

# HYDROLOGICAL CONDITIONS OF DRAINED LAKE BASINS OF THE ANADYR LOWLAND UNDER CHANGING CLIMATIC CONDITIONS

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**ABSTRACT.** The lakes of the Arctic lowlands are both the unique indicator and the result of climatic and permafrost changes. Remote sensing methods and field measurements were used to consider the patterns and features of the morphometric indicators dynamics of the Anadyr lowland lakes over 65 years. We analyzed the parameters of 36 lakes with an area of 0.02–0.3 km<sup>2</sup> located in the bottoms of drained lake basins, in river floodplains, on sea-shore terraces. Field studies were conducted on 22 typical lakes. The considered dynamics of seasonal thawing are based on the monitoring of the active layer for 1994–2020. Due to an increase of mean annual air temperature by 1.8 °C, as well as an increase and then a decrease in the mean annual precipitation by 135 mm, the average share of a lake area in the study area decreased by 24%. It is shown for the first time that cryogenic processes of the lacustrine coastal zone affect the change in the area of lakes simultaneously with the influence of precipitation and air temperature. Based on field observations, we considered two causes of natural drainage: discharge of the lakes through newly formed thermokarst and thermoerosional surface flow channels and decrease in suprapermafrost groundwater recharge as a result of changing depth of seasonally thawed active layer in the coastal zone.

**KEYWORDS:** thermokarst lakes, active layer, suprapermafrost groundwaters, climate warming, Chukotka

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## INTRODUCTION

The article is devoted to the search and study of the impact of climatic changes on the feed and discharge of lakes in the drained lake basins of the Anadyr lowland. The research methodology included remote analysis of water capacity in basins and field observations of cryogenic processes. The novelty of the research lies in the detailed analysis of the climate influence on the hydrology of lakes through cryogenic processes in the shore zone of water bodies.

The drained permafrost lake basins (Alas, Khasyrey, and Emylkyn<sup>1</sup>) occupy a special place among the natural complexes studied by remote sensing methods. This is due to their wide distribution on the arctic plains, as well as to interaction of surface and ground waters in drained lake basins (DLB) of surface and ground waters, embedded and seasonally thawed ice-containing peat deposits, and a vegetation cover with specific heat-insulating and

water-retaining properties. In contrast to autonomous landscapes, the response of the super-aquatic system to climatic changes is multifactorial and variable (Konishchev 2011). It depends not only on the climate but also on sources of feed and the intensity of water exchange in lakes and bogs, geomorphology and hydrography of the basins, permafrost top ice content, hydrophysical and chemical properties of peat soils, and lake sediments. Most of DLB in the cryolithic zone was formed during climate warming at the Pleistocene and Holocene boundary as a result of thawing and shrinkage of soils of the ice complex (General geocryology, 1978; Romanovsky 2003; Rodionova 2013). In the river basins of the Anadyr lowland, there are observed modern cryogenic processes: frost heaving, formation of wedged ice, thermal erosion, thermal abrasion, and various forms of thermokarst (Chukotka: Natural-economic essay 1995, Krivoshchekov 2000).

Since recently, scientists have been widely using remote sensing methods in spatial analysis to generalize

<sup>1</sup>Chukchi name of drained lake basins used by reindeer herders

changes in the natural environment. This, first, concerns the processing of data from space imagery and aerial photography. The effectiveness of such work is determined by the quality of the interpretation of the surface images and the representativity of the samples of the studied area. The percentage of deciphered objects confirmed by field observations is essential. In conditions of climate fluctuations, the use of remote sensing methods together with monitoring of the components of the natural environment enables identifying the factors and mechanisms of the impact of global warming on natural landscapes.

DLB are attractive for remote sensing since they enable retrospective analysis of the morphology of lakes based on cartographic data and satellite images of different years. The list of works devoted to the remote study of the dynamics of the lake area in the Arctic lowlands is very long. This article does not overview these publications and is not intended to provide their exhaustive analysis. We considered the works listed below as the most interesting and significant ones.

It was found that during 1965–2016, the area of lakes in the Kolyma R. lowland decreased by 7%, averagely (Veremeeva, 2017). At the same time, it was noted that the interannual dynamics of climatic indicators does not affect the water capacity of the objects. The later study (Veremeeva et al. 2021) of the lower reaches of the Kolyma River indicated an increase in precipitation and thermokarst-dependent water capacity of lakes in 1999–2013 and 1999–2018 by 0.89% and 4.15%, respectively. The work (Kapralova 2014) shows that changes in the total area of lakes within one area are subject to statistical laws. Methodological aspects of remote retrospective analysis are considered in the case of the Eurasian lowlands (Rodionova 2013). At the same time, the author notes a slight increase in the water capacity of lakes and expresses the opinion that global climate warming slightly effects the water capacity of the lowlands in the northern hemisphere. Other studies consider dynamics of areal thermokarst and number of thermokarst lakes in Western and Eastern Siberia (Dneprovskaya 2009; Bryskina 2015; Salva 2020) and track the changes in the water capacity in Yamal areas caused by anthropogenic impact (Sannikov 2012).

Intensive remote studies of the lakes in the Arctic plains were conducted in North America. In 1948–2013, the authors noted a decrease in the area and number of lakes in northern Alaska by 30.3% and 17.1%, respectively (Andresen 2015). An earlier study in western Alaska conducted in the period from 1949 to 2002 showed draining of 50 out of 7,400 remotely analyzed lakes (Hinke 2005). The reduction in the area of lakes in northern Canada is described by researchers (Labrecque 2009; Marsh 2009; Lantz 2015). The authors draw attention to the drainage of large lakes due to the extension of existing lakes and the formation of new surface flow paths. The problem of water discharge under abnormal weather conditions is considered in the example of lakes in northeastern Alaska (Nitze 2020). Abnormal precipitation in the winter period of 2017–2018 led to erosion of the shores and a one-time discharge of 192 lakes.

Changes in the water capacity of lakes were recorded in mountain permafrost conditions of China, on the Qinghai-Tibet Plateau (Luo 2015). Researchers noted an increase in the number of small and large thermokarst lakes in 1969–2010.

The estimates of changes in the lakes' water capacity in the Arctic latitudes contradict hypotheses about the change in the water capacity of the basins. Most of the

works register decrease in the area of water bodies and lack of evidence of thermokarst activation during an over 50-year observation period (Romanenko 1999; Jones 2011, 2015). In a short, about 10–20 year long, observation series, we registered activation of thermokarst and an increase in ratio of lake surface in the basins due to the formation of new small water bodies (Tomirdiario 1973; Sannikov 2012; Chen 2013; Arp, 2015; Boike 2016; Nesterova 2020). At the same time, it is confirmed that the area of large lakes is reduced. Drainage of reservoirs, increased evaporation, accumulation of bottom sediments and overgrowing of reservoirs, complete thermokarst, thermal abrasion, and processing of icy soils along the shores of lakes are indicated as the reasons for the drainage of the basins.

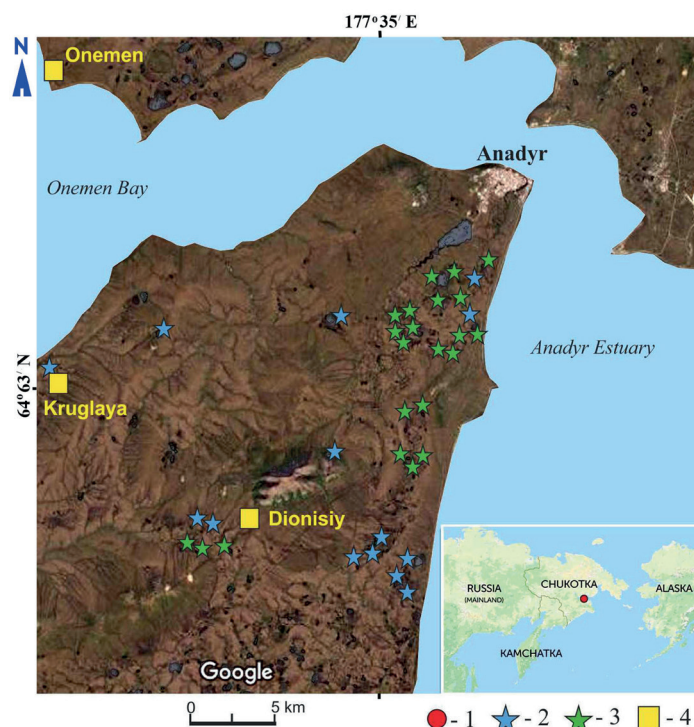
Lakes and thermokarst in Chukotka and in particular in the Anadyr lowland were actively studied by geocryologists and hydrogeologists in the last century. Among the recent works that consider in detail the problems of the genesis and transformation of water bodies, the works (Lyubomirov 1990; Krivoshchekov 2000; Tregubov 2010; Ruzanov 2014) should be noted. Lyubomirov examines the conditions for the formation and evolution of the lakes of the Anadyr lowland. Krivoshchekov analyzes the experience of reclamation of lakes for meadow cultivation. Tregubov and Ruzanov focus on the applied significance of lakes as sources of water supply, analyze the genesis of water bodies and their interaction with submerged taliks. The results of remote sensing studies of 8,305 thermokarst lakes in the Anadyr lowland are provided in the work by Rodionova (2013). According to the interpretation of Landsat satellite images made in the period from 2009 to 2013, the surface area of 338 water bodies (4% of the sample) was reduced by 86 km<sup>2</sup> (3.3%). And only one lake out of the surveyed water bodies slightly increased its water capacity. Field observations were not conducted; hydrological processes and overgrowth of water bodies were named as the reasons for the change in the area of the lakes.

## The Study Area

The Anadyr lowland is located in the southeastern outskirts of Chukotka covering an area of 35 thousand km<sup>2</sup> (Fig. 1). The climate of the territory is subarctic marine. According to the Anadyr meteorological station, the mean annual temperature for the period 1981–2010 is -5 °C. Annual precipitation is 382 mm; most of it falls in winter. The thickness of continuous permafrost decreases from 300 m to 50 m from north to south, where it becomes discontinuous. The temperature of frozen soils at the bottom of the layer of annual heat turnover varies from north to south from -7.1 °C to -1 °C. The depth of seasonal thawing in undisturbed lowland landscapes is 45–55 cm.

The area occupied by lakes ranges from 20% to 60% (Geophysics ... 1987; Krivoshchekov 2000; Rodionova 2013). The area of the lakes varies from hundreds to several square kilometers. Lake water is characterized by a hydrocarbonate and sodium composition, neutral or slightly acidic reaction, and low salinity of 15–30 mg/L (Lyubomirov 1990). As for chemical composition of waters of the lakes located on low sea-shore terraces near the coastline, the proportion of chlorides in them increases; salinity can increase from 20–50 mg/L to 1.5–2.0 g/L. The waters of the drained lake basins are color and contain increased concentrations of total iron.

Despite the long history of studying the lakes of the Anadyr lowland, there is no consensus on their origin, and no optimal classification of water bodies has been proposed



**Fig. 1. Study area scheme: 1 – study area in the inset; 2 and 3 – lakes studied based on cartographic data only (2), based on cartographic data and field observations (3); 4 – active layer monitoring sites**

(Ruzanov 2014). Summary of the different points of view on the conditions of their formation allows distinguishing aqueoglacial lakes, glacial fluvial dam lakes, water-erosion flood plain lakes, water-fluvial lagoon-like lakes, thermokarst cave-in lakes, and thermokarst secondary lakes. Groups of erosion-fluvial and thermokarst lakes are confined to drained lake basins. Floodplain and lagoon-like lakes are found in river valleys and on the coast of the Anadyr Estuary. Thermokarst cave-in lakes are found in elevated areas of distribution of embedded relict glacial landforms and Late Pleistocene permafrost. These are deep (3–5 m) lakes with an uneven funnel-shaped bottom formed when embedded ice deposits thawed out and the surface subsided (Tregubov 2010). Secondary thermokarst lakes with a flat bottom and a depth of 1.2–3.0 m are the most widespread, occupying the bottom of the DLB or flattened watershed saddles (Tomirdiario 1972). It is important to note that old or modern thermokarst as a cryogenic phenomenon is inherent more or less in all categories of lakes. Therefore, S.V. Tomirdiario classified most of the lowland lakes as thermokarst lakes (Tomirdiario 1972, 1973).

The objects of our direct study included 36 lakes with an area of 0.01–0.50 km<sup>2</sup> located at a distance of 7–36 km south and southwest of the city of Anadyr (see Fig. 1). The reservoirs are located within the DLB, confined to the inter-ridge watershed relief depressions (5)<sup>2</sup>, gentle slopes (10), river valleys (15), and sea-shore terraces (6). The absolute marks of the water's edge vary from 8 m to 80 m, the depth of the lakes is 1–4 m, the salinity of the waters is 15–60 mg/L. According to the pattern of water exchange, we classified all surveyed lakes into landlocked lakes and lakes with seasonal overflow (20), lakes with permanent overflow (11), and drainage lakes (5).

The dynamics of the depth of seasonal thawing were analyzed based on the results of long-term monitoring of the active layer (AL) at the sites of the international CALM<sup>3</sup> program (see Fig. 1), (Abramov et al. 2019). This is the Onemen platform, which occupies the flattened top

of a tundra ridge, 26 m high, with hummocky moss and cotton grass vegetation. The Dionisiy site, covered with spotty-lumpy large-grained dwarf moss-forb tundras, is located on a slope of 2–3° in the mountain foot at an altitude of 120 m. The Kruglaya site was laid out in 2010 on the bottom of the DLB with a polygonal relief and moss-dwarf shrub vegetation. The absolute bottom heights are approximately 6 m. In general, the sites represent typical landscapes of catchments and the bottom of the DLB.

## METHODS

The choice of research methods was determined by the need to answer the questions:

1. How has the water content of the Anadyr lowland lakes changed over the past 65 years against the background of climatic changes?

2. Is it true that water bodies really form a single general set of objects and are characterized by general patterns of morphometric changes? To what extent do the geomorphological position, feeding, and discharge conditions of lakes determine the change in their morphometric parameters?

3. What are the current exogenous-cryogenic processes occurring in the coastal zone of lakes, in their catchment area, and along the surface flow paths?

4. How does the depth of seasonal thawing change in the catchment area, in the bottoms of basins, and along the shores of lakes?

5. What permafrost reliefs are formed on the bottoms of inflows and outflows?

Substantially, it was necessary to check the assumptions of predecessors about the reasons for the drainage of reservoirs located in different climatic and geocryological conditions.

According to the order and content of the tasks determined, the methods were divided into the auxiliary laboratory and basic field methods. The laboratory research methodology is based on a comparative analysis on one

<sup>2</sup>Here and below, the number of lakes is indicated in brackets

<sup>3</sup>Circumpolar Active Layer Monitoring



scale (1: 25000) of the contours of lakes on a topographic map compiled from aerial photography of 1953 and satellite images from the Google Maps application based on the results of the 2018 survey (Fig. 2). Morphometric characteristics of lakes, i.e. perimeter, area, and linear dimensions, were defined using the Universal Desktop Ruler V. 3.8.6498 software. Statistical lake parameters (arithmetic mean, skewness, kurtosis, and frequency) were calculated using Microsoft Excel tools.

During the fieldwork in August 2020, 22 lakes were surveyed. The technical capabilities of instrumental measurements allowed studying reservoirs with an area of 0.01–0.4 km<sup>2</sup>. Transverse dimensions were measured using an RGK D1000 laser rangefinder. The measurement range was 3–1000 m; technical accuracy at a distance of 500 m was 1.0–1.8 m (depending on weather conditions).

Each water body was surveyed along the perimeter. We obtained information on the state of coastal ledges, feeder creeks, and surface flow channels; we revealed ground sloughing and determined depth at the coast, shoals, composition of the bottom soil, groundwater outlets, as well

as salinity (electrical conductivity) and pH of lake waters. In the coastal zone, we recorded floodplain terraces, polygonal relief, frost mounds, and thermokarst depression lakes with a diameter of 3–15 m.

The depth of seasonal thawing along the shores of lakes in swampy areas and dry terraces was measured with a 1.2 m metal probe. Soil moisture was measured at a depth of 25 cm using a TK-100-01 moisture meter. In the monitoring sites with a size of 100 × 100 m, the thawing depth in the active layer was measured annually from August 25 to September 5 using a 10 × 10 m pattern (Onemen since 1994, Dionisy since 1996, Kruglaya since 2010).

## RESULTS

The table in the appendix A summarizes laboratory and field research data. The results of a comparative analysis of the morphometric characteristics of the lakes are summarized in the diagrams below. The histogram shows the frequency distribution of lakes with different water capacity variability (Fig. 3a).

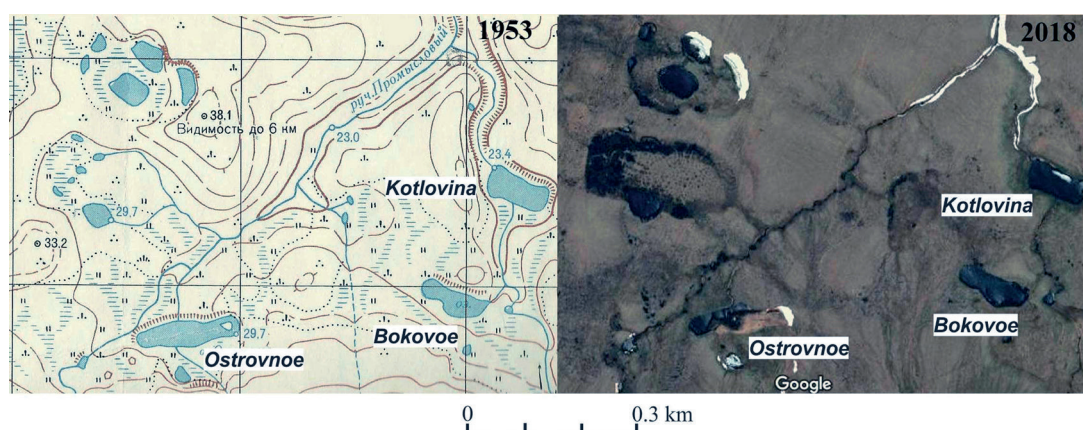


Fig. 2. An example of a comparative analysis of lakes in the valley of the creek Promyslovyy on a topographic map (left) and on a satellite image (right)

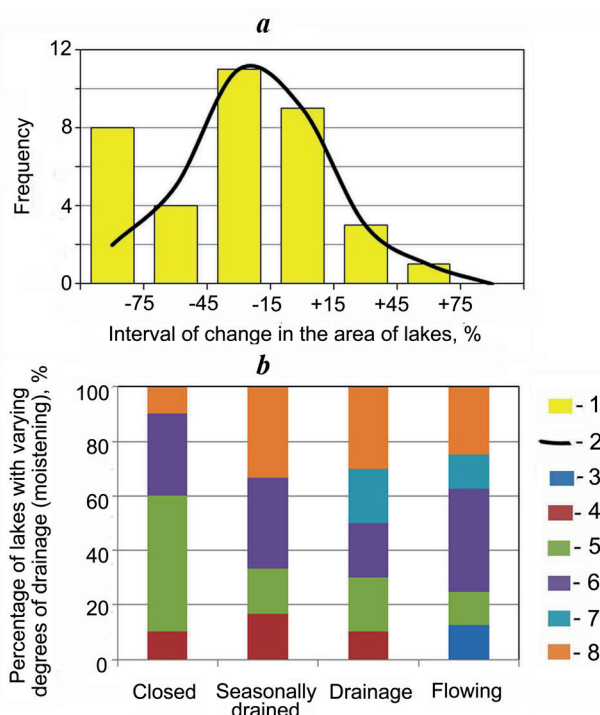


Fig. 3. Distribution of occurrence frequency of lakes with different drainage-watering degrees and the proportion of lakes with different drainage-watering degrees – in groups with different types of water exchange (b). Color and symbols designate: 1 – distribution histogram, 2 – distribution curve without taking into account the lakes drained by land melioration; lakes with varying drainage-watering degrees: 3– 75:45%, 4– 45:15%, 5– 15:(-15)%, 6– (-15):(-45)%, 7– (-45):(-75)%, 8– (-75):(-100)%

The normal distribution of frequencies is disturbed by a large number of water bodies dried up by 90% or more. As it was found out, five out of eight such lakes were drained during melioration in the 1970s for meadow cultivation. These are the lakes Glubokoe, Peschanoe, Kamenistoe, Yazyk, and Sosednee (see Appendix A). After excluding them from analysis, the empirical distribution acquired a normal form (see the distribution curve) with an average percentage of reduction in the area of the water surface of -0.24 (-24%), a standard deviation of 0.36, an asymmetry of -0.31, and a peaked kurtosis of 0.52.

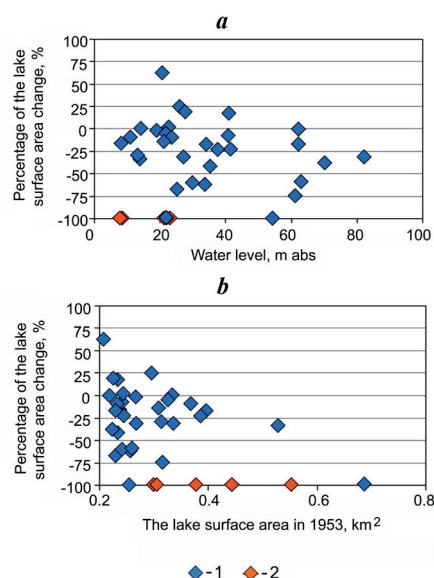
Terminal lakes have retained their water capacity to the greatest extent, in comparison with open and drainage lakes (Fig. 3b). The dotted graph of the distribution of lakes according to the absolute height of the water's edge shows two clouds of scattered objects separated by a height interval of 40–60 m (Fig. 4a). In the relief of the territory, this height interval corresponds to the mountain foothills covered with a trail of diluvial sediments and tundra ridges, the outliers of the 3rd sea terrace, composed of low ice-bearing glacial-marine sediments dated back to the early interglacial transgression (Newest ... 1980; Lyubomirov 1990). This partly explains the absence of lakes at these heights. In another dot plot, lakes are grouped according to their original size (Fig. 4b). The scattering cloud bounds an almost isosceles triangle of 0.2 km<sup>2</sup> horizontally and -24% vertically. As the initial area of water bodies increases, the spread in the amount of their drainage-watering degrees decreases. This is probably because parameters of small water bodies change rapidly and reflect current, possibly cyclical, changes. The larger the reservoir, the more resistant it is to local impact and the more slowly its parameters change.

Field measurements of the transverse dimensions of the reservoirs showed that the size of seven lakes remained almost the same; five lakes were completely dry; in three lakes, water surface area increased; and in seven lakes, it reduced.

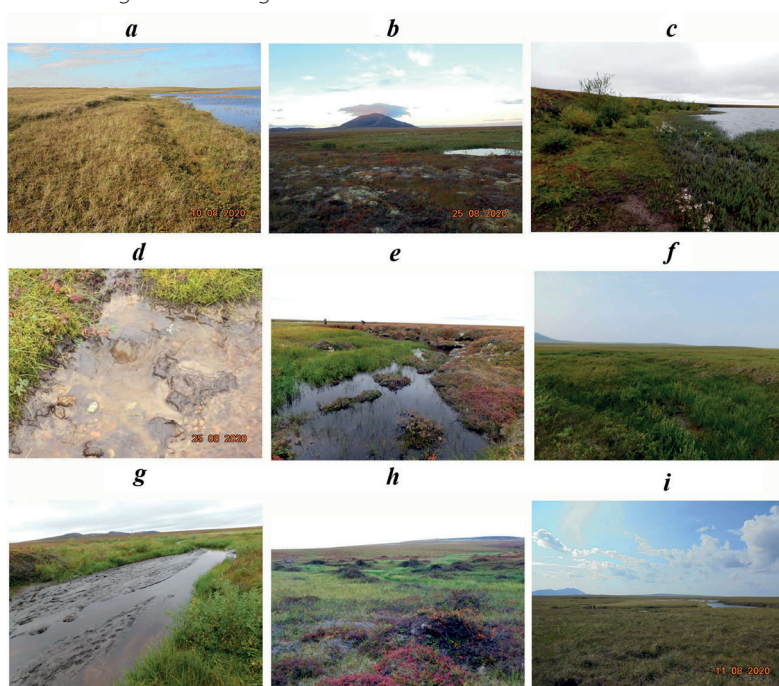
In comparison with the result of the analysis of satellite images in 2018 (June), the deviation of the observed parameters, i.e. lake area increase and lake shore draining, in 2020 from the calculated ones was 5–10%. Morphology of the shores (open shoals or flooded shores) indicates that this is a consequence of the interannual dynamics of the feeding and discharge of water

bodies. The size of open water bodies with low, bogged shores and small bogged catchments decreased. Field transverse dimensions of terminal, seasonally open, and drainage lakes, which constitute the majority, were increased compared to the 2018 image.

The results of the field survey proved the complex structure of the shore zone of the lakes. It is expressed in presence or absence of lake terraces, degree of development of thermal erosion, thermokarst, and thermal abrasion along the shores, in the morphology of the drainways, in the material of bottom sediments of lakes and groundwater outlets. Fragments of two terraces with ledges 0.3–0.5 m high were found in the DLB of various drainage degrees (Fig. 5a).



**Fig. 4. Distribution of lakes with different degrees of drainage – watering, depending on hypsometric position (a) and area of water bodies according to aerophotos taken in 1953 (b): 1 – lakes without traces of technogenic impact, 2 – lakes with proven facts of melioration**



**Fig. 5. Field observations of the shore zone of the Anadyr lowland lakes: a – ledges of lake terraces, b – polygonal dwarf shrubs of the upper terrace of the lake, c – large shrubs along the coast at the footslope, d – outflows of suprapermafrost waters at the footslope, e – thermokarst and thermal erosion along the sides of the lake drainage channel, f – newly formed drainways on thawing ice of polygons, g – traces of water discharge from a drained lake in a channel, h – frost heave mounds on the lake shores, i – thermokarst lake 10 m from a drying lake**



The upper terrace is distinguished by a polygonal relief, composed of peat deposits with a thawing depth of 50–55 cm and a moisture content of 65–75% (Fig. 5b). Vegetation cover is represented with shrub moss-and-lichen. The lower terrace is mostly boggy; areas with a polygonal, sometimes mound relief are subject to thermokarst – the intersections of polygonal wedges are filled with water. The vegetation cover varies from moss-cotton grass to forb-sedge and sedge-sphagnum. The depth of seasonal thawing is 45–50 cm; humidity is more than 80%. The shores of the lakes adjacent to the ridges' convex slopes are distinguished by solifluction sloughing and thermal erosion ditches. Drainage of the coast at the footslope causes springs with woody shrubs along the shores (Fig. 5c).

Thermoabrasive shores, due to the relatively small size of the reservoirs, are developed to a limited extent, mainly on elongated reservoirs oriented to the south-east (Skvazhinnoye, Ovalnoye, and Mysovoye). Among the general regularities, more or less inherent in all lakes, there is a combination of a coastline of ledges and cliffs with a height of 0.3–0.5 m and boggy coastal shoals. Another regularity concerns new or renewed surface flow channels in the majority of drained lakes. These can be both rectilinear melioration canals and natural zigzag paths of the surface flow along the thawed polygonal wedges of the first DLB terrace, or pre-existing inter-lake channels widened and deepened by thermokarst and thermal erosion (Fig. 5d, 5e).

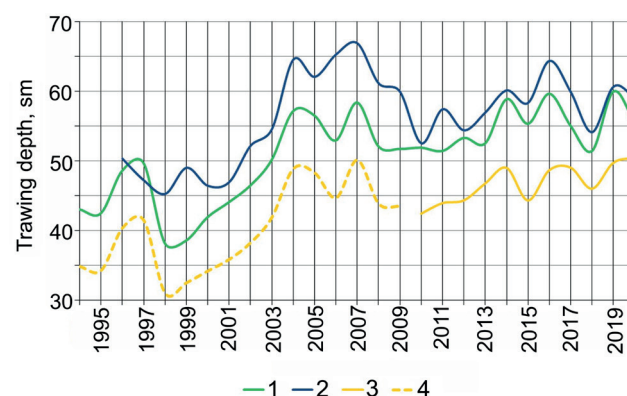
Monitoring of the geocryological conditions of the Anadyr lowland is limited to a 25-year period (Tregubov 2019) (Fig. 6).

During the observation period, the thawing depth at the Onemen reference site, which occupies an autonomous position in the relief, increased by 15 cm, or 36% of the initial value. A slightly smaller increase (by 27%) in the thawing depth was noted in the transit (transsuperaqual) conditions of the Dionisiy site. An intermediate position is occupied by the superaqual Kruglaya platform. Taking into account the retrospective data interpolation, the increase in the thickness of the AL within its limits was 12 cm, or 34%. All landscapes are characterized by fluctuations in the depth of seasonal thawing lasting from 2.7 to 9–11 years. The mean annual temperature of the active layer in the

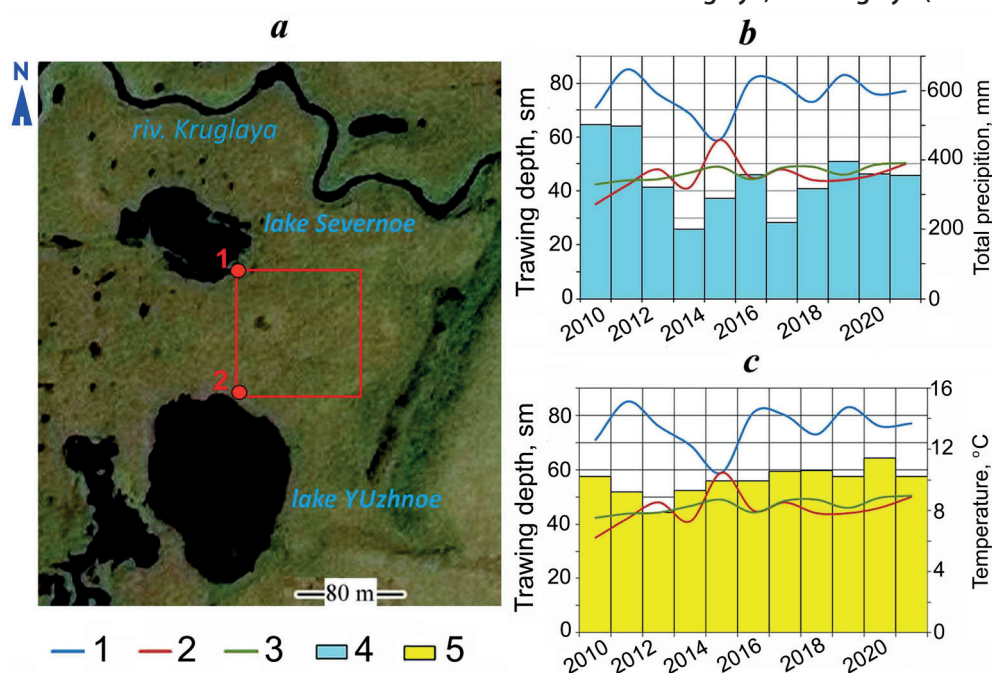
depth interval of 20–50 cm at the Onemen site increased by 2.5 °C over 20 years of observations (Tregubov 2020). The mean annual temperatures of the active layer of the Dionisiy site remained unchanged.

The result of observations of seasonal thawing at the northwest and southeast ends of the Kruglaya site, located at the DLB bottom, is shown in Fig. 7.

These are the shores of two secondary thermokarst lakes: gentle boggy (point 1) shore of the terminal lake Severnoye and steep, 1.2 m high (point 2), shore of the open lake Yuzhnoye. As can be seen, the dynamics of the active layer seasonal thawing of the two shores over the 10-year observation period is different (see Fig. 7b, 7c). Against the background of the general increase in the magnitude of seasonal thawing, the thickness of the thawed layer on the boggy shore decreased sharply in 2011–2015 and thawing depth decreased on the elevated dry shore of the lake in 2013–2014. Analysis of the dynamics of climatic indicators suggests that this is due to an abnormally sharp drop in precipitation in 2010–2013 (by 302 mm) in relation to an increase in the mean annual air temperature in 2012–2014 from -7.5 °C to -4.5 °C. Amplitude of fluctuations in precipitation in 2016–2017 is twice less (140 mm). Consequently, the thawing depth on the boggy coast slightly decreased in 2017 (see Fig. 7b). Such phenomena



**Fig. 6. Dynamics of seasonal thawing at the active layer monitoring sites: 1 – Onemen (Rogozhnyy), 2 – Dionisiy, 3 – Kruglaya, 4 – Kruglaya (retrospective)**



**Fig. 7. Dynamics of seasonal thawing at the Kruglaya site (a) against the background of changes in the annual precipitation (b) and air temperature (c): thawing depth at point 1 (1), at point 2 (2) on average over the site area (3); 4 – the annual amount of precipitation; 5 – mean air temperature of the frost-free period of the year**

are in good agreement with the well-known conclusions of geocryologists about the dual effect of moisture on the thawing and freezing regime of the active layer (General Geocryology 1978). A decrease in the precipitation volume leads to drainage of the low shores of thermokarst lakes and a decrease in the depth of thawing along the shores of coastal bogs. At the same time, a decrease in the moisture content of high shores, on the contrary, contributes to an increase in the depth of seasonal thawing due to the higher intensity of heat turnover in polygonal tundras as compared to tundra bogs.

## DISCUSSION

Elementary statistical analysis of permafrost climatic conditions showed that the area of water bodies tends to decrease. The average drainage volume is 24%; the confidence interval for a normal distribution of changes in the area of lakes with a probability of 95% is in the range from 46.6% to -94.6%. Analysis of possible hydrological and geomorphological reasons for drainage shows a completely explainable causal relationship. It is expected that the smallest losses of the area of the water mirror are inherent in terminal and seasonally-overflow lakes. The change in the area of the lakes is associated with their position within the DLB and the relative excess of the water edge over the erosion basis. The lakes located in the headwaters of creeks or occupying the upper position in a cascade of lakes turned out to be significantly drained: Beloye, Uvalnoe 2, Verkhovaloe, Mezhdurechnoye, Ostrovnoye, and Gusinoe 3 (see Appendix A). These lakes are characterized by the formation of the new or deepening existing surface flow paths. In most cases, the lakes located along the edge of the hollows at the foot of the slope retained their water content: Severnoye, Uvalnoye, Ovalnoye, Bokovoe, and Podgornoye. This is due to the larger catchment area and stable feeding of the lakes with suprapermafrost waters. At the same time, the sample contains quite a few exceptions from the patterns described above. For example, the lake Skvazhinnoe, the area of which increased due to thermal abrasion by 18%; the open lake Novoe, the bed of which expanded by 63% due to activating thermokarst along the repeatedly wedged ice of the above-floodplain terrace; the terminal lake Mysovoe, located in the center of the boggy bottom of the basin, the water surface of which decreased by 33%. And also a group of the terminal and seasonally open lakes located at the foot of the slope, with an area varying from -17% to -60% (Besstochnoye, Uglovoe, Ostrovnoe, and Poduvalnoe). Thus, information on the conditions facilitating the drainage of lakes or preservation of their water capacity is insufficient to predict hydrological processes. Thus, it is required to conduct a more detailed analysis, taking into account the regime of lake feeding and discharge, climatic changes and cryogenic processes.

For this purpose, it is necessary to consider the changes in the climatic conditions of the territory. From the middle of the last century to the present, the mean annual air temperature has increased by 1.81 °C, with year-to-year fluctuations of 1.5–3 °C (Fig. 8). The annual precipitation increased by 61.6 mm with the amplitude of interannual fluctuations up to 300 mm. The duration of the frost-free period increased by 4 days (Tregubov 2020). Variations in the values of climate indicators are due to fluctuations of different amplitude with a period of 3–5 years. Over the past 25 years, the air temperature has increased by 1.7 °C, and the annual precipitation has decreased by 135 mm. The amplitude of interannual fluctuations in temperature and precipitation has decreased (see Fig. 8). The duration of

the frost-free period increased by 12 days with an average value of interannual fluctuations of 5 days (Tregubov 2020).

The information on evaporation capacity dynamics is not available. According to the known calculation schemes of zoning and literary sources for the warm season in the studied area, it is approximately 200–250 mm (Geofizika ... 1987; Postnikov 2014). Evaporation capacity probably increased with an increase in temperature and duration of the warm frost-free period.

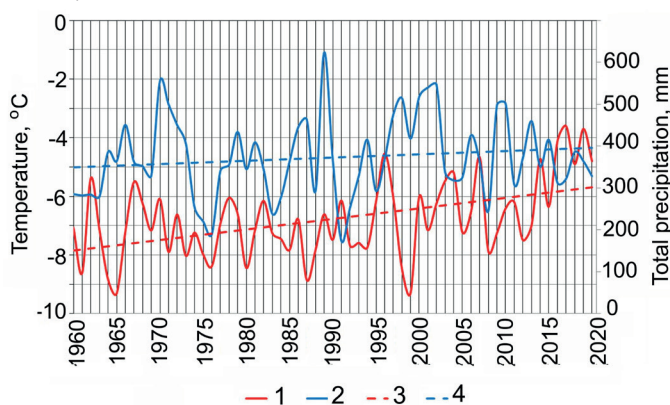
Open and seasonally open secondary thermokarst lakes with an increase in air temperature, and hence evaporation, will have a negative long-term water balance even with a constant or partially increasing amount of precipitation. This is due to the limited capabilities of the lake basin in the accumulation and retention of moisture and the absence of other feed sources, except for atmospheric precipitation. An increase in the water content and area of such lakes is possible only due to the deepening and expansion of the bed during the development of thermokarst and thermal abrasion.

A local source of replenishment of lake water and preservation of the area of water bodies can be ground ice meltwater in the composition of the increasing suprapermafrost flow. In the present case, this applies to the lakes located at the foot of extended slopes. The intensity and availability of this feed source are limited by the ice content of the permafrost roof and wedges and icy horizons' melting time.

But the hydrological regime of the lakes is influenced not only by long-term changes in climate indicators but also by short-term fluctuations in their values. Often, fluctuations in the mean annual temperature and the amount of precipitation are in antiphase. Hot dry summers and warm winters precede years with high water and summer-autumn floods, i.e. 1962–1966, 1978–1979, 1991–1994, 1996–1997, 2004–2006, 2011–2013, 2017–2018 (see Fig. 8). Positive temperature extremes correspond to the maxima of interannual fluctuations in the depth of seasonal thawing (see Fig. 6). These facts, as well as the field observations by the authors, make it possible to represent the stages of formation of lake water discharges:

1. The maximum seasonal thawing is reached in conditions of dry hot summer, long autumn, and warm snowy winter; thermokarst is activated along the surface ground ice; talik zones that do not freeze completely during winter are formed in flow troughs.

2. With the onset of floods, the hollows of the lake flow paths are subject to thermal erosion; they deepen and provide a flow of meltwaters, which drain before the



**Fig. 8. Dynamics of mean annual temperature and precipitation according to the Anadyr weather station:**  
1 – mean annual temperature, 2 – total precipitation, 3 – linear trend of temperature, 4 – linear trend of total precipitation

beginning of the intensive melting of the lake ice cover. The main water discharge falls on the summer-autumn floods caused by prolonged rains. This is the period of the maximum thawing depth along the lake shores in the surface flow paths.

3. In the years following the draining of the lake, the flow channel is closed due to silting and sloughing of the washed-out and thawed shores. Drainways become useless. Given sufficient feed, the lake bed is filled with water. In the event of insufficient atmospheric precipitation, absence or interception of suprapermast flow, the lake bottom overgrows and becomes a tundra bog or a herb-grass meadow.

Discharges as a reason for the drainage of the DLB were noted in (Lantz 2015; Nitze 2020). But the authors describe this process more as an extraordinary event and do not consider it as a natural phenomenon for the permafrost zone. According to residents, the bed of the lake Gusinoe 3, which is often visited by hunters and gatherers of wild plants, since 1994 has been drained three times and re-filled with water.

Despite the attractiveness of the discharge model as a reason for the cyclic change in the water content of lakes, it does not explain the variety of hydrological drainage regimes. In most of the surveyed lakes, water surface area decreased slightly and they do not contain any newly formed elements of the drainways. Among these reservoirs, there are many terminal or seasonally open lakes, differing in the catchment area. The last remark makes it impossible to unambiguously relate the drying up of these lakes only with an increase in evaporation, since lakes with a large catchment area should be less affected by a decrease in precipitation and an increase in the mean annual temperature.

The results of the analysis of the seasonal thawing dynamics of the shores of the lake Severnoe (see Fig. 7), together with observations of thermokarst and frost heaving in the coastal strip of drying water bodies, allowed proposing a cryogenic hypothesis of their partial natural drainage. It is based on the interaction of lakes with the suprapermast aquifer of the DLB. Figure 9 shows a schematic model of this interaction.

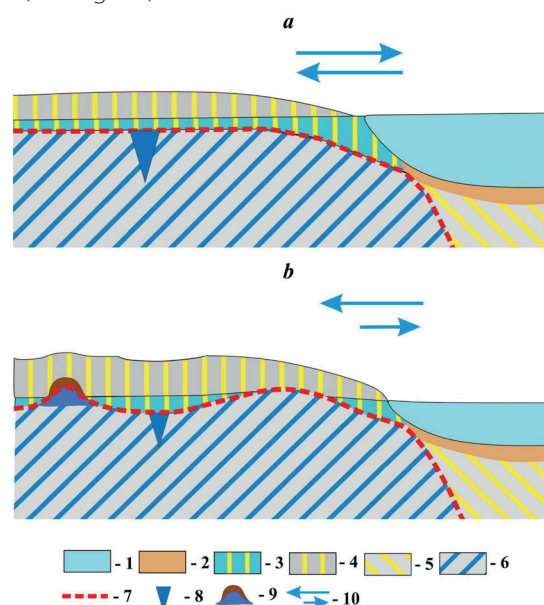
With a constant amount of annual precipitation and seasonal thawing depth, area of the water surface and depth of the reservoir are within the seasonal dynamics (Fig. 9, a). During the floods period, the lake feeds the suprapermast aquifer at the bottom of the basin. In May–June, the overflow floods the adjacent marshy shore. In August–September, this occurs due to the reverse filtration of the flood excess of lake waters through the deeply thawed active layer of the coastal strip. The return flow into the lake occurs during the summer dry season through the suprapermast horizon, if the thawing front of the active layer occupies a position above the water level in the lake.

Under conditions of interannually fluctuated climatic parameters, the dynamic equilibrium is violated. A decrease in precipitation and an increase in the mean annual temperature lead to increased evaporation, water recedes from the shores, decreased level and water surface area. This, in turn, leads to deeper freezing and a decrease in the depth of seasonal thawing of the coastal strip (see Fig. 9, b). Therefore, for example, over a ten-year observation period, the interannual decrease in the area of the lake Severnoye reached 27% – the water receded from the control point (No. 1) by 6 m. This happened in 2014, with a decrease in the annual precipitation in 2013 to 200 mm (see Fig. 7 b). When the low shores are drained, the suprapermast

aquifer is separated from the lake by a frozen bulkhead and forms two unequal areas – coastal and drainage areas (Fig. 9b). The dependence of lake feeding on the catchment area decreases. Water exchange is disturbed. In short-term periods of high water level, the lake still feeds the suprapermast horizon, but the reservoir does not recharge during the summer low-water period. As a result, drying out intensifies and reaches a maximum in 1–2 years after the decrease in the amount of precipitation.

Within the catchment area in the suprapermast horizon, with an increase in thawing depth, activation of thermokarst along icy horizons and underground ice is followed by the formation of subaerial talik zones. Freezing of such taliks result in heaving mounds (Fig. 5h). As a result, after the establishment of a new dynamic equilibrium of water exchange, this leads to the development of hilly tundra bogs with thermokarst satellite lakes of a large partially drained reservoir on the catchment in the bottom of the DLB (Fig. 5i). This situation has not been previously described, but it is quite typical. It is easily recognized on satellite images and during field observations in the DLB. Sometimes the associated lake is located 10–15 m from a large partially drained reservoir. Moreover, there are no signs of modern thermokarst on the shores of the dying lake.

The proposed conceptual dynamic model is not universal. Under conditions of increasing atmospheric humidity, the water exchange between the lake and the suprapermast aquifer can increase. An increase in air temperature will lead to the activation of thermokarst and an increase in the area of the reservoir. The lack of atmospheric nutrition may not immediately affect the water content of the lakes located at the foot of the extended slopes of the ridges. An increase in the depth of seasonal thawing in the catchment area leads to the melting of the icy horizons of the transitional layer, ground ice, and an increase in the suprapermast flow and feeding of such lakes (see Fig. 6d).



**Fig. 9. Model of interaction of lake waters and suprapermast aquifer under static climatic conditions (a) and with a decrease in precipitation against the background of an increase in air temperature (b):**  
 1 – lake; 2 – bottom sediments; 3 – suprapermast aquifer; 4 – active layer; 5 – underlake talik zone; 6 – permafrost; 7 – permafrost roof; stylized image of wedge ice (8) and permafrost heaving mounds (9); 10 – direction and intensity of water exchange (description in the text)



The dynamic model partly explains the paradox of simultaneous development of thermokarst in the bottom of the DLB along the ice wedges, formation of new wedge ice, attenuation of thermokarst along the shores and drainage of large lakes, and formation of new local point thermokarst lakes, which confused the predecessors and modern researchers (Lyubomirov 1990; Labrecque 2009; Boike 2016; Nesterova 2020). Within the framework of the considered model, the nature of the process is determined by the excess of the shores and the surface of the terraces relative to the water edge in the lake and the topography of the permafrost roof.

## CONCLUSIONS

1. In the period from 1953 to 2018, the area of the water surface in the drained lake basins of the Anadyr lowland, ranging in size from 0.008 km<sup>2</sup> to 0.5 km<sup>2</sup>, reduced by an average of 24%. The largest percentage (40–100%) of drainage was registered in open and flowing water bodies located at the sources of streams and cascades of lakes. The smallest decrease in the water surface (0–40%) is typical for closed water bodies located at the foot of long slopes. The area of three out of 36 lakes was increased. Field observations conducted in these lakes recorded manifestations of thermokarst and thermal abrasion, as well as the inflow of drainage water from drained lakes.

2. The reasons for the drainage of reservoirs included anthropogenic and natural processes: melioration of lakes for meadow growing (1965–1985); natural discharges of lake waters; changing conditions for feeding reservoirs with suprapermfrost waters. Discharges occur in conditions of abnormally high precipitation preceded by an increase in the depth of seasonal thawing, activation of thermokarst, and thermal erosion. Changes in the surface flow conditions of suprapermfrost waters are caused by a differentiated change in the depth of seasonal thawing in the coastal zone of closed and seasonally drained lakes.

3. Favorable conditions for the discharge of lake waters are repeated at intervals of 3–12 years; this is typical of open lakes with an excess of the water edge over the base of erosion by 1 m or more. The area of the water surface of closed lakes located in the central part of the depressions decreases due to the weakening of the supply of groundwater from the suprapermfrost horizon. The coastal zone of drying lakes are characterized by bogging areas, frost heaving, and thermokarst, isolated from the reservoir by frozen barriers. It is assumed that this is the main mechanism of drainage of secondary thermokarst lakes, which have exhausted their expansion potential due to thermokarst and thermal abrasion. In the 20-year perspective, permafrost drainage of lakes in the bottom of the DLB is expected to be followed by expansion of the area of mound tundra bogs with numerous thermokarst lakes. ■

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## Appendix

## Appendix A. Results of survey of the Anadyr lowland lakes

Name of the lake; center coordinates	Landscape position; relief height (m)	Morphometric characteristics: transverse dimensions (m); perimeter (m); area (km <sup>2</sup> )		Area fluctuation (%)	Field observations:	
		1953	2018		lake dimensions, m	Feed and discharge, landforms, coastal conditions, cryogenic processes, M (mg/L); pH
Mysovoe; 64.683469, 177.430887	Bottom of a bogged basin, head; 13.7	750x525; 2743; 0,328	750x410; 2400; 0,219	-33	745x410	Suprapermafrost groundwater, seasonal discharge, swampy overgrown shores, fragments of a 0.3 m high terrace. 21; 5.63
Severnoe; 64.688643, 177.4444	Bogged basin bottom, head; 14	500x475; 1490; 0,134	495x485; 1436; 0,135	1	522x475	Suprapermafrost groundwater, seasonal discharge, steep shores 0.3–0.5 m high. 44; 6,3
Yazyk; 64.681728, 177.453460	Footslope, head; 8,5	563x225; 1487; 0,099	350x45; 726; 0,02.	-80	325x30	Suprapermafrost groundwater, seasonal discharge, melioration canal, swampy overgrown shores, drained bays. 31; 6.12
Yuzhnoe; 64.670861, 177.430286	Seashore terrace 2, head; 18,8	385x190; 950; 0,066	390x200; 1000; 0,067	-1	401x205	Suprapermafrost groundwater, seasonal discharge, steep shores 0.3–0.5 m high, drowned valleys. 26; 6,06
Kamenistoe; 64.695155, 177.48887	Seashore terrace 1; 7,8	500x325; 1500; 0,105	Drained	-100	-	-
Sosednee; 64.689982, 177.481490	Seashore terrace 1; 8	275x250; 747; 0,038	240x200; 693; 0,032	-16	-	-
Klin; 64.615247, 177.409687	Footslope, river terrace; 41,3	375x225; 974; 0,045	220x200; 782; 0,035	-22	225x196	Suprapermafrost surface and groundwater, flowing, permanent surface flow, steep shores 0.5 m high, new runoff channel, thermal erosion. 19; 5,45
Uvalnoe; 64.607151, 177.389345	Footslope, river terrace; 40,6	377x130; 918; 0,042	312x120; 893; 0,039	-7	315x120	Suprapermafrost groundwater, seasonal discharge, top overgrown and solifluction sloughing shores
Skvazhinnoe; 64.594008, 177.411146	Gentle slope, inter-ridge saddle; 40,8	378x127; 983; 0,034	310x175; 900; 0,040	18	320x181	Suprapermafrost groundwater, surface flow paths not found, steep shores 0.3–0.5 m high, thermal abrasion, rafts. 15; 5,7
Poduvalnoe; 64.586863, 177.395439	Footslope, river terrace; 33,5	400x175; 1069; 0,057	346x100; 756; 0,022	-61	330x90	Surface (stream) and underground suprapermafrost waters, constant discharge, steep sloughing shores, extended surface flow path, thermal erosion. 15; 7,2
Krugloe-Protochnoe; 64.593050, 177.392006	River terrace; 35,1	250x250; 725; 0,034	200x210; 516; 0,020	-41	200x196	Surface (stream) and underground suprapermafrost waters, constant discharge, steep sloughing shores, extended surface flow path, thermal erosion. 21; 6,46
Glubokoe; 64.671840, 177.39019	Seashore terrace 2; 21,3	750x500; 2038; 0,244	Drained	-100	-	Dried bottom, overgrown with herbs, woody forms of shrubs, terraces 0.5–1 m high, bogged melioration canal, frost mounds 0.5–1 m high
Peschanoe; 64.664826, 177.39526	Seashore terrace 2; 23	875x750; 3032; 0,352	Drained	-100	-	Dried bottom, overgrown with herbs, woody forms of shrubs, terraces 0.5–1 m high, bogged melioration canal, frost mounds 0.5–1 m high
Peremychka; 64.662108, 177.383331	Seashore terrace 2; 22	600x525; 1727; 0,177	Drained	-100	-	Drained, bogged bottom, terraces 0.5–1 m high, constant discharge (creek), frost mounds 0.5–1 m high
Gusinoe 1; 64.656010, 177.404789	River terrace; 25,8	425x275; 1227; 0,096	440x250; 1443; 0,120	25	442x255	Discharge from the lake Gusinoe 2, underground suprapermafrost waters; seasonal drainage; bogged shores, flooded lowlands, thermokarst in the coastal zone. 22; 5,82

Gusinoe 2; 64.652299, 177.394060	River terrace; 22,5	250x200; 743; 0,044	250x150; 806; 0,045;	2	250x141	Discharge from the lake Gusinoe 3, underground suprapermfrost waters; seasonal drainage; bogged shores, thermokarst in the coastal zone. 24; 5,6
Gusinoe 3; 64.655679, 177.385734	River terrace; 25	325x200; 753; 0,030	110x100; 406; 0,010	-67	120x84	Underground suprapermfrost waters; constant drainage; terrace 0.5 m high, shallows, frost mounds in the coastal zone.15; 5,4
Ovalnoe; 64.659132, 177.471565	Seashore terrace 2, slope; 21,6	510x275; 1640; 0,126	460x290; 1365; 0,120	-5	465x290	Underground suprapermfrost waters; seasonal discharge; two terraces 0.3–0.5 m high, thermal abrasion, overgrown shallows. 84; 5,93
Kotlovina; 64.651674, 177.458261	Seashore terrace 2, drainage; 23,4	312x180; 763; 0,033	230x100; 737; 0,030	-9	235x96	Drainage lake; steep shore 0.5–1 m high; overgrown sandy shore. 39; 7,02
Bokovoe; 64.647322, 177.452596	Seashore terrace 3, slope; 27,5	310x120; 753; 0,026	280x120; 817; 0,031	19	300x120	Suprapermfrost surface and underground waters, head; steep shore 1 m high; flooded lowland. 19; 6,11
Ostrovnoe; 64.645962, 177.427963	Seashore terrace 3, slope; 29,7	475x175; 1045; 0,042	240x90; 767; 0,017	-60	248x88	Suprapermfrost groundwater, constant discharge, bogged overgrown bottom, two terraces 0.5–1 m high, frost mounds, thermokarst in the coastal zone
Novoe; 64.663313, 177.462295	River terrace, head	125x75; 345; 0,008	140x140; 423; 0,013	63	-	-
Istochnoe; 64.663783, 177.301417; 33,9	Basin divide, saddle, head; 20,5	750x500; 1952; 0,196	620x410; 1684; 0,163	-17	-	-
Beloe; 64.617337, 177.327010	River terrace, slope; 54,1	425x275; 998; 0,055	Drained	-100	-	-
Pribrezhnoe; 64.540627, 177.404515	Seashore terrace 1, footslope; 10,8	573x475; 1536; 0,168	480x430; 1506; 0,153	-9	-	-
Gus; 64.551546, 177.355764	Seashore terrace 3; 27	625x300; 1786; 0,136	500x250; 1544; 0,094	-31	-	-
Uzkoe; 64.530183, 177.379367	Seashore terrace 1, footslope; 13	1000x250; 2322; 0,114	650x180; 1556; 0,081	-29	-	-
Mutnoe; 64.513347, 177.311217	Slope, head; 21,7	875x750; 3102; 0,486	130x90; 382; 0,009	-98	-	-
Mutnoe- Maloe; 64.515231, 177.323835	River terrace, slope; 21	425x400; 1203; 0,109	400x300; 1106; 0,094	-14	-	-
Uglovoe; 64.511094, 177.226073	Footslope; 37,4	650x575; 1865; 0,186	550x350; 1501; 0,144	-23	-	-
Istok; 64.656823, 177.099387	Basin divide, saddle, head; 82	400x250; 986; 0,068	310x170; 837; 0,047	-31	-	-
Mezhdurechnoe; 64.549186, 177.139899	Basin bottom, head; 61	575x325; 1625; 0,116	Drained	-100	-	Suprapermfrost underground waters; steep sloughing shore. Frost mounds and thermokarst in the coastal zone, deep surface flow path

Besstochnoe; 64.546604, 177.126166	Footslope; 62	325x175; 698; 0,030	400x220; 621 0,025	-17	-	-
Podgornoe; 64.545534, 177.143676	Footslope; 62	350x120; 684; 0,019	280x90; 667; 0,019	0	287x94	Suprapermafrost underground waters, springs, seasonal discharge; steep sloughing shore 0.3–2 m high. Solifluction. 15; 6,11
Verkhovoe; 64.546308, 177.182986	Slope, head; 65,8	425x230; 1063; 0,060	300x140; 720; 0,025	-58	-	-
Uvalnoe 2; 64.557926, 177.136895	basin divide, saddle top; 70	250x150; 619; 0,024	190x110; 489; 0,015	-38	-	-