ISSN 1875-3728, Geography and Natural Resources, 2023, Vol. 44, No. 3, pp. 253–259. © Pleiades Publishing, Ltd., 2023.
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REGIONAL PROBLEMS OF ENVIRONMENTAL STUDIES AND NATURAL RESOURCES UTILIZATION

Giant Taryn Aufeis in the Northeast of Russia

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Received August 8, 2022; revised November 20, 2022; accepted April 5, 2023

Abstract—This article describes the compilation procedure and contents of the Atlas of giant taryn aufeis, a specific form of glaciation in the northeastern part of the Eurasian continent resulting from the freezing of groundwater that has come to the surface. The Atlas consists of two parts: analytical with illustrations and cartographic. Part I presents an overview of the extensive history of research on aufeis and the results of the digitization of small-scale maps that describe the dependence of aufeis fields on permafrost–hydrogeological, hydroclimatic, geomorphological, and geotectonic conditions. A special section of the Atlas is devoted to hazardous glacial and permafrost–geological phenomena that affect the engineering development of the territory. The results of the study indicate that about 5% of the territory of northeastern Russia can be described as an aufeis-prone zone. Part II of the Atlas contains over 100 maps of the distribution of taryn aufeis along the basins of major rivers of northeastern Russia (Yana, Indigirka, Kolyma, Anadyr, and Penzhina). The maps indicate the current positions and sizes of about 7000 aufeis fields as identified from Landsat and Sentinel-2 satellite images; they are compared with the Cadastre of Aufeis by A.S. Simakov and Z.G. Shil'nikovskaya (1958). An analysis of the data has revealed ambiguous trends of changes in aufeis fields. On the one hand, their number increased by the 21st century, but, on the other hand, the total preablation aufeis area decreased. Information on retrospective and current locations of aufeis fields is presented in the form of a digital database for large rivers of northeastern Russia. Most of the data collected in the Atlas requires detailed analysis.

Keywords: permafrost, aufeis resources, aufeis regulation, distribution and dynamics of aufeis, mapping, aufeis hazard

DOI: 10.1134/S1875372823030010

BACKGROUND

The first detailed descriptions of taryn aufeis were made by Alexander von Middendorff (1815–1894), Karl von Ditmar (1822–1882), and Gerhard von Maydell (1835–1894) during their travels through Eastern Siberia in the middle of the 19th century [1–3]. However, the systematic study of taryn aufeis began only 100 years later. In 1939, an expedition to the basin of the river Indigirka was undertaken with the purpose of determining what water reserves are responsible for dozens of square kilometers of aufeis present in the middle of continuous permafrost in freezing Siberian winters. It took only 3 months for the researchers to reach a very significant conclusion: the aufeis are maintained by large sources of sub- and intrapermafrost groundwater [4]. This conclusion defined the opportunities for water supply to the developing mining industry in the northeast of Russia [5]: taryn aufeis began to be used as the primary indicative sign for locating groundwater deposits [6, 7].

In 1947 the Northeastern Geological Department of Dalstroy commissioned two geologists (Simakov and Shil'nikovskaya) to compile a cadastre and a map of taryn aufeis in the northeast of the country [8, 9] to be used to assess the potential water resources of the region. The necessary information was obtained based on black-and-white aerial photographs, topographic maps, and field observations of geological parties. The work took 10 years. The handwritten map of the aufeis created by the geologists consisted of 10 sheets of scale

1 : 2000000, which were photo-reproduced in up to four copies of scale 1 : 5000000. A total of 7 448 aufeis with areas ranging from 0.01 to 81.1 km^2 were recorded. The cadastre of aufeis contains information on their names (generally assigned based on the name of the river), the size of aufeis glades, aufeis area at the date of detection, and the method of ice fixation. According to ground observations on 245 aufeis fields, the average ice thickness was calculated to be 3 m. The total volume of aufeis in the northeast of the Soviet Union was estimated at 31.5 billion m^3.

Based on [8, 9], dynamic groundwater reserves of the northeastern part of the Soviet Union were calculated; the volume of aufeis nourishment and runoff was estimated [10, 11]; and patterns of spatial distribution of aufeis [12] and their relationship with other forms of glaciation [13, 14] were identified.

By the present, the needs of the developing local mining industrial and social infrastructure related to the efficient use of hydroclimatic resources have significantly changed. New methodological research methods have been developed, the technical base has been improved, and it has become possible to obtain isochronal data on aufeis phenomena across extensive territories through serial aerospace imaging [15]. The introduction of unmanned aerial vehicles opened up broad opportunities for studying seasonal and long-term dynamics of aufeis phenomena. All that prompted the team of authors, a group of young scientists, to develop a long-term program for studying taryn aufeis on the new information and methodological platform. The first stage of the program was the project of creating and publishing the *Atlas of Giant Taryn Aufeis of Northeastern Russia* [16] (hereinafter the Atlas). The purpose of the Atlas is to obtain up-to-date data on the distribution, morphological features, and dynamics of groundwater aufeis in the Verkhoyansk-Kolyma orogenic belt and the Chukchi Peninsula and also to assess their role in the formation of water resources and cryogenic hazards in the region.

Work on the Atlas involved solving the following tasks:

(1) perform an information search and analysis of materials on aufeis and aufeis processes in northeastern Russia accumulated over the past 150 years, compile a historical overview of the data, and develop a draft layout of the Atlas;

(2) digitize cadastre data and aufeis maps and historical maps containing information about hydroclimatic, geological, and permafrost conditions in the region; bring figures from literature sources to a uniform format; extract data from graphs given in publications on aufeis for further analysis;

(3) select satellite images of different scales and flight dates for the purposes of studying aufeis phenomena and assess their data capacity and resolution; select methods for detecting (decrypting) aufeis and aufeis glades in satellite images;

(4) determine the contours and location (coordinates) of aufeis fields on satellite images and topographic maps; calculate morphological characteristics of aufeis (area, length, width, and perimeter); adjust the indicators to the time of maximum development (the beginning of ice ablation); compare the results with data of the cadastre [9] and the aufeis maps created by A.S. Simakov and Z.G. Shil'nikovskaya [8];

(5) compile databases for the main basins of the rivers Yana, Indigirka, Kolyma, Anadyr, etc.; calculate the current indicators of aufeis content and aufeis resources of the region.

MATERIALS AND METHODS

The main work on digitizing historical maps, including aufeis maps [8], in the form of a point dataset was carried out using the ArcGIS software. Figures were created in Adobe Illustrator; data from graphs were extracted with GetData Graph Digitizer and then processed in Microsoft Excel.

Modern-day location and characteristics of aufeis were determined on images from the Landsat-8 satellite (OLI radiometer) obtained after the melting of seasonal snow cover. Over 100 scenes were processed in total; the earliest of the selected survey dates is May 15 and the latest is June 26. The images were downloaded from the US Geological Survey web service [17]. More than 50% of all aufeis data were obtained from images taken from May 31 to June 6, 2016, a period of continuously relatively cloudless weather. The method of identifying aufeis based on Landsat data is described in [18].

For each aufeis identified on satellite data, the following main characteristics were determined: the date and identifier of the satellite image on which the aufeis was identified, aufeis area, and average aufeis height according to GMTED-2010 DEM data [19]. For aufeis with an area greater than 0.1 km^2, length and maximum width were also calculated.

The availability of the aufeis cadastre made it possible to perform mutual verification of retrospective and satellite data. The verification was based on determining adjacent (nearest) objects between the point layer of aufeis based on cadastre data and the polygonal layer obtained from Landsat images. Aufeis comparison was based on two criteria: the maximum distance between the compared aufeis does not exceed 5 km, and they are located in the valley of the same watercourse or within the same aufeis glade.

The data on current locations of aufeis obtained from satellite images and a digitized map [8] in the form of a point dataset with data sourced from the aufeis cadastre [9] were used to create and register databases on aufeis located in basins of large rivers of northeastern Russia.

Trends in year-by-year changes in aufeis were analyzed based on satellite mapping data from the satel-

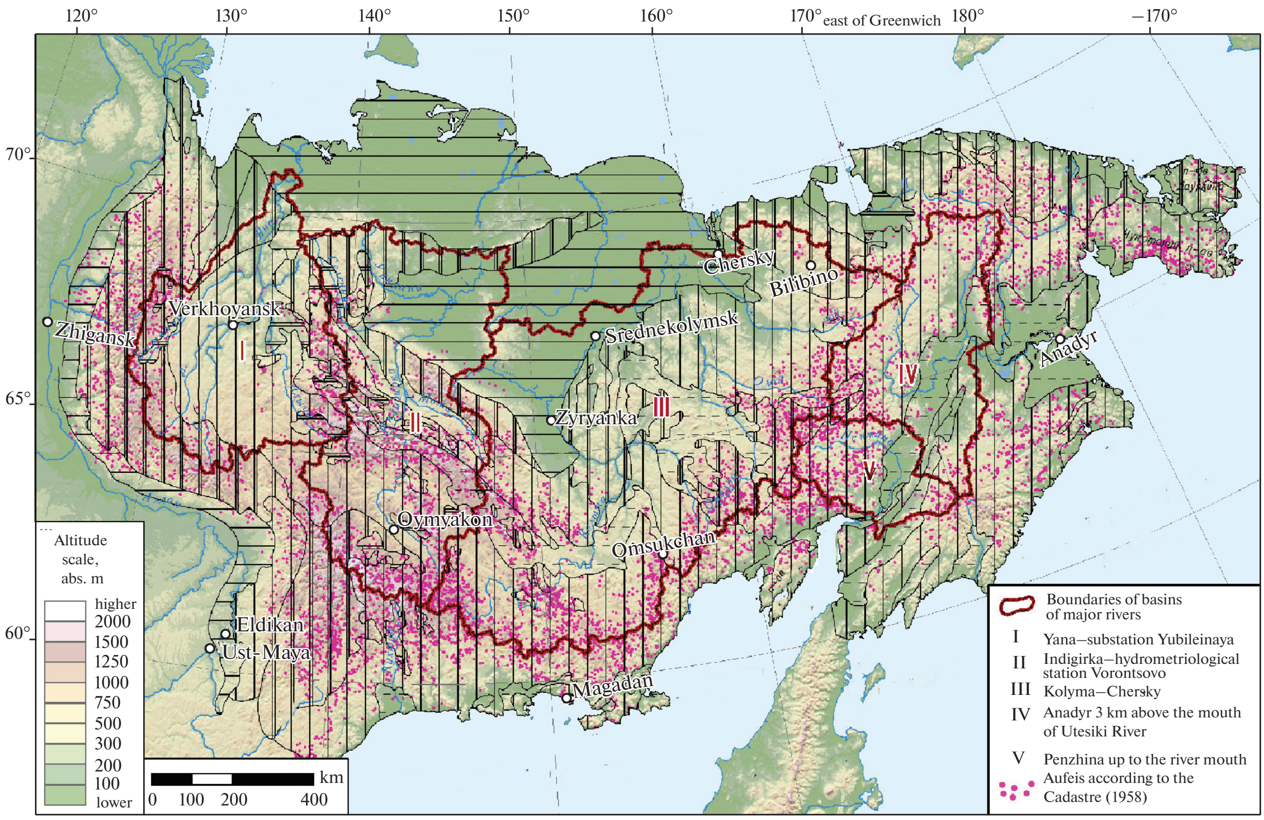

Fig. 1. Map of permafrost conditions of hydrogeological structures based on the materials of Tolstikhin [7]. Example of a digitized map from Part I of the Atlas of taryn aufeis [16].

lites Landsat-1 (MSS sensor, 1973–1974), Landsat-7 and 8 (2000–2019), and Sentinel-2 (2019); an analysis of the area of individual aufeis within a single year was conducted for 2019.

Field recordings of aufeis and aufeis landscapes were obtained using unmanned aerial vehicles: DJI Phantom 4 pro v2.0 and DJI Mavic Air 2 quadcopters. Video and photo recordings were taken from a height of 10–500 m.

Aufeis areas were determined based on satellite images for the survey date. Maximum preablation aufeis areas were calculated using the method of B.L. Sokolov (1975) [11], which provides estimates of the proportion of aufeis area that decreased over a certain period. The calculations require the following information: aufeis area on the satellite image, survey date, the absolute height of the position of the aufeis, and the date of the steady transition of the average daily air temperature to above 0°C (taken as the ablation start date) according to the nearest meteorological station. The earliest ablation start date (April 23, in the Kolyma River basin) and the latest (May 12, in basins of rivers of the Chukchi Peninsula) were determined.

Aufeis resources were calculated based on the following dependence: $W = \alpha F^n$, where W and F are aufeis volume (thousand m^3) and area (thousand m^2), respectively; $\alpha = 0.75$; $n = 1.12$ [20]. The calculations used the maximum area of individual aufeis, determined using Sokolov's method [11].

RESULTS AND DISCUSSION

Atlas Structure

The Atlas consists of two parts: analytical with illustrations and cartographic.

Part I presents an overview of the history of the study of giant taryn aufeis; describes their origin, shape, structure, variations over time and across space; and describes the dependence of features of aufeis fields on permafrost–hydrogeological, hydroclimatic, geomorphological, and geotectonic conditions. The text is supplemented with numerous generalizing graphs, diagrams digitized from literature sources, and color photographs. Of particular value is the series of 14 small-scale thematic maps of aufeis formation conditions (Fig. 1), which are overlaid with a layer of aufeis locations according to the 1958 cadastre [9].

Part II of the Atlas contains maps of the distribution of taryn aufeis in the basins of major rivers (Yana, Indigirka, Kolyma, Anadyr, and Penzhina), small rivers of the Chukchi Peninsula (Amguema, Lyulyu-

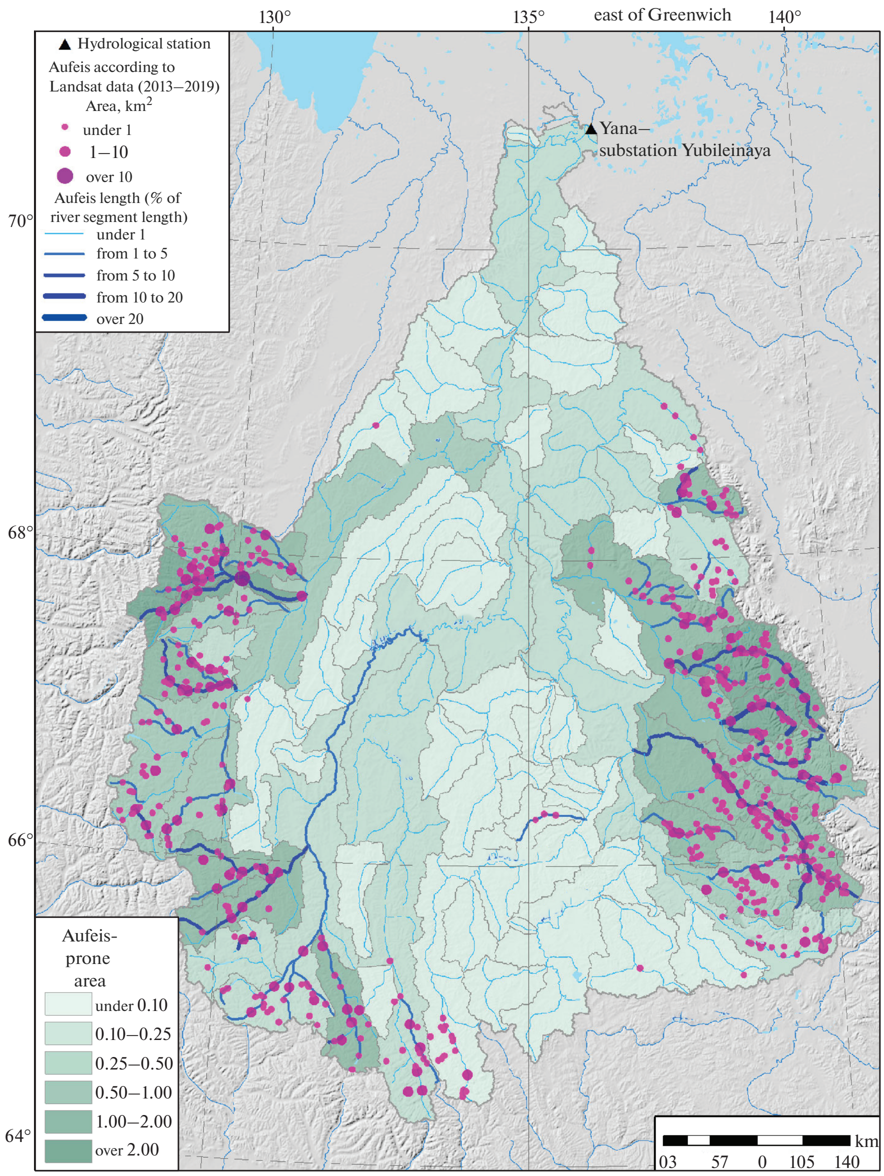

Fig. 2. Aufeis hazard level in the basin of the Yana river according to modern Landsat images (2013–2019). An example of a map from Part II of the Atlas of taryn aufeis [16].

veem, and Palyavaam), and rivers of the Sea of Okhotsk (Ulbeya and Nyadbaki) compiled based on [9] and on modern-day data obtained from Landsat satellite images (Fig. 2). Medium- and large-scale maps and satellite images of major aufeis reveal seasonal and long-term dynamics of aufeis phenomena, as well as landscape conditions of aufeis formation. In total, the second part of the Atlas contains more than 100 maps reflecting the current geographical location and size of about 7000 aufeis fields.

Cartographic materials for each large basin are supplemented with graphs characterizing the ratio of aufeis areas of different gradations, the unevenness of their distribution (Lorenz curves), changes in the number and total area of ice by altitude zones, etc. Maps and numerous illustrations are accompanied by explanations and tables of generalized data. The compiled materials require thorough analysis and generalization.

Database Content

The database is a compilation of uniform information on aufeis locations (latitude, longitude, and altitude) and features for both the retrospective and current periods in the form of two separate layers (shapes). Attribute tables contain aufeis dimensions as identified on Landsat images, data from [9], a cross index (ID) for the aufeis identified on satellite images and indicated in the cadastre [9], and additional infor-

Table 1. Aufeis resources of the main basins of rivers of northeastern Russia according to [16]

River	Basin area, km^2	Relative aufeis content, %	Aufeis area, km^2	Aufeis volume, km^3	Aufeis water reserves, mm
Yana	224000	0.23	505	1.10	4.5
Indigirka	305000	0.55	1663	4.25	11.0
Kolyma	643000	0.19	981	2.20	3.0
Penzhina	73500	0.26	189	0.40	5.1
Anadyr	156000	0.26	398	0.85	5.1
Amguema	26400	0.39	192	0.20	7.5
Total	1427900	–	3838	9.0	–
Average	–	0.31	–	–	4.4

Dash indicates not defined.

mation. In total, four databases on aufeis of the basins of the rivers Yana, Indigirka, and Kolyma and of the Chukchi Peninsula have been created[1]. They can be used to assess the current aufeis coverage of the river basins of northeastern Russia and consider the distribution of aufeis fields depending on various factors.

Information on Aufeis Northeastern Russia

At this stage of research, it was possible to conduct a primary comparison of retrospective and modern-day data. The comparison showed that, for the basins of large rivers—the Yana, Indigirka, and Kolyma, as well as rivers of the Chukchi Peninsula—the total number of aufeis according to [9] was 4642; according to Landsat images it was 6683. For the same territory, the area of aufeis according to the cadastre [9] was 7181 km^2 and, according to satellite images, it was only 3579 km^2. Thus, the number of aufeis has increased by 30%, while the area has reduced by more than 50%. However, this comparison is given for aufeis areas as determined for the survey date, at which time they could have already partially melted.

[1] Certificate of state registration of the database "Aufeis of the Northeast of Russia: GIS Catalog for the Chukchi Peninsula" no. 2021620267, O.M. Makar'eva, A.N. Shikhov, A.A. Ostashov, N.V. Nesterova, A.A. Zemlyanskova, A.V. Semakina, and V.R. Alekseev. Published February 12, 2021. Registered December 24, 2020; Certificate of state registration of the database "Aufeis of Northeastern Russia: GIS Catalog for the Indigirka River Basin" no. 2021620317, O.M. Makar'eva, A.N. Shikhov, A.A. Ostashov, N.V. Nesterova, A.A. Zemlyanskova, A.V. Semakina, and V.R. Alekseev. Published December 24, 2021. Registered December 24, 2020; Certificate of state registration of the database "Aufeis of Northeastern Russia: GIS Catalog for the Kolyma River Basin" no. 2021620332, O.M. Makar'eva, A.N. Shikhov, A.A. Ostashov, N.V. Nesterova, A.A. Zemlyanskova, A.V. Semakina, and V.R. Alekseev. Published February 26, 2021. Registered December 24, 2020; Certificate of state registration of the database "Aufeis of the Northeastern Russia: GIS Catalog for the Yana River Basin" no. 2021620333, O.M. Makar'eva, A.N. Shikhov, A.A. Ostashov, N.V. Nesterova, A.A. Zemlyanskova, A.V. Semakina, and V.R. Alekseev. Published February 26, 2021. Registered December 24, 2020.

Adjusted dimensions of 6683 aufeis, calculated using Sokolov's method [11], showed that the total preablation area of taryns could reach 4529 km^2; i.e., it is 22% larger than the data taken from satellite images. This information was used for calculating aufeis resources (the total volume of aufeis during the period of maximum aufeis development) and also for assessing the role of aufeis phenomena in the formation of cryogenic hazards in the region.

The total volume of taryn aufeis in basins of large rivers of northeastern Russia at the beginning of the ablation period amounted to more than 10.6 km^3, which is equivalent to 5 mm of aufeis discharge. Table 1 shows the distribution of aufeis resources for the outfalls of large rivers—the Yana, Indigirka, Kolyma, Penzhina, Anadyr, and Amguema. The high aufeis content of the mountainous part of the Indigirka River basin is caused by the elevated degree of cryolithozone discontinuity due to neotectonic activity in the area and high energy of the relief. The lowest relative aufeis content (0.19%) is in the Kolyma River basin, a large part of which is occupied by low-lying areas with continuous permafrost.

Information on the area and volume of aufeis was used to calculate the average aufeis thickness: for $F \leq 0.001$ km^2 it was found to be equal to 1 m; the average thickness of large aufeis increases to 2.7 m with the increase of their area.

Aufeis create conditions hazardous for people, plants, and animals, as well as for the functioning of vehicles and engineering structures. We divide aufeis hazards in the region into three types. Slope aufeis hazards occur when ground (suprapermafrost) waters freeze on mountain slopes, in thalwegs of steeply dipping valleys, and on cliffsides and coastal cliffs; floodplain hazards occur as a result of the activity of non-freezing groundwater sources (intrapermafrost, subpermafrost, and deep circulation waters); riverbed hazards occur when rivers and subsurface groundwater are frozen.

The Atlas [16] contains aufeis hazard maps (see Fig. 2) compiled for all major river basins in the region.

The hazard indicator is the share of the catchment area occupied by taryn aufeis. Riverbed aufeis hazards are characterized by the relative length of aufeis within riverbeds. An analysis of the maps showed that the greatest degree of this hazard is typical for mountainous areas, where aufeis of all three categories are widespread. On the plains, riverbed-type aufeis prevail, but on river sections located more than 500 km away from the source, this type of aufeis occurs sporadically, mainly in coastal parts of watercourses.

CONCLUSIONS

For the first time since 1958, data on the current distribution of giant taryn aufeis in northeastern Russia have been updated and generalized. The analysis of retrospective and modern materials included in the Atlas showed that the data of the 1958 cadastre [9], used as reference in numerous research studies and still widely relied upon as a data source, are not representative of the current state of the cryolithozone and the distribution of aufeis. The authors have revealed significant changes in the total number and maximum area of aufeis in the studied region: according to satellite images, there are now 30% more aufeis than indicated in the 1958 cadastre [9], but their total area is almost 50% smaller. According to modern data [16], the total volume of taryn aufeis in the basins of the rivers Yana, Indigirka, Kolyma, Penzhina and rivers of the Chukchi Peninsula at the beginning of the ablation period is more than 10.6 km^3, or 5 mm layer of aufeis discharge. This value is more than twice as low as the value indicated in O.N. Tolstikhin's work [7]. The current state of all taryn aufeis (their location, size, and variability) reflects the thermodynamic state and spatial structure of the cryolithozone of individual river basins and the region as a whole.

The total area of aufeis-prone territory in the mountains of northeastern Russia is at least 5%, and the vast majority of it is in the most accessible places—the bottoms of river valleys and intermontane basins. The Atlas, together with the developed databases, can serve as an information basis for further interdisciplinary research and planning of long-term monitoring of aufeis and the cryolithozone of northeast of Russia in the context of climate change.

FUNDING

The study was performed as part of the research project of the St. Petersburg State University "Comprehensive Assessment of Natural and Anthropogenic Factors of Intensification of Water Exchange Processes in the Cryolithozone in the Context of Climate Change" (id 75295776).

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Translated by A. Ovchinnikova

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