a channel of subglacial drainage was probably being formed during the outburst. From the sea side on the glacial surface, the channel traces are not visible, since the outlet of the outburst channel to the sea bay was much lower than sea level. Thus, before the lake drainage, an ice dam had floated-up, the lake's water rushed into the bay under high pressure, forming a drain channel under the glacier. The state of the lake before and after the water discharge is shown in Fig. 4, *a*, *b*.

To calculate the liquid runoff into the lake depression, the boundaries of the catchment basin has been determined (Fig. 5). The drainage area of the lake is (167 ± 1.1) km^2, (73.6 ± 1.4) km^2 of which is occupied by glaciers. In the south, much of the catchment basin area is disposed in the north slope of the Semenov-Tyan-Shansky ice dome. In the east, the basin borders cover part of the Wojciechowski glacier. Large perennial snowfields have been noted at the foot of glaciers on the southern shore of the lake. Glaciers and large snowfields are absent in the northern part of the basin (Fig. 5).

The average snow reserves, which have been calculated according to the results of snow measurements in the neighboring basin (basins of the Amba and Musketovka rivers), have been taken into account in the calculation of liquid runoff. Average snow reserves in the lake basin are considered in two altitudinal ranges (below and above 200 m) and are 75 and 200 mm respectively. For the calculation, it has been assumed that outside the glaciers the snow cover melts completely during the summer. Summer melting of snowfields in erosive incisions adds 20 % to the value of background snow reserves. The area of the extraglacial part of the catchment basin below the level of 200 m is (27.23 ± 0.80) km^2, above the level of 200 m it is (65.91 ± 2.10) km^2. The area of snowfields above 200 m has not being taken into account, since their number in the upper part of the slopes is small.

Although the glaciers in that region lie predominantly above 200 m, the melting on them continues throughout the summer. At the same time, below 500 m, the snow cover goes-off completely, and runoff from the glacier continues due to the melting of ice. The value of summer ablation has also been calculated for the altitude ranges 123–200 and 200–400 m with an average height of 160 and 300 m, respectively. The area of glacier ablation has been taken equal to 40 km^2, and the border height of the glacier's alimentation has been assumed to be 400 m. The magnitude of summer ablation on the glaciers has been calculated using the Khodakov–Krenke formula $A = (T_g + 9.5)^3$ (where T_g is the mean summer air temperature at the estimated elevation) [*Khodakov, 1965*] under the condition of a temperature gradient equal to −0.7 °C per 100 m of ascent. Here, the temperature jump during the transition to the glacial surface, amounting to 1 °C has been taken into account.

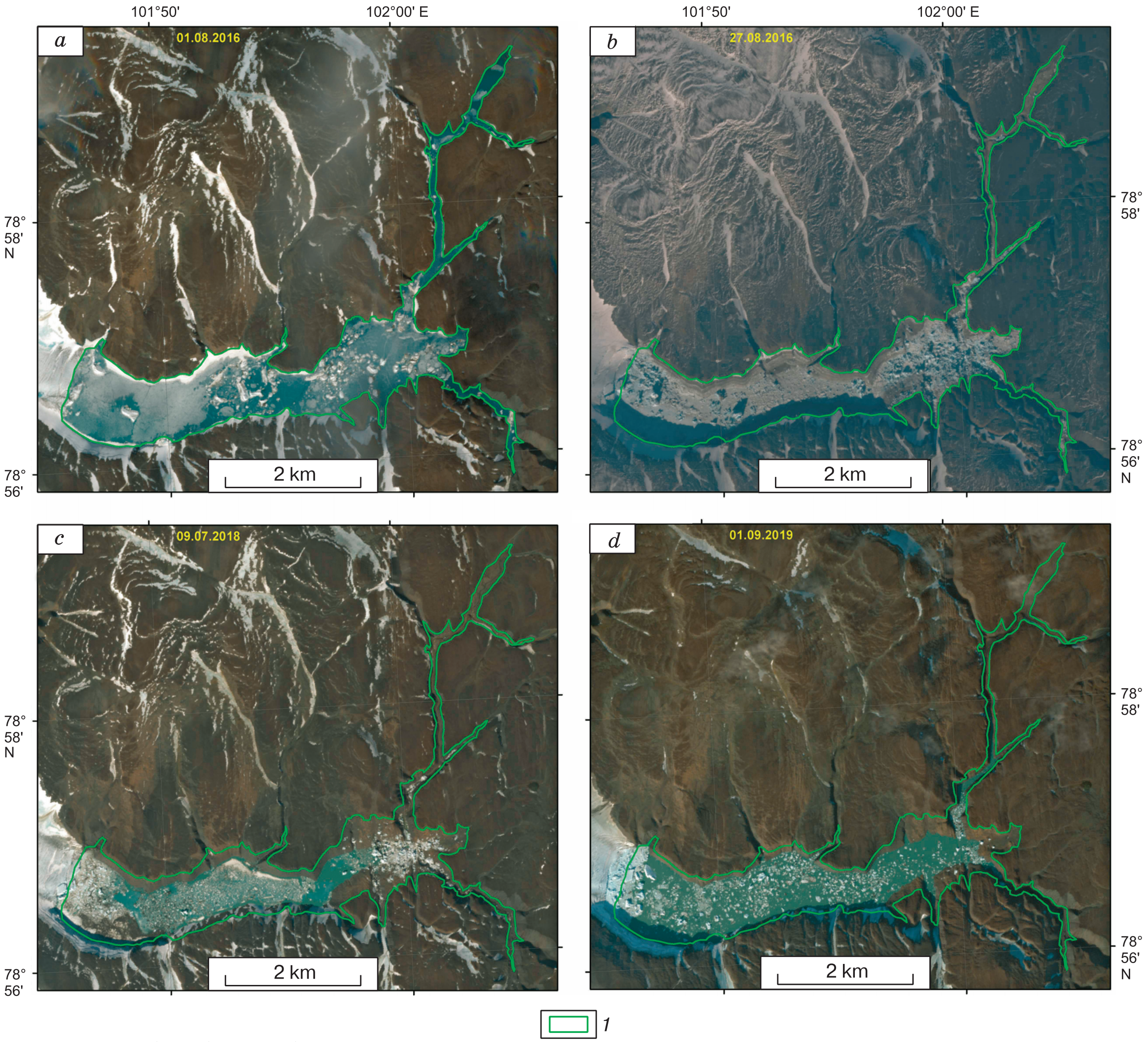

Fig. 4. Spartakovskoye Lake.

a – with a maximum water level on 08/01/2016; *b* – after the drainage of water on 08/27/2016; *c* – 07/09/2018; *d* – 09/01/2019. *1* – the shoreline of the lake with a maximum water level on 08/01/2016.

The mean summer air temperature for the "warm" summer variant is −0.4 and −3.1 °C, that for the "cold" summer variant is −1.4 and −4.1 °C. Glacier surface areas (including adjacent large snowfields) for the elevations below and above 200 m are (0.12 ± 0.04) and (73.52 ± 1.41) km^2, respectively. The calculated value of ablation at an elevation of 160 m has been 750 mm, that at an elevation of 300 m has been 260 mm ("warm" summer). The meltwater runoff out of the glacier ablation area has been accepted equal to the value of summer ablation. Above 400 m, the runoff from glaciers has not been taken into account, since a significant part of meltwater remains in the zone of superimposed ice. The results of the calculation of the annual liquid runoff are given in Table 1.

The components of liquid runoff of the Spartakovskoye Lake catchment basin are displayed in Fig. 6. Most of the meltwater (about 43 %) comes from glacial surfaces, about 29 % of it comes from the snow melting in the mountains, about 5 % of it produces the melting of little-snow areas along the shoreline of the lake, about 22 % of the meltwater comes due to liquid precipitation, and 1 % of it comes from the melting of small snowfields in erosive incisions.

According to calculations, the annual runoff values vary from 37.1 to 48.2 million m^3 depending on

Fig. 5. The catchment basin of Spartakovskoye Lake.

1 – the shoreline of the lake with maximum water level on 08/01/2016; *2* – the border of the drainage basin; *3* – a watershed of the lake and Bazovaya River basins. A Sentinel-2 satellite image of 09/01/2019 is in the background.

the summer weather conditions – the mean summer air temperature and the amount of liquid precipitation. The evaporation from snow cover, which can significantly reduce the amount of runoff, has not been taken into account during the calculation. So, on gently-sloped uplands, where the declivities are low and the snow thickness is less than 25 cm, the snow cover almost completely evaporates in the first half of summer. In the catchment area of Spartakovskoye Lake about 12 % of the territory has a similar relief, the evaporation values from that territory can amount to 1.5 million m^3. Thus, evaporation from the gently-sloped and less-snow areas can reduce the runoff by 3.3–4.0 %.

Table 1. **Estimated runoff value in the catchment basin of Spartakovskoye Lake for various options of mean-summer air temperature and the amount of liquid precipitation**

Mean-summer air temperature, °C	Estimated runoff (million m^3) with the amount of liquid precipitation	
	75 mm	100 mm
–1.0 (cold summer)	37.1	40.4
0.0 (warm summer)	44.9	48.2
Average	41.0	44.3

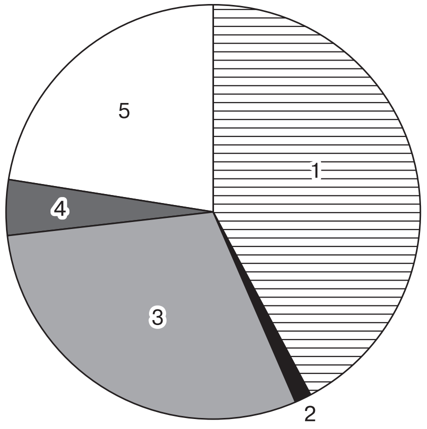

Fig. 6. The average proportion of runoff in the catchment basin of Spartakovskoye Lake during the summer melting:

1 – glacier and perennial snowfields (42.6 %); 2 – snowfields in erosive incisions (1.0 %); 3 – snow cover outside the glacier above elevation of 200 m (29.4 %); 4 – that below elevation of 200 m (4.6 %); 5 – liquid precipitation (22.4 %).

With some assumptions regarding the calculation of snow reserves, the values of ablation and evaporation, we obtain that the annual runoff in Spartakovskoye Lake is about 38.5–42.8 million m^3. The estimated increase in snow reserves in the basin by 20 % gives an increase in the runoff by only 7 %, since the bulk of the water comes from the glacier due to ablation. Therefore, with that annual runoff, the filling of the lake to a maximum level takes about 10 years.

The alimentation of the lake due to ice fragments remaining after the drainage of the lake has not been taken into account. The estimation of ice volume of the icebergs broken off a glacial dam after the drainage of the lake during its filling in 2018–2019, gives a value of 10–15 million m^3 of ice.

DISCUSSION OF THE RESULTS

Breakthroughs of glacial-dammed lakes are numerous in Greenland and the Canadian Arctic archipelago, are found on Svalbard and Novaya Zemlya. On the Severnaya Zemlya Archipelago, on the October Revolution Island, a change in the level of Figurenoye Lake was fixed [*Bolshiyanov, Makeev, 1995*], but, apparently, the drainage of the lake had occurred through the ice channel and had not been catastrophic. By size, Spartakovskoye Lake is one of the largest in the Russian Arctic, and by volume it is the largest glacier-dammed lake in Russia. When the maximum level is reached, the lake overflows into the valley of the Bazovaya River, which belongs to the Laptev Sea basin. The outburst of the lake takes place into Spartak Fjord which belongs to the Kara Sea basin. For the forecast of a lake outburst-flood, the state of the outlet glacier is of interest, namely, the height of the ice dam in the northern (lowest) part, since the lake outburst is occurred as a result of the ice dam floating-up under the influence of hydrostatic forces.

Near the northern coast of the fjord, a network of echelon-like cracks is found on the surface of the outlet glacier, since in that part of the glacier its translational movement sharply changes the direction from north to west. The ice crushing zone contributes to the floating-up of individual blocks of ice. The key moment of the lake outburst is the floating-up of an ice dam and the discharge of water under the glacier into the fjord. The rapid development of the subglacial channel provides a drainage even after the lake water level falls. High water level of the lake (122.9 m) contributes to a significant pressure of water. The dam floating-up creates the conditions for the inflow of the large water volumes, and the development of the subglacial channel during the outburst goes extremely fast. According to the model estimates [*Clague, Mathews, 1973; Glazyrin, Sokolov, 1976*], the maximum water discharge could reach 5500 m^3/s. We do not know the initial dimensions of subglacial channel, as well as the time of the dam's floating-up, and the time interval of the outburst. Presumably, the lake outburst during the floating-up of the dam occurs quite quickly, and it can last only several days. If we assume that the beginning of the outburst belongs to the interval from August 17 to August 25, then the average water discharge could be from 520 to 4675 m^3/s. The maximum water discharge at the time of an outburst exceeds many known estimates of the outburst-floods of large lakes in the Arctic. For example, the water discharge during the outburst of Vatnsdalur Lake (Iceland) reached 3000 m^3/s [*Clague, Mathews, 1973*]. On Novaya Zemlya, an outburst-flood of Olginskoye Lake, formed by the Shokalsky Glacier, is known; the water discharge during it has reached 1600 m^3/s [*Chizhov et al., 1968*]. There are numerous data on the floods of Merzbacher Lake (Tien Shan), which is comparable in size with Spartakovskoye Lake. The maximum water discharge during the outburst-flood has reached 500 m^3/s [*Konovalov, 1990*].

The outburst of Spartakovskoye Lake is a catastrophic phenomenon, during which significant masses of water are transferred and a large amount of energy is released. Many aspects of such phenomena remain to be poorly studied. An interesting process is the development of the subglacial channel under the condition of the water contact with cold ice, and the significant water discharge. The uniqueness of the lake also lies in the fact that it has a maximum level of filling, so the state of the lake outburst is regulated by the height ice dam. With the dam height less than 140 m the breakthrough of the lake becomes inevitable and even predictable, as the destruction of the dam occurs in blocks, the floating-up of which becomes noticeable on the glacier's surface in the satellite images. In 2016, before the drainage of the lake, long transverse cracks had been formed on the surface of the ice dam, which were associated with the floating-up of ice blocks.

An analysis of the 2017 DEM has revealed that the height of the surface of the ice dam in its north part had decreased significantly compared to 2016 (Fig. 7). The ice dam height profiles of 08/14/2011, 08/09/2013 and 04/15/2016, have been compiled on the corresponding fragments of the "strip" DEM ArcticDEM v3.0, which had been adjusted similarly to the "strip" fragments of 04/11/2017 and 08/08/2017. The greatest deformations of the ice dam have been noted in its northeastern part, where a channel of a lake outburst had supposedly being formed. Compared to previous years, the height of the ice surface has decreased by 60 m. At the same time, the dam height in the central part of the glacier has changed a little (within the limits of 5 m). Subsequently, in the course of the lake's filling with water, the broken-off ice blocks have occurred to be icebergs. In 2019, the boundary of the ice dam receded 300–400 m from the boundaries of 2016, the total volume of the broken-off part amounted to about 35 million m^3. On 09/01/ 2019 the lake level increased to about 80 m, the lake's area increased to (4.48 ± 0.24) km^2, and its volume amounted to (184.5 ± 15.5) million m^3. That volume of water is quite consistent with our estimates of annual runoff, which take into account the melting of icebergs in the lake's basin. Perhaps an outburst of the lake, collapsing of ice blocks and a decrease in the height of the ice dam in the northeastern part will also lead to the decreasing of the surface height of the outlet glacier. In that case, the next outburst will occur before the lake level reaches its maximum mark.

It should be noted that similar drainages of the Spartakovskoye Lake occurred earlier repeatedly, as indicated by traces of terraces on the sides of the lake basin, found in the lake's bay in 2017 (Fig. 8). Numerous horizontal lines on the slopes marked the position of the water level in different years.

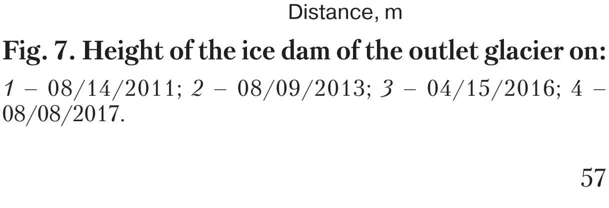

Fig. 7. Height of the ice dam of the outlet glacier on:
1 – 08/14/2011; *2* – 08/09/2013; *3* – 04/15/2016; 4 – 08/08/2017.

Fig. 8. Traces of terraces on a slope of the Spartakovskoye Lake basin (Photo by R.A. Chernov, May 1, 2017).

Analysis of available satellite images permits to suggest that the previous drainage of Lake Spartakovskoe has occurred in 2006. Pictures of the lake of 2006, not covered by clouds, could not be found in free access. However, the ASTER photograph of 07/16/ 2005 displays that the coastline of the lake is close to its position on 08/01/2016. Measured by the adjusted "strip" fragment of DEM ArcticDEM v3.0, the water level has amounted to (105 ± 3) m above sea level. That allows us to conclude that the runoff into the lake until the end of the warm season of 2005 could not be enough to reach the water level, at which the overflow of water into the Bazovaya River basin begins.

The ASTER satellite image of 05/09/2007 displays that most of the lake basin has been drained, the bedrock outcrops and ice heapings have been noticeable. It is difficult to determine an exact level of the residual lake in the western part of the lake basin on 05/09/2007 due to insufficient resolution of the ASTER image, seasonal snow cover and poor lighting conditions for decryption. Obtained values of the water-edge height are within the range of 20–30 m. That means that the discharge of water from Lake Spartakovskoye has occurred in the previous warm season, i.e. in the summer of 2006.

Summer melting in the lake basin ensures the filling of the lake to its maximum level for about 10 years. In current climatic conditions, the filling of the lake's basin to the maximum level is possible by the end of the summer of 2024; therefore, another outburst of the lake can occur in 2024–2025. Predicting of its outburst-flood becomes a real challenge during the remote monitoring of the water level and the height of the ice dam. The possibility of partial destruction of the ice dam due to a change in the position and hydrothermal state of the outlet glacier is not excluded.

CONCLUSIONS

The outburst-flood of the glacier-dammed Spartakovskoye Lake has occurred due to the floating-up of an ice dam formed by the outlet glacier of the Semenov-Tyan-Shansky dome. Based on the interpretation of satellite images and DEM processing, the maximum level of Lake Spartakovskoe has been set at (122.9 ± 1.0) m. With a sufficient height of the ice dam, the maximum level is determined by the height of the point of the lake-water overflow into the Bazovaya River valley. The lake's area at the maximum level has amounted to (6.63 ± 0.42) km^2, and its volume has been equal to (404.3 ± 21.9) million m^3. In August 2016, the part of the ice dam adjacent to the lake had been breached by hydrostatic forces. In the period from August 16–25, 2016, an outburst of the lake had occurred. By August 27, the drainage of water from the lake had been completed. The volume of water displaced from the lake to the sea, as well as the estimated values of water discharge at the time of the outburst-flood were comparable to the largest outburst-floods of lakes in the Arctic.

The calculation of runoff in the catchment basin of the lake demonstrates that each year, depending on summer climatic conditions, the lake receives from the basin from 37.1 to 48.2 million m^3 of water due to liquid precipitation, melting of snow and ice. According to calculations, the lake is filled up within 10 years, as evidenced by the interpretation of the satellite image data. The previous outburst-flood of the lake occurred in 2006, when its minimum water level had been recorded. Given the existing climatic conditions, the next outburst-flood of Spartakovskoye Lake will probably take place in 2024–2025. The condition of the ice dam is also important for predicting an outburst-flood. So, in the summer of 2017, a significant decrease in the dam surface in the northeastern part and a retreat of its boundary by 300–400 m had been recorded.

In the future, the studying of Lake Spartakovskoye may provide the important information on the outburst-flood mechanism in the Arctic glacier-dammed lakes and their interaction with the strata of cold glaciers. The scale of the outburst-flood of the Spartakovskoe glacier-dammed lake is unique, and despite the inaccessibility of the region, the likelihood of registration and research of the next outburst-flood the lake is high.

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