Chapter

The Influence of Climate Warming on the Hydrological Regime of Thermokarst Lakes in the Subarctic (Chukotka, Russia)

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Abstract

Using remote methods and materials for meteorological observations, climate changes and the area of 36 thermokarst lakes located in the Anadyr lowland in Chukotka over a 65-year period were analyzed. More than 20 lakes were studied by field methods. With an increase in the average annual air temperature by 1.8°C and an increase in the amount of annual precipitation by 135 mm, the total area of the lakes mirror decreased by 24%. Cryogenic processes have had a significant impact on the decrease in the water quantity of lakes. Thermal erosion in drainage channels has led to multiple discharges of water in abnormally warm years. The heaving of permafrost in the coastal zone affected the reduction of the lake catchment area. If the trends of climate change continue, further drainage of large lakes and an increase in the number of small sag pond is expected in the next 25 years.

Keywords: thermokarst lakes, thermal erosion, active layer, global warming, Chukotka

1. Introduction

Periglacial plains of the Late Pleistocene in East Asia currently represent the distribution areas of thermokarst-drained lake basins (DLB). The beginning of the formation of lake basins is associated with climate warming and areal thermokarst at the turn of the Late Pleistocene and Holocene [1, 2].

The ratio of the total surface of lakes to the catchment in Arctic lowlands of the cryolithozone locally reaches 60%. Secondary thermokarst lakes are mostly located within the boundaries of the DLB on the terraces of river valleys and the sea coast. Such reservoirs are formed as a result of the melting of Holocene underground ice, which is accompanied by subsidence of the surface and filling of depressions with water. The area of thermokarst lakes varies from 0.001 to 20 km^2. The depth of most lakes is 1–1.2 m and rarely exceeds 3 m [2–5]. In winter, shallow reservoirs freeze to the bottom. The age of most modern thermokarst lakes in the DLB is several 100 years, exclusively up to a 1000 years [1, 3]. The water of the lakes has a brown color, contains a significant amount of dissolved organic substances, and is not suitable for water supply [4]. At the same time, the DLB, together with lakes, swamps, and floodplains of rivers, are ecologically significant wetlands: nesting sites for migratory birds, summer feeding of freshwater fish fauna, and spring pastures of wild reindeer [6]. Having a significant total area, lakes significantly impact the microclimate: they increase air humidity and reduce seasonal and daily temperature differences. In the summer, the runoff of the water of small rivers is provided, and excessive precipitation is deposited in the flood. Despite the ubiquity and duration of existence in the cryolithozone, thermokarst lakes are quite sensitive to interannual and long-term changes in water supply and runoff conditions. This prompted researchers from various fields of science to study the influence of modern climate warming on the water content of thermokarst lakes.

Global warming is not the result of an increase in solar activity, but is associated with changes in atmospheric air circulation on a planetary scale, which lead to an increase in air temperature [7–9]. Therefore, the ongoing climate changes should be considered as a shift of the boundaries of climatic areas in the latitudinal and meridional direction. In the high latitudes of the northern hemisphere, this is a redistribution of the zones of distribution of marine, temperate, and sharply continental subarctic and Arctic climates. The change in the location of the borders of climatic areas is accompanied by both an increase and a decrease in solar insolation, average seasonal air temperatures, as well as an increase or decrease in precipitation. The most contrasting and dynamic climatic changes in the arctic and subarctic occur in the transition zone from the ocean to the continent.

Regional transformations of climatic conditions have a corresponding impact on the water balance of territories. Depending on the type of changing climate, the atmospheric nutrition of water bodies, the intensity of evaporation, and river runoff vary in different ways. In general, this allows us to assume that knowledge about the trends of regional climatic changes and the rate of waterlogging of the lake is sufficient to predict the parameters of the lake's water content. However, the validity of this approach is not confirmed by the results of numerous remote studies of the hydrological regime of lakes in the subarctic lowlands of Eastern Siberia and North America [10–12]. In the cryolithozone, in areas with different climates and trends in its changes, the same type of changes is often recorded: the drainage of large lakes and an increase in the number of small reservoirs [1, 3]. This suggests that, along with the climate, the dynamics of the lake area is influenced by transboundary factors of changes in the hydrological regime, leveling the diversity of regional climatic changes. It is obvious that such a factor, given the thermokarst origin of lakes and the spread of permafrost in the subarctic, may be cryogenic processes, which are most affected by global warming and climatic fluctuations.

In this chapter, using the example of thermokarst lakes of the Anadyr lowland of the Bering Sea coast in Chukotka, changes in the area of lakes under the influence of climatic dynamics of seasonal melting, thermokarst, permafrost heaving, and thermoabrasion are considered. The scientific work is based on the results of research of predecessors, remote comparative analysis of cartographic materials from different years and, importantly, on field measurements of lake sizes and observations of cryogenic processes.

2. Predecessor studies

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 [13]. At the same time, it was noted that the interannual dynamics of climatic indicators does not affect the water capacity of the objects. In a later work, when studying the areas of distribution of rocks of the ice complex, an increase in the area of thermokarst lakes was noted in 1999–2013 by 0.89% and in 1999–2018 by 4.1% [14]. The work shows that changes in the total area of lakes within one area are subject to statistical laws [15]. Methodological aspects of remote retrospective analysis are considered in the case of the Eurasian lowlands [16]. 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 and track the changes in the water capacity in Yamal areas caused by anthropogenic impact [10, 17–19]. 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 [20]. An earlier study in western Alaska conducted in the period from 1949 to 2002 showed draining of 50 out of 7400 remotely analyzed lakes [11]. The reduction in the area of lakes in northern Canada is described by researchers [12, 21, 22]. The authors pay attention to the drainage of large lakes due to the formation of new ways of surface runoff. The problem of water discharge under abnormal weather conditions is considered in the example of lakes in northeastern Alaska [23]. 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 QinghaiTibet Plateau [24]. Researchers noted an increase in the number of small and large thermokarst lakes in 1969–2010.

Lakes and thermokarst in Chukotka and, in particular, in the Anadyr lowland began to be actively studied by geocryologists and hydrogeologists in the last century. Among the works in which the problems of genesis and transformation of water bodies are considered in detail, the works [3–5, 25] should be noted. Lyubomirov investigates the conditions of formation and evolution of the lakes of the Anadyr lowland (1990). Krivoshchekov analyzes the experience of recultivation of lakes for the cultivation of meadows (2000). Tregubov [4] and Ruzanov [5] focus on the applied significance of lakes as sources of water supply, and analyze the genesis of water bodies and their interaction with hydrogenic talics. The results of remote sensing studies of 8305 thermokarst lakes in the Anadyr lowland are presented (2013) in the work of Rodionova [16]. According to the interpretation of Landsat satellite images taken between 2009 and 2013, the surface area of 338 water bodies (4% of the sample) decreased by 86 km^2 (3.3%). And only one lake from the surveyed reservoirs has slightly increased its water capacity. Field observations were not carried out; Hydrological processes and overgrowth of reservoirs were named as the reasons for the change in the area of lakes. Case studies of recent years of Tregubov with co-authors characterize changes in permafrost and climatic conditions of the Anadyr lowland (2020) over the past 25 years and analyze climatic changes in the water balance [26].

Thus, in most studies, a decrease in the area of water bodies is recorded, and there is no evidence of activation of thermokarst during a more than 50-year observation period [27–29]. In a short series of observations lasting about 10–20 years, the authors noted the activation of thermokarst and an increase in the proportion of lake surface in basins due to the formation of new small deepening lakes [1, 19, 28–33]. At the same time, it is confirmed that the area of large lakes is decreasing. Surface water runoff, increased evaporation, accumulation of bottom sediments and overgrowth of reservoirs, complete thermokarst, thermal abrasion, and treatment of icy soils along the shores of lakes are indicated as the reasons for the drainage of basins.

Summing up the results of the review of studies of changes in area lakes of lowlands in the high latitudes of the northern hemisphere, we note the following:

1. Long periods of observations of changes in the number and area of lakes show a tendency to drain large reservoirs. The short-term analysis gives contradictory results about changes in the water content of lakes, which is probably due to interannual fluctuations in climatic conditions.

2. In subarctic regions, where intermittent and insular permafrost is becoming common, there is an increase in the water content of lakes and swamps with an increase in climate humidity. In the areas of occurrence of rocks of the ice complex, the authors record the preservation or a slight increase in the water content of lakes over the past 15–20 years.

3. Most remote studies are not confirmed by the author's field observations of reservoirs, the establishment of the causes of degradation of lakes, or the preservation of their morphology. Conclusions about the causes of dehumidification or increase are hypothetical.

4. When interpreting the results of the assessment of the lake character of lowlands and the water content of specific lakes, materials for monitoring seasonal thawing of the active layer and field observations of the activity of cryogenic processes due to climate fluctuations were practically not used.

3. The study area

The Anadyr lowland is located on the southeastern outskirts of Chukotka and covers an area of 35,000 km^2. The climate of the territory is subarctic, moderately continental, and marine. According to the Anadyr Meteorological Station, the average annual temperature for the period 1981–2010 is −5°C. The annual precipitation is 382 mm; most of it falls in winter. The thickness of the continuous permafrost decreases from 300 to 50 m from north to south, where it becomes intermittent. 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 flat landscapes is 45–55 cm. The area occupied by lakes ranges from 20 to 60%. Lake water is characterized by a bicarbonate-sodium composition, a neutral or slightly acidic reaction, and a low salinity of 15–30 mg/l. As for chemical composition of waters of the lakes located on low sea-shore terraces near the coastline of Anadyr Estuary, 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 brown color and contain increased concentrations of total iron.

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. Tomirdiaro classified most of the lowland lakes as thermokarst lakes [1]. Thermokarst lakes of the sinkhole type are located on elevated areas of the distribution of relict glacial landforms and permafrost of the late Pleistocene. These are relatively deep (3–5 m) lakes with an uneven funnel-shaped bottom, formed during the melting of ice deposits and subsidence of the surface. The most common secondary thermokarst lakes with a flat bottom and a depth of 1.2–3.0 m, occupying the bottom of DLB or flattened saddles of watersheds. The objects of our direct study included 36 lakes with an area of 0.01–0.50 km^2 located at a distance of 7–36 km south and southwest of the city of Anadyr (**Figure 1**). The reservoirs are located within the DLB, confined to the interridge watershed relief depressions (5)[1], gentle slopes (10), river valleys (15), and sea-shore terraces (6). The absolute marks of the water's edge vary from 8 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).

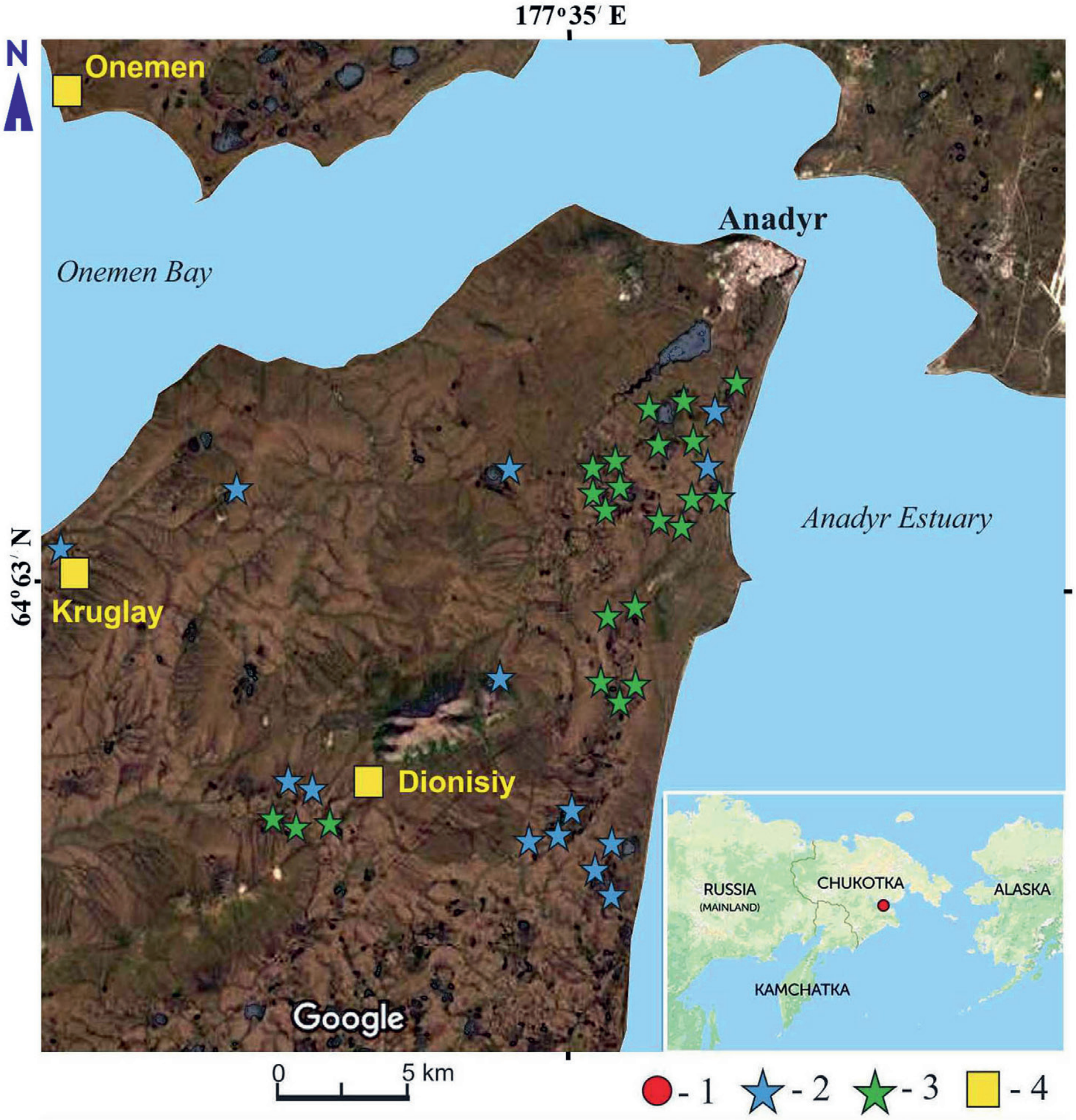

Figure 1.
Location of the study area: 1 – The study area on the inset map; 2 – Lakes studied on the basis of cartographic data; 3 – Lakes studied on the basis of cartographic data and field observations; and 4 – Monitoring areas of the active layer.

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[1] Here and below, the number of lakes is indicated in brackets.

The lakes are fed by summer precipitation; snowmelt water and summer melt water of seasonal and perennial underground ice. The melt water of the underground ice enters the lakes as part of the underground runoff of the suprapermafrost waters.

The dynamics of the depth of seasonal thawing was analyzed based on the results of long-term monitoring of the active layer (AL) at the facilities of the international CALM[2] program (see **Figure 1**). This is the "Onemen" site, which occupies the flat top of a tundra ouval with a height of 26 m, covered with hummocky moss and cotton. The site of "Dionisiy", covered with a bumpy yernikov moss-grass tundra, is located on a slope of 2–3° at the foot of the mountain at an altitude of 120 m. The "Round" site was laid in 2010 on the bottom of the DLB with polygonal relief and sphagnum-sedge vegetation. The absolute height of the bottom is approximately 6 m. In general, the plots represent typical landscapes of catchment basins and the bottom of the DLB.

4. Methods

The main objectives of the research part of the work were: statistical verification of the representativeness of lake area measurement data; analysis of trends in lake water content; identification of the causes and leading factors determining the hydrological regime of lakes in the conditions of modern climate change. At the preliminary, preparatory stage of the work, the boundaries of the research area were determined, and a list of lakes that are suitable for reliable remote and direct assessment of morphology and size was compiled. The laboratory research methodology is based on a comparative analysis on the same scale (1:25,000) of the contours of 36 lakes on a topographic map compiled on the basis of aerial photography in 1953 and satellite images from the Google Maps application based on the results of the 2018 survey (**Figure 2**). Morphometric characteristics of lakes, that is, perimeter, area, and linear dimensions, were determined using the Universal Desktop Ruler V. 3.8.6498 software. Statistical parameters of the lake (arithmetic mean, asymmetry, kurtosis, and frequency) were calculated using Microsoft Excel tools.

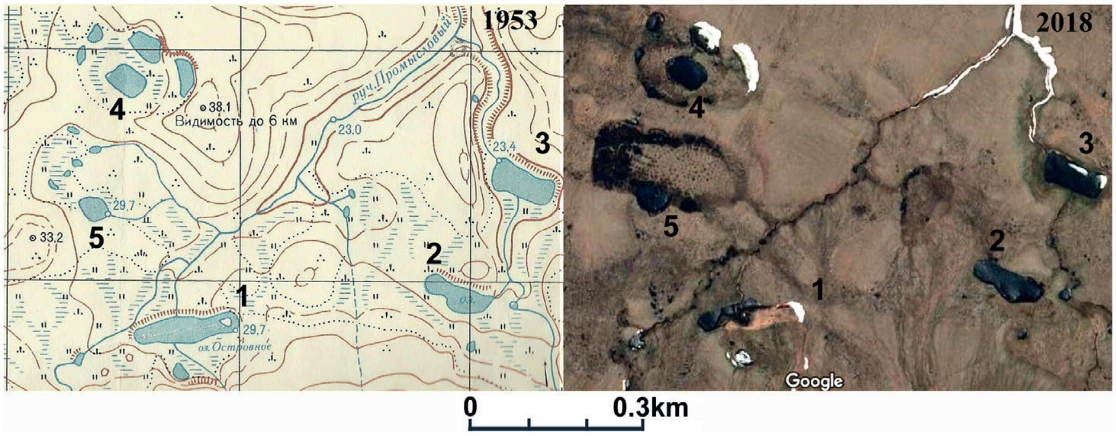

Figure 2.
An example of a comparative analysis of lakes in the valley of the creek Promyslovyy on a topographic map (left) and on a satellite image (right).

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[2] Circumpolar Active Layer Monitoring.

The field stage of the work took place in August 2020, and 22 lakes were surveyed. The technical capabilities of optical devices made it possible to study reservoirs with an area of 0.01–0.4 km^2. The transverse dimensions were measured using an RGK D1000 laser rangefinder. The measurement range was 3–1000 m; the technical accuracy at a distance of 500 m was 1.0–1.8 m (depending on weather conditions). The absolute height of the water edge of the lakes was determined by the elevation marks on topographic maps at a scale of 1:25,000. During field observations, the height of the water's edge was determined in accordance with the measurements of the GPS navigator (Garmin Legend HCx). Each reservoir was surveyed along the perimeter. We have received information about the state of coastal ledges, feeding streams, and surface runoff channels; we identified the landslip slope and determined the depth of lakes, the area of shoals, the composition of the bottom soil, groundwater outlets, as well as the salinity (electrical conductivity) and pH of lake waters. In the coastal zone, we recorded floodplain terraces, polygonal relief, ice mounds, and tand thermokarst depression lakes with a diameter of 3–15 m. The depth of seasonal thawing along the shores of lakes in swampy areas and on dry terraces was measured with a metal probe 1.2 meters long. Soil moisture was measured at a depth of 25 cm using a TK-100-01 moisture meter.

At monitoring sites measuring 100 × 100 m, the depth of thawing in the active layer was measured annually from August 25 to September 5 according to the 10 × 10 m scheme (Onemen since 1994, Dionisiy since 1996, Round since 2010).

5. Results

The results of statistical analysis of remote analysis data are shown in the diagrams below. The histogram shows the frequency distribution of lakes with different water capacity variability (**Figure 3**). Frequency distribution analysis is necessary in order to understand how homogeneous the data sample is. It was important to find out how many isolated frequency distributions were in the data array and, accordingly, the processes that determine the water content of lakes. One normal frequency distribution has been revealed, which is disrupted by a large number of reservoirs that have dried up by 90% or more. As it turned out, five of the eight such lakes were drained during land reclamation in the 1970s for the cultivation of meadows.

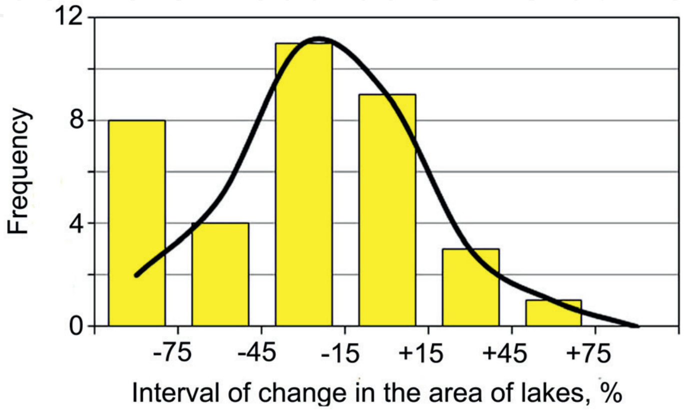

Figure 3.
Histogram of the frequency of occurrence of lakes with varying degrees of watering and drainage. The distribution graph is shown without taking into account lakes drained as a result of land reclamation.

After excluding them from the analysis, the empirical distribution acquired a normal form (see the distribution curve) with an average percentage decrease in the water surface area of −0.24 (−24%), a standard deviation of 0.36, an asymmetry of −0.31 and a peak kurtosis of 0.52.

Pie charts show the ratio of changes in the area of lakes in groups with different runoff conditions (**Figure 4**). Closed lakes that do not have surface runoff paths have preserved their water surface area to the greatest extent. Feeding and drainage such lakes occurs as part of the suprapermafrost waters of the active layer. Among the reservoirs with seasonal runoff during high water, the drained lakes are twice as large as those that have preserved or increased their area. Lakes with constant flow and flowing lakes represent a variety of changes in water content. At the same time, among the flowing lakes, there are the largest number of reservoirs that have increased their area by 45–75%, but there are no lakes with an increase in water content within 45–15%. There is also a surprisingly small amount in the drainage range of 55–25% among closed lakes and lakes with seasonal wastewater (see **Figure 4**).

A pointed diagram of the distribution of lakes by the absolute height of the water's edge shows two clouds of scattered objects separated by an interval of heights of 40–60 m (**Figure 5a**).

In the relief of the territory, this interval of heights corresponds to the foothills of hills covered with a plume of deluvial sediments and tundra ridges, remnants of the 3rd marine terrace, composed of ice-bearing glacial–marine sediments belonging to the early interglacial transgression. This explains the absence of lakes at these heights. In another dot graph, lakes are grouped according to their original size (**Figure 5b**). The dissipating cloud bounds an almost isosceles triangle with an area of 0.2 km^2 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

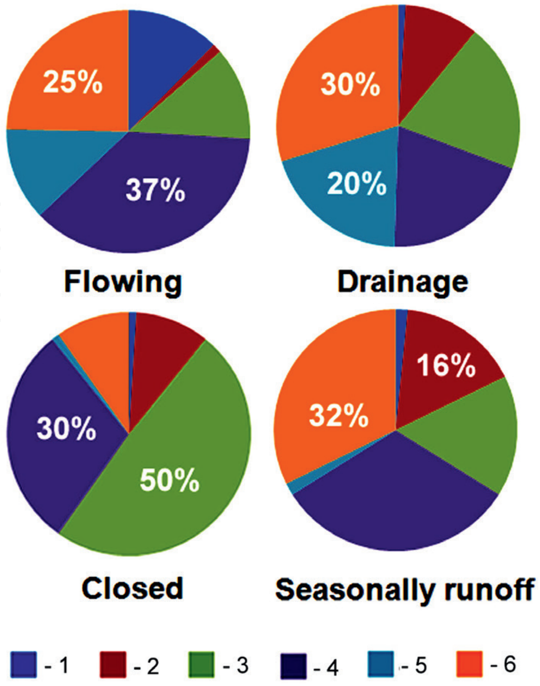

Figure 4.
The ratio of the number of watered and drained lakes in groups with different flow conditions: 1-2 — lakes whose area has increased significantly: 1 – 1,75:1,45; 2 – 1,45:1,15; 3 – lakes without significant changes 1.15:0.85; 4-6 — lakes in which there was a decrease in area: 4 – 0.85:0.55, 5 – 0.55:0.25, and 6 – 0.25:0.

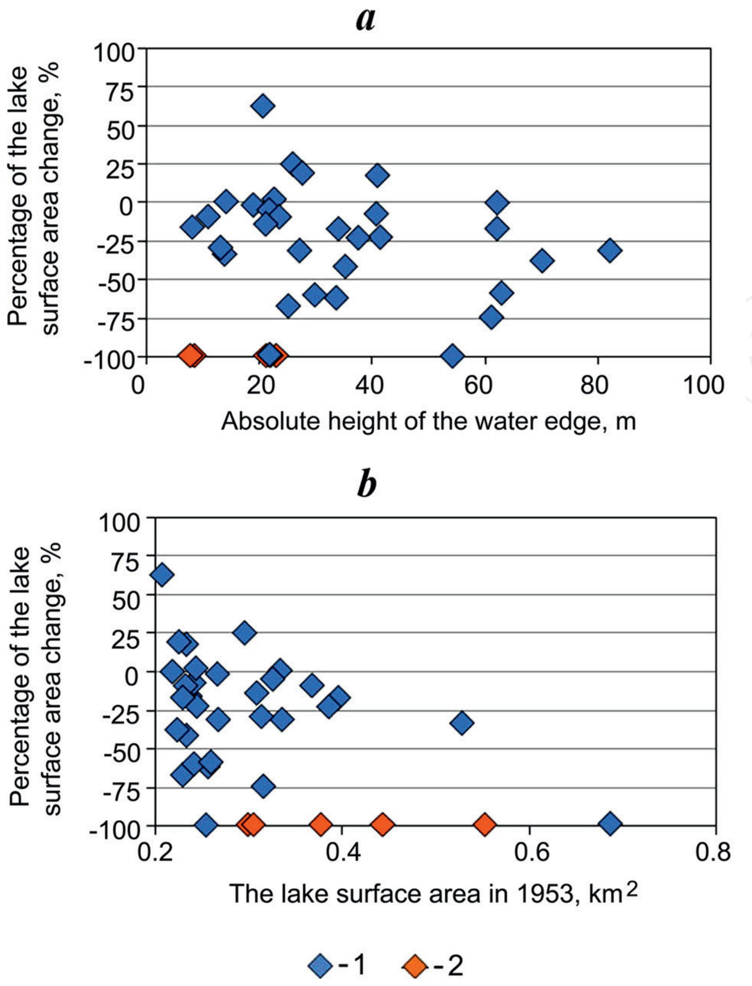

Figure 5.
Distribution of lakes with different degrees of drainage – Watering, depending on hypsometric position (a) and area of water bodies according to aero photos taken in 1953 (b): 1 – Lakes without traces of technogenic impact, and 2 – Lakes with proven facts of melioration.

because the 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.

The results of field measurements of reservoirs showed that the size of seven lakes remained virtually unchanged; five lakes were completely dry; in three lakes, the water surface area increased; and in seven lakes, it decreased. Compared with the result of the analysis of satellite images in 2018 (June), the deviation of the observed parameters, i.e., the increase in the area and drainage of the shores of the lake, in 2020 from the calculated ones was 5–10%. The morphology of the shores (open shoals or flooded shores) indicates that this is a consequence of the interannual dynamics of nutrition and runoff of water bodies. The size of open reservoirs with low, swampy shores, and small swampy catchments has decreased. The field transverse dimensions of thermokarst, seasonally open, and drainage lakes, which make up 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 the presence or absence of lake terraces, the degree of development of thermal erosion, thermokarst, and thermal abrasion along the shores, 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 (**Figure 6a**). 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% (**Figure 6b**). Vegetation cover is represented by 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 (**Figure 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 southeast. Among the general regularities, more or less inherent in all lakes, there is a combination of a coastline of ledges and 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 ice wedges of

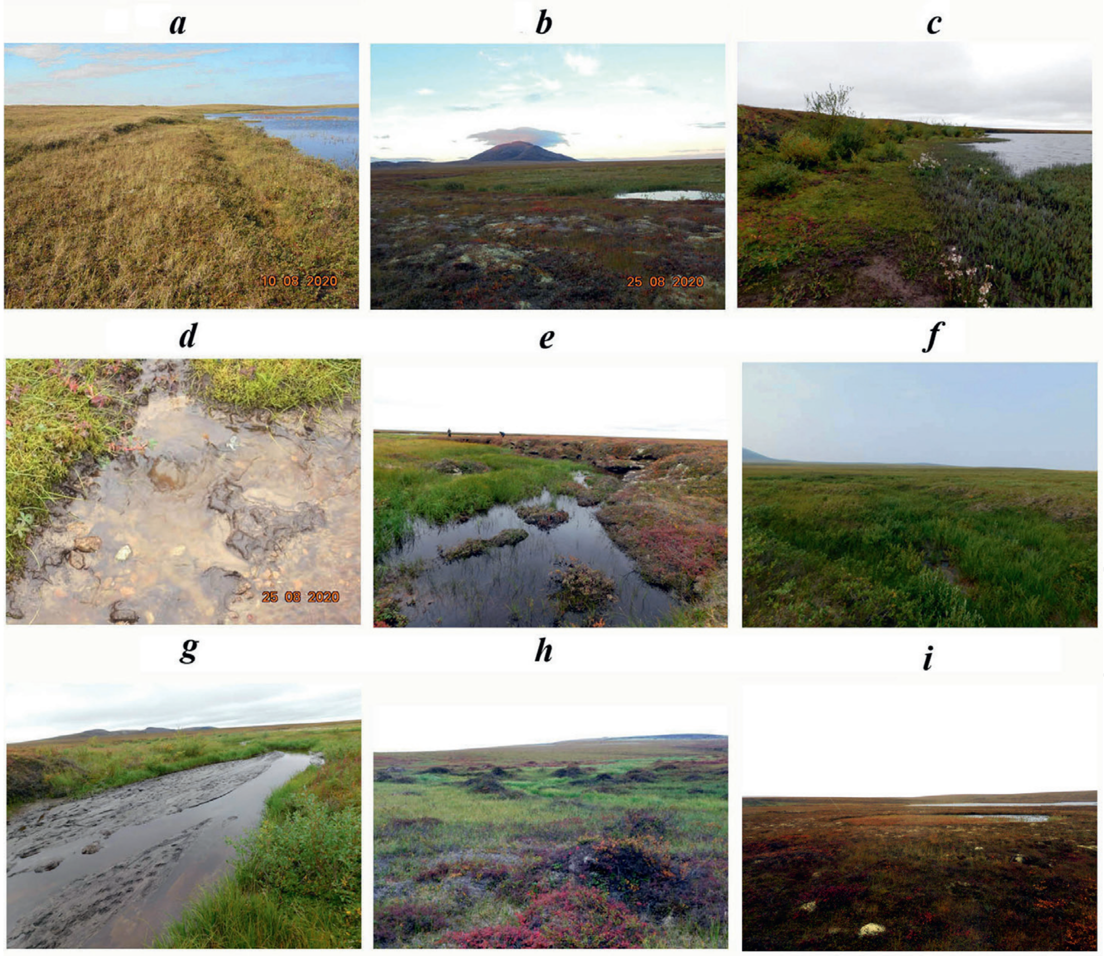

Figure 6.
Field observations of the coastal zone of the lakes of the Anadyr lowland: A – Ledges of lake terraces, b – Polygonal dwarf shrub tundra on the upper terrace of the lake, c – large shrubs along the shore at the foot of the tundra ouval, d – Sources of suprapermafrost waters on the lake shore, e – Thermokarst and thermal erosion along the drainage channel, f – Newly formed drainage channels along the thawed ice of polygons, g – Traces of water discharge from the drained lake into the channel, h – Permafrost mounds along the shores of the lake, i – and Thermokarst lake-saucer 30 m from the drying lake.

the first DLB terrace or preexisting inter-lake channels widened and deepened by thermokarst and thermal erosion (**Figure 5d** and **e**). In the coastal zone of lakes at the foot of tundra ouval, there are often mounds of permafrost heaving 1–1.5 m high (**Figure 6h**). The low shores are characterized by small thermokarst lakes-saucers 5–15 m across (**Figure 6i**).

The bottom sediments of the lakes were studied from the ice in the winter of 2021 and earlier, in 2010, when determining the depth of thermokarst lakes and the thickness of the ice [18]. The bottom sediments are represented by a layer of black organic silt 0.4–0.5 m thick. Depending on the position in the relief and the geological structure of the territory, the silt layer is underlain by peat, sandy loam, or loam.

Monitoring of the depth of seasonal thawing of the active layer of the Anadyr lowland is limited to a 29-year period (**Figure 7**). During the observation period, the depth of thawing at the Onemen control site, which occupies an autonomous position in the relief, increased by 13 cm, or 31% of the initial value. A slightly smaller increase in the depth of thawing (by 22%) was observed in the transit (trans-water) conditions of the Dionisiy site. The intermediate position is occupied by the superaqual landscape of the "Round" site. Taking into account the retrospective interpolation of the data, the increase in the thickness of AL within its limits was 9 cm, or 26%. All landscapes are characterized by fluctuations in the depth of seasonal thawing, lasting from 2.7 to 9–11 years. The average annual temperature of the active layer in the depth range of 20-50 cm at the Onemen site increased by 2.5°C over 20 years of observations. The average 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 **Figure 8**. These are the shores of two secondary thermokarst lakes: gentle boggy (point 1) shore of the closed 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 **Figure 8b** and **c**).

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

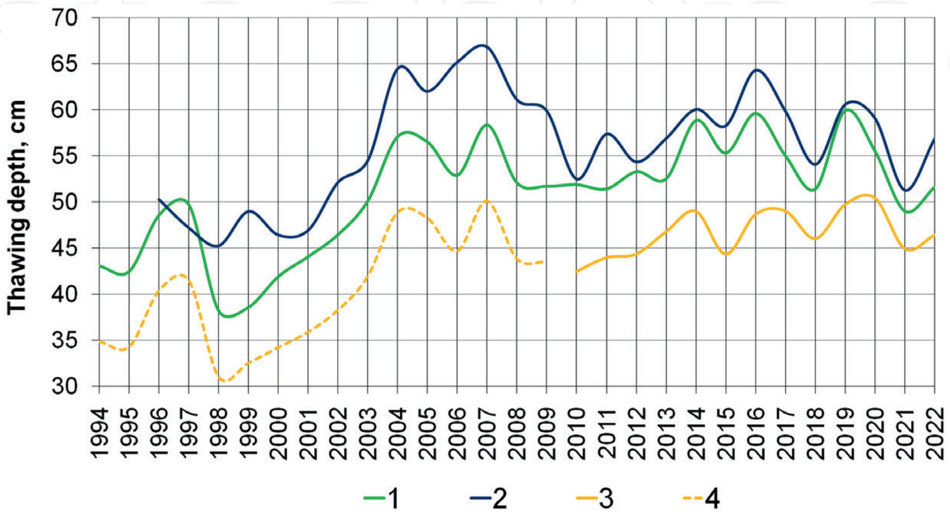

Figure 7.
Dynamics of seasonal thawing at the active layer monitoring sites CALM: 1 – Onemen (Rogozhnyy), 2 – Dionisiy, 3 – Kruglaya, and 4 – Kruglaya (retrospective).

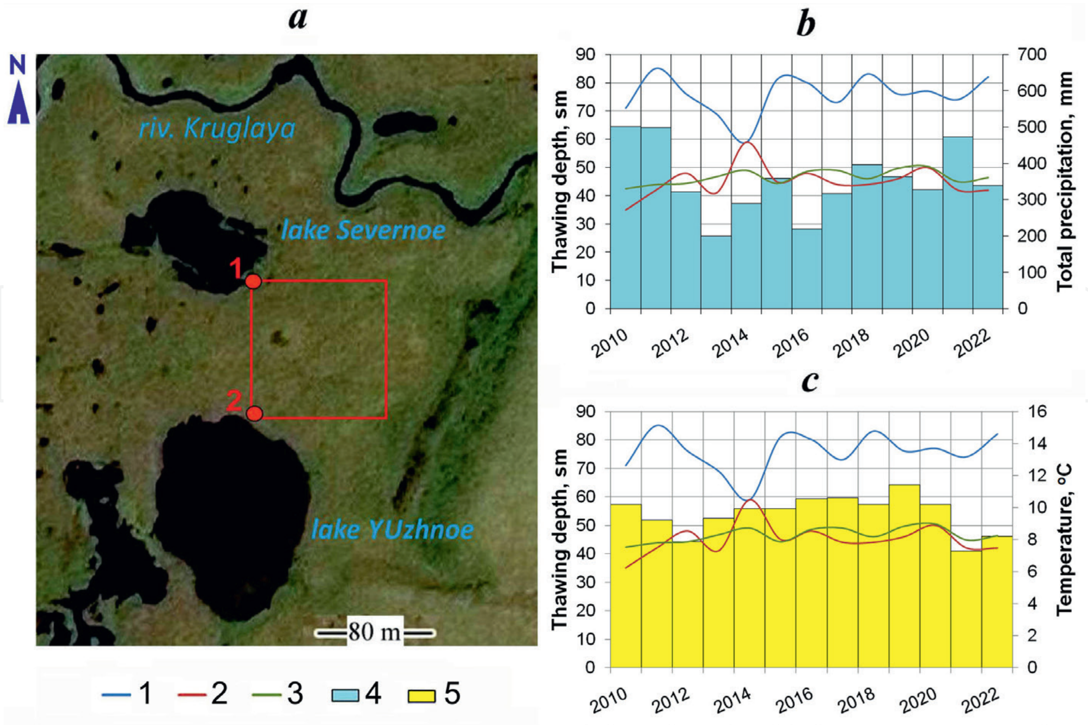

Figure 8.
The dynamics of seasonal thawing at the "Kruglaya" site (a) against the background of changes in annual precipitation (b) and summer air temperature (c): The depth of thawing at point 1 (1), at point 2 (2) on average over the area of the site (3); 4 – Annual precipitation; and 5 – Average air temperature in the frost-free period of the year.

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 **Figure 7b**). Such phenomena, 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 tundra's as compared to tundra bogs.

The dynamics of air temperature and annual precipitation are shown in **Figure 8**. The graphs are compiled from observations at the Anadyr weather station. From the middle of the last century to the present, the average annual air temperature has increased by 2.1°C with fluctuations from year to year by 1.5–3°C. At the same time, the air temperature in summer increased by 1.6°C, and in the cold period - by 3.0°C. Annual precipitation increased by 61.6 mm, with the amplitude of interannual fluctuations up to 300 mm. The increase in precipitation was due to an increase in the number of snowfalls. Over the past 25 years, the air temperature has increased by 1.7°C. During this period of time, the annual amount of precipitation has practically not changed and has reduced the amplitude of fluctuations. The duration of the frost-free period in the region increased by 12 days with an average value of interannual fluctuations of 5 days.

6. Discussion

The tangible impact of global warming on the climate of the Anadyr lowland has been recorded since the late 90s of the last century. This does not contradict the known data on climate change in the Arctic and Subarctic. Climate changes in the region are expressed in the reduction of continental influence and the expansion of the boundaries of the subarctic marine climate area. This happens due to an increase in temperatures and an increase in precipitation during the cold season. Winters become warmer and snowier; the warm period increases its duration but remains cool enough with the same amount of precipitation. Such climate changes should contribute to increasing the inbound part of the water balance and preserving the water content of lakes. However, the results of remote studies and field observations reveal a different picture.

Elementary statistical analysis of lake area measurement data has shown that the size of water bodies tends to decrease. The average value of the sample is −24%; the confidence interval for a normal distribution with a 95% probability is in the range from +46.6% to −94.6% of the change in the area of lakes. That is, under the conditions of climate change over the past 65–70 years, it is a statistical norm that only 1/5 of the lakes have retained and increased their water content to 12%, and the remaining lakes have reduced the water surface area to 60%. This conclusion is not contradicted by the data shown in the pie charts (see **Figure 4**).

To analyze the possible hydrological and geomorphological causes of drainage, let us turn to the facts. The smallest losses of the water mirror area are inherent in closed lakes. The change in the area of lakes is associated with their position within the DLB and the relative excess of the water level above the erosion base. Lakes located in the upper reaches of streams or occupying the upper position in the cascade of lakes turned out to be significantly drained. These lakes are characterized by the formation of new or deepening existing surface runoff paths. In most cases, the lakes located on the edge of the DLB at the foot of the slope have retained their water content. This is due to the larger catchment area and stable supply of lakes with suprapermafrost waters. At the same time, there are exceptions to the patterns described above. For example, one of the lakes, oriented by the rose of the winds of the warm period, increased the area by 18% due to thermal abrasion of the windward shore. Another example is a small lake on a river terrace, the area of which has increased by 63% due to the activation of thermokarst along the ledge of the above-floodplain terrace with underground ice. A closed thermokarst lake with an area of 0.35 km^2, located at the bottom of the DLB, for unknown reasons reduced the water surface by 33%. The decrease in the area of a group of lakes by 17–60%, located at the foot of the slopes of tundra hummocks, cannot be interpreted. Thus, information about the conditions of the location of lakes that contribute to their drainage or preservation of water content is not enough to predict hydrological processes.

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. 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 (see **Figure 9**). 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. Positive temperature extremes correspond to the maxima of interannual fluctuations in the depth of seasonal thawing. These facts, as well as the field observations of the authors, allow us to present the stages of formation of lake water discharges as follows:

1. Maximum seasonal melting in conditions of dry hot summer, long autumn, and warm snowy winter. In such years, thermokarst is activated in the channels of the channels, and in winter nonfreezing talik zones are formed.

2. With the beginning of the flood, the channels of lake channels are subjected to thermal erosion; they deepen and ensure the flow of meltwater. The massive discharge of lake water falls on summer-autumn floods caused by prolonged rains.

3. In the years following the draining of the lake, the riverbed is closed due to siltation and landslide of the eroded and thawed banks. Drainage channels become useless. With sufficient precipitation, the bottom of the lake is filled with water. In case of insufficient precipitation, the bottom of the lake becomes overgrown and turns into a tundra swamp or a grassy meadow.

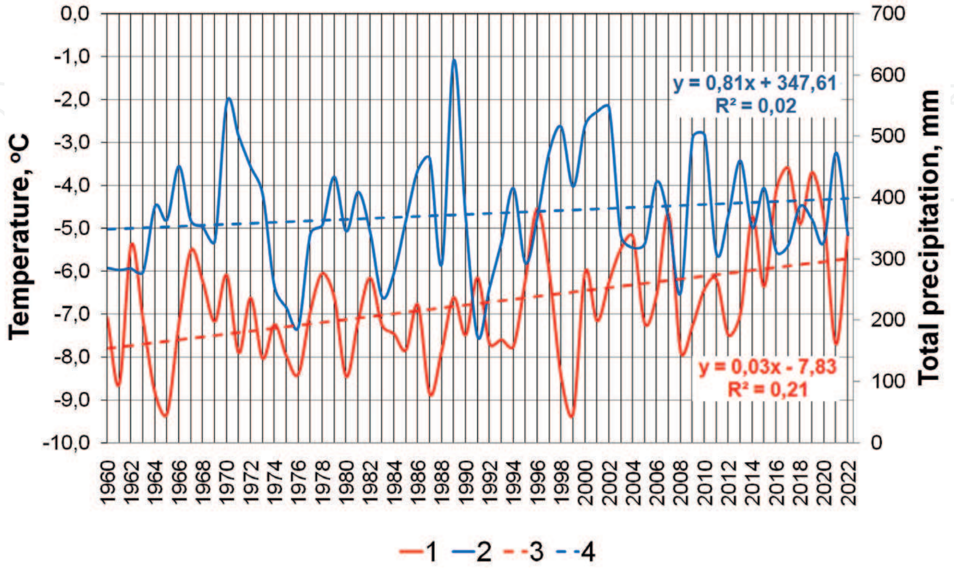

Figure 9.

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, and 4 – Linear trend of total precipitation.

Discharges as a reason for the drainage of the DLB were noted in [22, 23]. 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 of Anadyr, one of the studied lakes with a constant flow, which is often visited by hunters and gatherers of wild plants, has been drained three times since 1994 and refilled with water.

Despite the attractiveness of the salvo discharge model as a reason for the drainage of lakes, it does not explain the slow and partial decrease in the area of reservoirs. In most of the surveyed lakes, the water surface area has decreased by 15–45%, and they do not contain any newly formed elements of drainage paths. Among these reservoirs, there are many closed or seasonally open lakes, differing in catchment area. The last remark does not allow us to unambiguously associate the drying of these lakes only with an increase in evaporation, since lakes with a large catchment area should suffer less from a decrease in precipitation and an increase in average annual temperature. The results of the analysis of the dynamics of seasonal thawing of the shores of Lake Severnoye (see **Figure 8**), coupled with observations of frost heaving in the coastal strip of drying reservoirs, allowed us to put forward a cryogenic hypothesis about their partial natural drainage. The assumption is based on the interaction of lakes with the suprapermafrost DLB aquifer. **Figure 10** shows a schematic model of this interaction. With a constant amount of annual precipitation and the depth of seasonal melting, the water surface area and reservoir depth are in equilibrium (**Figure 10a**). During floods, the lake feeds the aquifer of the active layer. This happens in summer due to the reverse filtration of excess lake water through the deeply thawed active layer of the coastal strip. Reverse underground runoff into the lake occurs during the summer dry season and at the beginning of winter through when the water level in the lake decreases. In the conditions of sharp interannual fluctuations of climatic parameters, the dynamic equilibrium is disturbed. A decrease in precipitation and an increase in the average annual temperature lead to increased evaporation, a reduction in the area of the water surface, drainage of low shores and shoals. This, in turn, leads to deeper freezing and a decrease in the depth of seasonal thawing of the coastal strip (see **Figure 10b**). Therefore, for example, during the 10–year observation period, the interannual decrease in the area of Lake Severnoye reached 27% – the water retreated from the control point (No. 1) by 6 m. This happened in 2014, while the annual precipitation in 2013 decreased to 200 mm (see **Figure 8b**). When the low shores are drained, the suprapermafrost aquifer is separated from the lake by a frozen partition and forms two unequal areas – coastal and drainage. The dependence of the lake's nutrition on the catchment area decreases. As a result, drying increases and reaches a maximum in 1–2 years after a decrease in precipitation. Within the catchment area in the upper permafrost layer, with an increase in the depth of thawing, thermokarst begins along ice horizons and veins of underground ice, which is accompanied by the formation of subaerial talik zones. The subsequent freezing of thawed watered soils leads to the formation of heaving mounds (**Figure 6h**).

As a result, after the establishment of a new dynamic equilibrium, several catchment basins coexist in the DLB: primary catchments of large drained lakes, reduced in area; many small catchments of newly formed thermokarst saucer lakes; catchments of marsh streams, bounded by embankments of permafrost. That is, while maintaining the overall water balance of the territory, the appearance of lake-swamp landscapes changes to one degree or another.

The ongoing changes in the DLB have a negative impact on wetlands: newly formed shallow reservoirs are subject to interannual climate fluctuations and are not favorable for the nesting of waterfowl and feeding of ichthyofauna. Drying up reservoirs are no longer able to regulate the microclimate of the basins to the same extent.

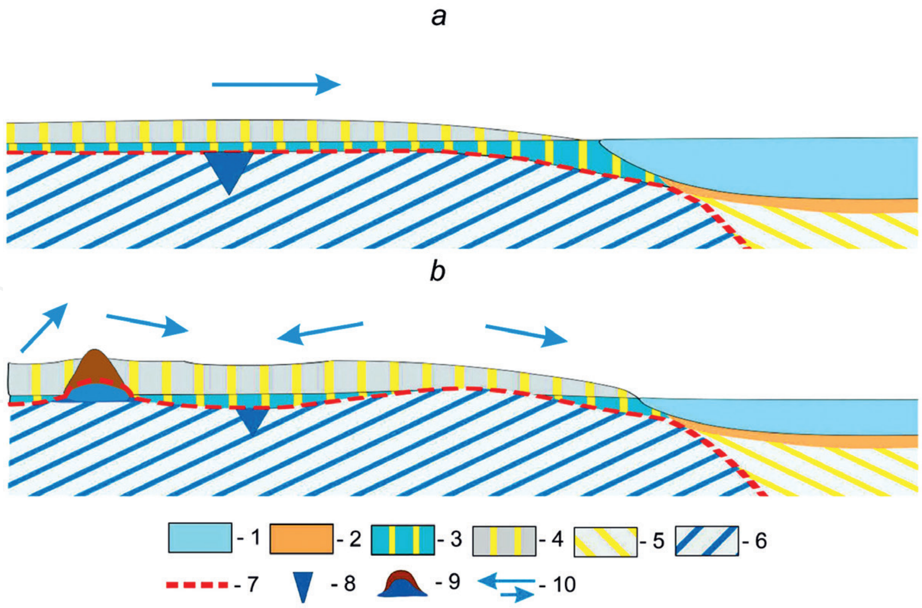

Figure 10.
Model of the interaction of lake waters and the suprapermafrost aquifer in static climatic conditions (a) and with climate warming (b): 1 – Lake; 2 – Bottom sediments; 3 – Suprapermafrost aquifer; 4 – Active layer; 5 – Talik zone under the lake; 6 – Permafrost; 7 – Roof of permafrost; 8 – A stylized image of wedge-shaped ice; 9 – Mounds of heaving permafrost; and 10 – The direction and intensity of water exchange (description in the text).

The proposed dynamic model of cryogenic processes affecting the water content of lakes and the density of their distribution is not universal. But it partially explains the paradox of the simultaneous development of thermokarst in the lower part of the DLB and the formation of new wedge-shaped ice on the upper terraces. Simultaneous weakening of thermokarst along the shores, drainage of large lakes with the formation of new local point thermokarst lakes. These, in fact, opposite natural processes have confused researchers many times and have not received a proper explanation [1, 3, 24, 30, 31, 33].

7. 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 to 0.5 km^2, 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 suprapermafrost 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

suprapermafrost 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 suprapermafrost horizon. The coastal zone of drying lakes is 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.

4. The undoubted advantage of this work is the emphasis on modern cryogenic processes in the coastal zone of lakes and in their catchments as a whole. This allows us to consider the impact of global warming on the lakes of the Arctic lowlands through the prism of climatic activation of cryogenic processes. Unfortunately, the authors do not yet have the opportunity to conduct coupled field and remote studies of the dynamics of water content in DLB lakes on the Bering Sea coast in North America, which would allow us to assess the degree of universality of the proposed models of exogenous cryogenic lake drainage. A logical continuation of the conducted research can be the organization of systematic instrumental observations of the water level and runoff of typical thermokarst lakes of the circumpolar lowland of the cryolithozone by analogy with monitoring of the active layer.

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