remote sensing

Article

Giant Aufeis—Unknown Glaciation in North-Eastern Eurasia According to Landsat Images 2013–2019

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Abstract: Based on the analysis of Landsat satellite images over the period of 2013–2019, the number (6683) and total area (4529 km^2) of giant aufeis fields (area $\geq$ 0.1 km^2) were estimated for the territory of North-Eastern Eurasia. The contribution of aufeis runoff to river streamflow in different seasons was calculated for 58 hydrological gauges (area 523–526,000 km^2). The contribution of aufeis and glaciers to water balance is compared. The aufeis resources vary from 0.4 to 4.25 km^3 (or 3.7–11 mm) for individual basins of large rivers. They are at least 10.6 km^3 in total or 5 mm of water depth on average for the study area. Aufeis annual runoff varies from 0.3 to 29 mm (0.1–22%, average 3.8%), with the share in winter runoff amount about 6–712% (average 112%) and the spring freshet 0.2–43% (average 7.1%). In general, the aufeis runoff exceeds the glacial runoff. The dynamics of aufeis formation are directly related to winter runoff, whose changes are observed in different parts of the cryosphere. The presented results are relevant for studying the impact of climate change on the hydrological cycle and its components in the permafrost regions of the Northern Hemisphere.

Keywords: aufeis; aufeis runoff; water balance; large permafrost rivers; North-East of Russia; aufeis area dynamic

Citation: Makarieva, O.; Nesterova, N.; Shikhov, A.; Zemlianskova, A.; Luo, D.; Ostashov, A.; Alexeev, V. Giant Aufeis—Unknown Glaciation in North-Eastern Eurasia According to Landsat Images 2013–2019. *Remote Sens.* **2022**, *14*, 4248. https://doi.org/10.3390/rs14174248

Academic Editors: Sergey V. Popov, Gang Qiao, Xiangbin Cui and Nikola Besic

Received: 30 June 2022
Accepted: 20 August 2022
Published: 28 August 2022

1. Introduction

Aufeis (icings, or "naled") are the ice fields formed annually due to layer-by-layer freezing of water that flows to the surface. The aufeis prevail in the Arctic and Subarctic regions, such as Siberia, Alaska, and Canada, and in the mountain areas with contrasting terrain and a complex system of taliks—in Northern Transbaikalia, Yakutia, North-East of Russia, as well as in the mountains of Central Asia. For example, about 5500 aufeis fields during 1985–2014 were identified in subarctic Canada based on the Landsat images [1]. There are 1402 known aufeis fields (with a total area of 277 km^2) in the territory of northwestern Canada, and they account for 0.04% of the study region [2]. The study by Brombierstäudl et al. (2021) [3] provided the first inventory of aufeis fields in the high mountain region of the Upper Indus Basin (UIB) based on a time-series analysis using Landsat imagery from 2010 to 2020, supported and validated by several field campaigns carried out between 2014 and 2020, and detected more than 3700 aufeis fields in an area of about 298 km^2.

Aufeis fields that form near permanent springs can occupy large areas (up to 3–5% of the territory in mountainous areas) and serve as a powerful regulator of underground and surface runoff in permafrost regions [4,5].

In Russia, the most favorable conditions for the formation of giant spring aufeis fields are characteristic of the basins of the Yana, Indigirka, Kolyma, as well as the Anadyr, and other rivers of the Chukotka Peninsula. The sizes of giant spring aufeis fields can reach tens of square kilometers [6]. These are hard-to-reach mountainous permafrost areas characterized by a significant transformation of the hydrological regime under the influence of climate warming [7,8]. Here, according to the data of Simakov and Shilnikovskaya (1958) [9], about 4600 aufeis fields are formed within a total area of up to about 7180 km^2 in the studied area. The aufeis is more widespread than glaciers in North-Eastern Eurasia, with a total area in the region of 246.3 km^2 (or 0.013%) [10].

The impact of climate change on the aufeis dynamics was rarely studied [1,5,11]. The response of aufeis to climate change depends on different mechanisms of the natural system, including changes in the dynamic of groundwater, surface water, and climatic features [12,13]. The studies of aufeis dynamics indicated a decrease in aufeis area in Alaska during 2000–2015 [14] and an increase in the number of aufeis fields, and a decrease in aufeis area in the North-East of Russia during 1950–2017 [11]. Despite the wide distribution of aufeis, much more attention is paid to the study of glacier cover and its impact on the runoff formation under climate change [15,16], while the aufeis research has almost descended in recent decades, particularly in Russia [5]. Aufeis resources also are underestimated and practically are not used. It is necessary to develop special methods of aufeis resources management for the future development of the region in response to the behavior of permafrost and the positive impact on the environment in a changing climate [13].

The aufeis glades of river valleys and the aufeis fields themselves are confidently identified on aerial and satellite images, which allows not only to study the long-term and seasonal variability of this phenomenon of the cryosphere but also to use the aufeis as indicators of the dynamics of the permafrost zone, water resources, groundwater reserves in hard-to-reach areas of the mountain permafrost zone of Russia and the world.

The aim of this study is the general assessment of water resources stored by aufeis and their role in the structure of water balance and the runoff formation of the largest and middle-size rivers of the permafrost zone of North-Eastern Eurasia, such as the Yana, Indigirka, Kolyma, Anadyr, Penzhina River and rivers of the Chukchi Peninsula, based on analysis of recent satellite images data.

The novelty of this paper is the use of the newly compiled aufeis dataset to assess the aufeis impact on the water balance of the region. Previously, the aufeis data were systematized based on data from 1940–1950s and have not been updated to date [9]. The presented results are relevant for the studies of climate change's impact on the hydrological cycle, its components, and feedback in permafrost regions.

The paper has the following structure. In Section 2, we present the study area. In Section 3, we shortly describe the used datasets and the methods to delineate the aufeis in remote sensing images and estimate the aufeis resources and flow component. Results of the analysis of aufeis fields distribution assessment and the impact on the water balance of selected basins are presented in Section 4, while the discussion of obtained results and the comparison with glacial contribution are described in Section 5. Finally, some conclusions are drawn in Section 6.

2. Study Area

The territory of North-Eastern Eurasia covers the Magadan Region, the Chukotka Autonomous Region, and the north-eastern territories of the Republic of Sakha (Yakutia) of Russia. It comprises the basin of large permafrost rivers, such as the Yana, Indigirka, Kolyma, Anadyr, Penzhina Rivers, and rivers of the Chukchi Peninsula. The terrain is mountainous, with the highest part located in the upper Indigirka River, and the maximum elevation reaches 3147 m. The climate of the study area is mostly continental, with the features of the sea climate at the coast (Figure 1).

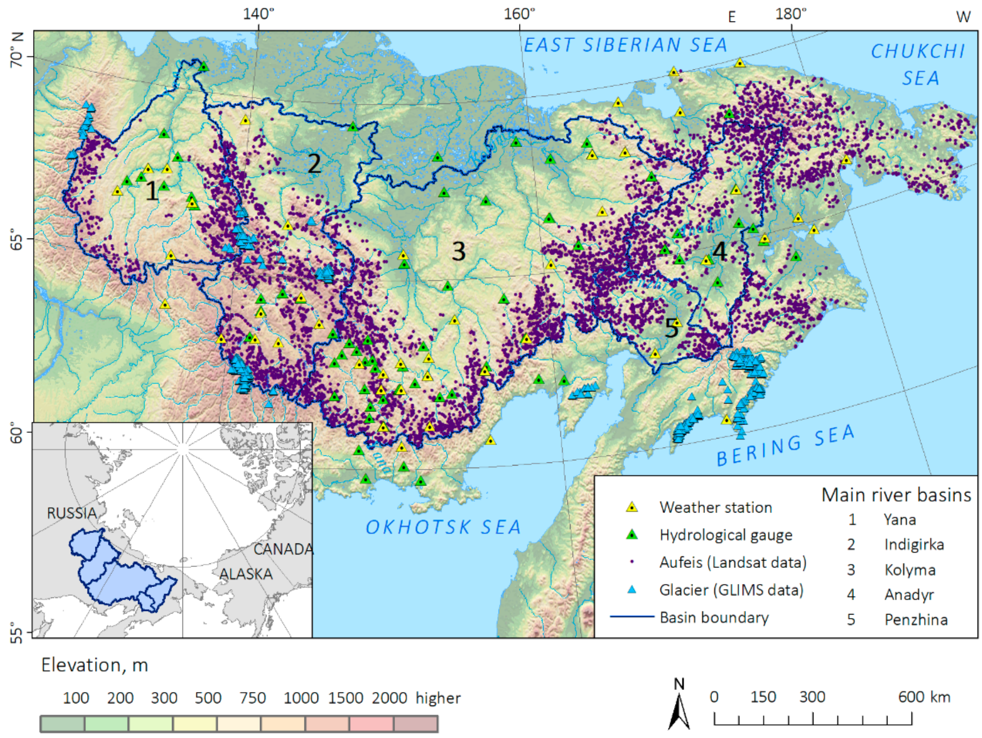

Figure 1. The study region.

The average long-term annual air temperature ranges from −15.7 °C at Oymyakon meteorological station (726 m) to −2.8 °C at Magadan (118 m). The multi-year average monthly temperatures reach −46.4 °C and 14.9 °C at Oymyakon and −16.4 °C and 11.8 °C at Magadan in January and July, respectively (1966–2015). The average annual precipitation varies widely: from 280 mm (Vostochnaya, 1288 m) to more than 550 mm in high-altitude areas and on the coast of the Okhotsk and Bering Seas (688 mm at Suntar-Khayata, 2068 m; 561 mm at Magadan). On average, precipitation amounts reach 300–350 mm, and their distribution is characterized by a large uncertainty due to the mountain area.

The entire territory is in the continuous permafrost zone, and sporadic permafrost areas are found only on the Okhotsk Sea coast [17]. The permafrost thickness in the high-mountain Yana and Indigirka River basins can reach more than 450 m; permafrost may be interrupted in taliks zones in river valleys. Thawing depths generally vary from 0.3 to 2 m [18].

The soil-vegetation cover of the mountainous part of the studied area may be schematized by four main landscapes: rocky talus with no vegetation, composed of coarse rubble with an admixture of loamy material (the depth of the active layer may reach up to 3–5 m depending on the slope aspect); mountain tundra with grass-moss cover and dwarf cedar bushes (active layer up to 1 m); taiga, consisting of sparse larch forests on the northern slopes and dense larch forests on the southern slopes; swampy light forests and meadow swamps confined to valleys and floodplains. A distinctive feature of the larch taiga and floodplain on wetlands is the presence of a peat horizon under the moss cover extending to depths up to 40 cm.

River regimes are characterized by high spring-summer water, high summer-autumn rain floods, and low winter water. Many small and medium-sized rivers freeze over in winter. The middle parts of the basins are composed of highlands and river valleys in the local depressions; in the lower parts of the basins, the main landscapes are tundra lowlands.

Aufeis are widespread in the study area [19]. Though aufeis can be of different origins [13], the largest aufeis fields are usually formed by groundwater.

3. Data and Methods

3.1. Aufeis Fields Delineation Based on Landsat Images

The datasets containing a current spatial distribution of aufeis fields in the basins of the largest rivers of North-East Russia were compiled based on late-spring Landsat-8 OLI satellite images, namely Landsat 8 Collection 1 Level 1 terrain-corrected product (L1T) with radiometric and geometric corrections, obtained between 2013 and 2019 [20–31]. In total, we obtained more than 130 Landsat-8 scenes with imagery dates from 15 May to 26 June, e.g., immediately after snowmelt. The Landsat-8 images were downloaded from the USGS web archive [32]. All images were preprocessed with the use of the QGIS Semi-Automatic Classification Plugin. Surface reflectance was calculated with atmospheric correction according to Dark Object Subtraction (DOS1) image-based algorithm [33].

The images for the period from 2013 to 2019 were used for mapping aufeis fields. However, more than 50% of all data on aufeis were obtained from images in 2016, when a long period without cloudiness was observed in early June. Identification of the aufeis fields was carried out using the geoprocessing models in the ArcGIS software packages. The methods of aufeis data collection and validation, as well as the limitations of the data, are described in detail in our previous study [11].

Aufeis fields have been automatically delineated from the Landsat images according to their high values of Normalized Difference Snow Index (NDSI) [34], exceeding 0.4. However, snow-covered areas and glaciers have the same high NDSI. To distinguish aufeis fields from them, we considered that the aufeis fields are widespread along streams or in immediate proximity to them, while snow-covered areas in late spring are mainly associated with mountain ridges and other elevated locations, i.e., relatively far from thalwegs. We extracted a network of thalwegs from the digital terrain model GMTED2010 [35] with a spatial resolution of 250 m and excluded from further analysis all areas located at more than 1.5 km from the nearest river or thalweg.

Subsequent visual inspection allowed the exclusion of snow- and ice-covered areas located in the river valleys and erroneously attributed to aufeis. The contours of several aufeis fields, partially overlapped with snow-covered areas, were also manually refined according to satellite images. In several mountainous areas located mainly in the Chukchi Peninsula and the Kolyma River basins, most aufeis fields are covered with snow up to early summer. Their identification required later images, obtained in the second half of June.

Morse and Wolfe (2015) [1] noted that in late-spring images, floodplain lakes are also covered with ice and could be mistakenly referred to as aufeis. Following their recommendations, we masked water surfaces using mid-summer images when all water bodies were not covered by ice and excluded them from further analysis. The modified Normalized Difference Water Index (mNDWI), proposed by [36], was used for water masking.

It is also of note that large aufeis fields often divide into several neighboring ones during the melting period [11]. When assessing the number of aufeis fields on satellite images, we aggregated such areas into one aufeis field if they are located at a distance < 150 m (five Landsat pixels) from each other and within one aufeis glade.

The compiled datasets include only relatively large aufeis fields, with an area exceeding 10,000 m^2. Numerous small aufeis fields were excluded from consideration since their identification from Landsat images is limited by the spatial resolution (30 m), as well as local aufeis fields may be mistakenly referred to as river ice and vice versa. In addition, the contribution of the local aufeis to the total aufeis area can be neglected according to [11].

3.2. Hydrological Data

Additionally, the monthly hydro-climate data containing long-term streamflow and climate observations were applied for hydrological estimates of long-term streamflow variability. It includes the mean monthly runoff for 58 hydrological gauges at the study basins with catchment areas from 523 to 526,000 km^2 and monthly air temperature and precipitations from 46 meteorological stations in the region from 1944 to 2015 [37] (Figure 1).

3.3. Correction of Aufeis Area

Aufeis resources are the maximum water reserves that are formed each year in the aufeis fields at the time of their maximum development. Assessment of aufeis resources is based on the maximum aufeis volume, which corresponds to the maximum aufeis area before the beginning of the ablation period. Therefore, it is necessary to use the data on the maximum aufeis area to correctly assess aufeis resources [38].

The satellite-derived datasets of the aufeis area have the following limitations [11]. Landsat images do not allow for the correct assessment of the maximum aufeis area since aufeis fields are covered with snow in the period of their maximum development. Cloudiness is also a substantial limitation to correctly estimating the maximum aufeis area, especially in mountainous regions. Therefore, the aufeis area given in our database may be substantially less than their maximum area due to the aufeis ablation process. According to Sokolov (1975) [38], large aufeis can lose up to 70% of their area and volume, and small aufeis can melt completely by the end of June.

In this study, we applied the method of aufeis area correction developed by Sokolov (1975) [38]. Based on the data of field observations of aufeis processes in the North-East region of Russia, Sokolov (1975) [38] proposed the scheme of aufeis area decrease during ablation season.

Figure 2 shows the schedule of relative aufeis area decreases during the warm period of the year, which depends on the number of days after the start of ablation and the maximum area of aufeis. The curve of 0.6–23 is based on observations at four aufeis with areas of 0.5–6.3 km^2 in the basins of the upper Kolyma River and South Yakutia (the Lena River basin) in 1962–1966. The curve of 0.5 is based on observations at two aufeis in South Yakutia; the curve of 0.25 resulted from the analysis of aerial observations data at the upper Kolyma basin in 1963. The curves 0.05, 0.1, and 0.15 are based on fragmentary information from literature sources on the ablation of small aufeis.

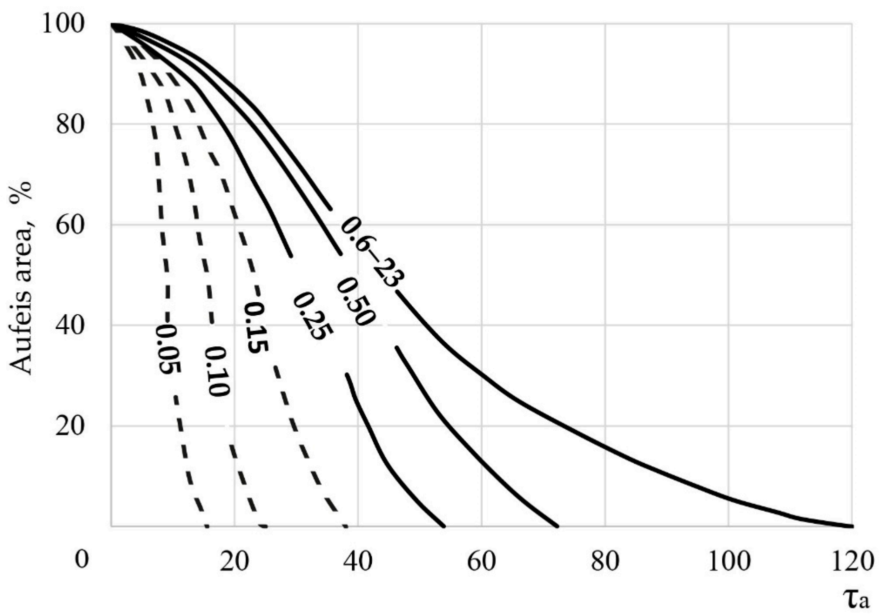

Figure 2. The aufeis area decrease during the warm period of the year, depending on the number of days (τ_a) after the start of ablation, and their maximum area (The numbers at the curves, km^2) adopted from [34]. Solid and dotted lines present the dependencies derived from observed data (solid) and extrapolated.

To verify the method proposed by Sokolov (1975) [38], we used the recent data on the giant aufeis area degradation process obtained from satellite images (Figure 3). The series of the area of six aufeis fields in the upper Indigirka River basin were derived from cloud-free Sentinel-2 images for the period of 2018–2021. The maximum area of analyzed aufeis fields varied from 8 to 21 km^2. In total, 202 images for 96 different dates from 23 May 2018 to 30 August 2021 were selected for the warm period of the year from May to the end of August. Also, the series of the Anmangynda aufeis field area reaching 5.8 km^2 located in the upper Kolyma basin were derived from 136 Landsat and Sentinel images for the period from 7 May 2000 to 4 September 2021. The initial dates of ablation were derived from air temperature series from the nearest meteorological stations corrected for lapse rate.

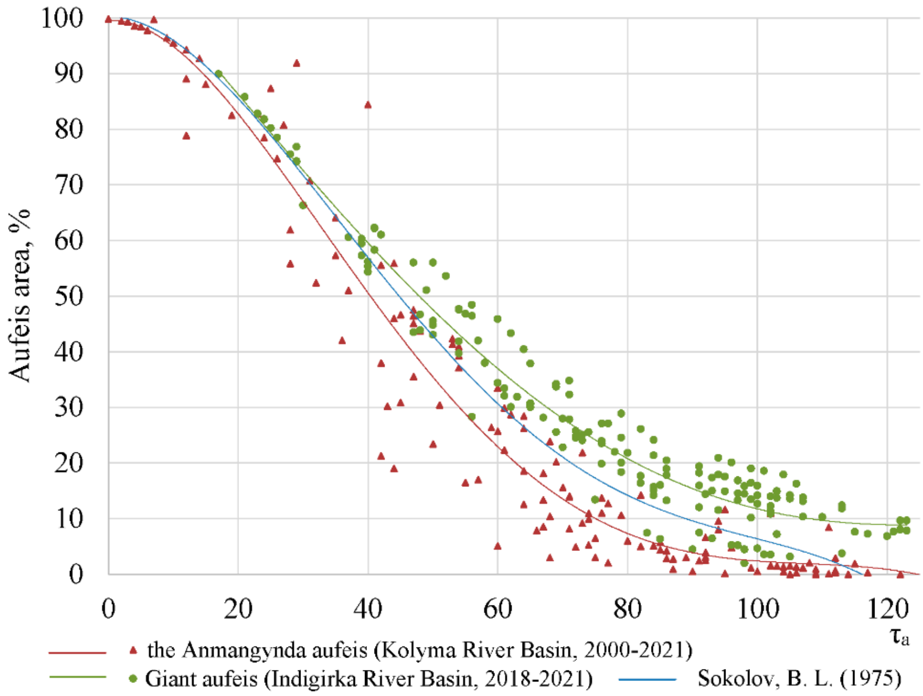

Figure 3. The comparison of the historical curve 0.6–23 by Sokolov (1975) [38] and recent aufeis area data in the Indigirka and the Kolyma River basins (2000–2021).

Aufeis area degradation assessment is shown in Figure 3 in relative units, where 100% is the maximum aufeis field area before the start of ablation. Analysis of the obtained data shows that the curve 0.6–23 km^2 proposed by Sokolov (1975) [38] lies in the middle between the curves for aufeis fields in the basin of the Indigirka River and the Anmangynda aufeis field.

The mean square deviation of the relative aufeis area for a group of aufeis in the Indigirka River basin ranges from 0 to 11% on a specific date for the Anmangynda aufeis, and it ranges from 0 to 19%. In the first month of ablation, the aufeis area degrades almost the same from year to year. This is because at first, the ice ablates almost only due to the impact of solar radiation, and later the ablation process is influenced by the thermal effects of river runoff, block destruction, heavy precipitation, and other dynamic factors. The rate of aufeis degradation also strongly depends on the shape of the aufeis field. Often several aufeis fields developing in one river valley form a united system that elongates along the river channel. In this case, even if the total area of an aufeis field may reach several tens of square kilometers, the destruction of ice field impacted by river flow goes much faster than for aufeis fields of more solid shapes.

Though many specific factors are not accounted for in the method proposed by Sokolov (1975) [38], introducing significant uncertainty in the calculation results for a single aufeis field, in general, the results of the assessment show that it may be used for the correction of aufeis area for the arrays of large aufeis fields. The lack of data on actual observations of the ablation regime of small aufeis fields makes it impossible to verify the correctness of the interpolation curves. Small aufeis fields are also difficult to identify in satellite images, as they merge with the snow cover and quickly collapse. However, an analysis of the regularities in the distribution of aufeis field sizes shows that in most aufeis areas, the main number of aufeis fields have areas larger than 0.5 km^2 [11]. In general, in the study region, 10% of the largest aufeis fields form more than 50% of the total ice area. Therefore, even large errors in the calculations of the melting area and volumes of small aufeis fields, which give a little aufeis runoff, will not have a significant impact on the result of the calculation as a whole for the river basin.

The area of the aufeis fields was adjusted upward based on aufeis area estimated by Landsat images, satellite imagery dates, the elevation of aufeis location, and air temperature from the nearest weather station. The air temperature lapse rate was used to account for the heterogeneity of the air temperature distribution in mountainous conditions. The average value of lapse rate of -0.85 °C per 100 m in May and June was estimated based on regional meteorological data [39,40]. The number of ablation days was determined for each aufeis field based on the data from the nearest weather station for the year when the aufeis was identified at the Landsat image. The date when the average daily temperature exceeded 0 °C was taken as the beginning of the ablation period. The nomograms presented in Figure 2 were used to estimate the aufeis area decrease, depending on the aufeis field size and the number of days after the start of ablation. If the corrected area exceeds the selected area range (Figure 2) during the first calculation, the second iteration of the dependency for the new aufeis area is conducted. Solid lines in Figure 2 presenting the aufeis area decrease are based on the analysis of the field data [38]. Dashed lines present the author's extrapolation for the aufeis fields of smaller size [38].

3.4. Estimation of Aufeis Resources and Their Role in Regional Water Balance

Knowledge of the aufeis features allows for solving some important practical issues, such as calculating the volume of water accumulated in the aufeis. Field observations obtained in the second half of the 20th century [38] allowed to establish the dependence of the main characteristics of aufeis—the area, volume, and average thickness. Despite the difference in aufeis formation conditions, the ratio of aufeis parameters at the end of winter is approximately the same based on the analysis of a large amount of data for the permafrost regions of Russia [38]. This is due to the common morphological structure of aufeis.

The dependence of the aufeis volume (W, thous. m^3) on the aufeis maximum area (F, thous. m^2) is mathematically described by

$$W = \alpha F^n \quad (1)$$

The parameters of the equation $\alpha = 0.75$ and $n = 1.12$ are estimated as the result of generalizing data on about 1200 aufeis [41]. According to these parameters, the average ice depth is about 1.0 m for aufeis with an area of 0.001 km^2 and increases to about 3.0 m for aufeis with area of 100 km^2 [37]. The root mean square error in calculating the volume of a single aufeis, taking into account the given coefficients, is about 35%. The values of α and n may differ significantly from their generalized values for different regions, depending on the genetic type of aufeis (the source of aufeis), the terrain (underlying bed), and the amount of solid precipitation (snow cover), air temperature and some other factors. For example, Tolstikhin (1975) [42], based on field observation data at five aufeis fields located in Central Yakutia and in the basins of the Indigirka and Kolyma rivers, obtained: $\alpha = 0.511$, $n = 1.146$.

The annual runoff was calculated for each study basin, as well as the runoff for the period of the low-flow cold season (October–April) and spring freshet (May–June). For the winter period, the contribution of runoff that is spent on the aufeis formation was calculated based on the volume of aufeis. The contribution of aufeis meltwater in the spring freshet was calculated on the assumption that 70% of the aufeis volume melts during the period May–June [38].

4. Results

According to the newly compiled data, the total number of aufeis fields is 6683, with a total area of 3702 km^2 (Table 1). Historical data based on aerial imagery performed in the 1940–1950s indicated 4642 aufeis fields with a total area of 7181 km^2 [9].

Table 1. Characteristics of the maximum aufeis area calculation in different river basins.

Metrics	Yana	Indigirka	Kolyma	Chukchi Peninsula	Penzhina	Total Study Area
The number of aufeis fields	583	1213	2210	2139	538	6683
Landsat-based aufeis area, km^2	426	1287	879	955	155	3702
Area of the largest aufeis field, km^2	10	72	19	22	6	
The earliest date of ablation	3 May	26 April	23 April	12 May	5 May	
Year of Landsat image and correction	2016	2017	2019	2015	2019	
Duration of ablation period (days) before the date of Landsat image, average, maximum	16, 31	18, 51	20, 54	16, 36	21, 39	
Corrected aufeis area, km^2	506	1663	1085	1086	189	4529
% increase in area after correction	19	29	23	14	22	22 *

* area-weighted value.

4.1. Correction of Maximum Aufeis Area

Since the Landsat images used to identify the aufeis fields could be obtained during the period of their active melting, it was necessary to retrieve the maximum area of the aufeis. The correction of the maximum area was conducted using the dependence of the aufeis volume on its area, taking into account the number of days of aufeis ablation until the moment the image was taken, based on the method [34]. On average, in the river basins, the calculated maximum area of aufeis turned out to be 15–30% higher than the area estimated from the Landsat images (Table 1).

The average and maximum duration of aufeis ablation for individual objects were 18 and 54 days, respectively, in the study region. Similar values for individual basins ranged from 16 days (at the Yana River basin) up to 54 days (at the Kolyma River basin). The earliest date of the beginning of ablation was 23 April 2019 at the Kolyma River basin, and the latest was 12 May 2016 at the river basins of the Chukchi Peninsula.

The total corrected (maximum) area of 6683 aufeis fields in North-East Eurasia was estimated at 4529 km^2. It increased by 22% compared to the initial Landsat-derived data (Table 1). The maximum increase (by 29%) is found for the Indigirka River basin, and the minimum increase (by 14%) appears for the Chukchi Peninsula.

According to Sokolov (1975) [38], the first stage of aufeis ablation is characterized by the breakthrough of large masses of underground water to the surface of aufeis before spring freshet runoff, leading to intense wetting of the snow and ice surface. Consequently, the heat balance of the aufeis surface changes dramatically. Thus, the positive energy balance, combined with the eroding and warming effect of underground waters, are the main factors that cause the ablation of aufeis even before the average daily temperature exceed 0 °C and before the beginning of snowmelt and spring flood. However, the radiation balance and underground water warming effect are not considered in the calculations. So, our estimates give a lower bound of the estimated aufeis area, but in fact, the maximum aufeis area may be even higher.

4.2. Aufeis Resources

Based on the corrected data of the aufeis area (Table 2), we found that the aufeis coverage in the large river basins of the North-East ranges from 0.19% in the Kolyma River basin to 0.55% in the Indigirka River basin. Table 2 and Figure 4 show the values of aufeis resources for the large river basins in the study region in volume (km^3) and depth (mm). The greatest aufeis resources in absolute values are typical for the Indigirka (4.25 km^3 or 11 mm), Kolyma (2.2 km^3 or 3.7 mm), and Yana (1.1 km^3 or 4.5 mm) River basins. A large amount of aufeis resources are found in the Penzhina River basin and the rivers of the Chukchi Peninsula despite their relatively small areas: Anadyr (0.85 km^3 or 5.1 mm), Amguema (0.20 km^3 or 7.7 mm), Penzhina (0.4 km^3 or 5.1 mm) River basins. Total aufeis resources are at least 2.6 km^3 in the basins of the Chukchi Peninsula. The high density of aufeis fields distribution in the mountainous parts of the river basins is caused by an increased degree of discontinuity in the permafrost zone due to the neotectonic activity of the territory [19].

Table 2. Aufeis and glacier resources of large rivers at North-Eastern Eurasia.

River Basin	Basin Area, km^2	Aufeis Coverage, %	Maximum Aufeis Area, km^2	Maximum Aufeis Volume, km^3	Aufeis Runoff, mm	Glacier Coverage, % [1]	Glacier Area, km^2	Glacier Volume, km^3
Yana	224,000	0.23	506	1.1	4.5	0.003	6.4	0.27
Indigirka	305,000	0.55	1663	4.25	11	0.057	173	8.19
Kolyma	643,000	0.19	1085	2.2	3.7	0	0	0
Penzhina	73,500	0.26	189	0.4	5.1	0	0	0
Anadyr	156,000	0.26	398	0.85	5.1	0.0004	0.6	0.02
Amguama	26,400	0.39	102	0.20	7.7	0.01	3.45	0.14
Total	1,950,000	0.23	4529	10.6	5	0.013	246.3	12.3

[1] The data on glacier area was taken from [10].

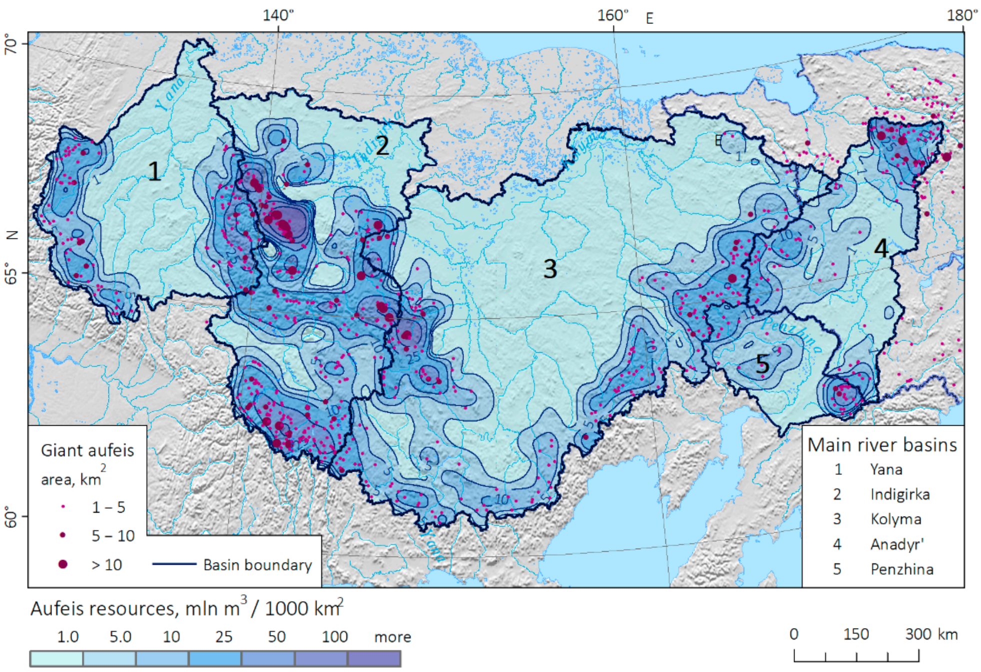

Figure 4. Aufeis resources of the North-Eastern Eurasia.

Giant aufeis fields make the main contribution to the formation of aufeis resources. For example, the total area of 66 aufeis fields with area of more than 10 km^2, according to the Cadastre [43], was 1683 km^2 (16% of the total area of 10,444 km^2 and 0.8% of the total number of 7448 aufeis fields).

The volume of individual giant aufeis field is measured in tens of millions of cubic meters. For example, the volumes of the Great Momskaya aufeis (area 66.2 km^2) and giant aufeis in the basin of the Syuryuktyakh River (area 78 km^2) (both in the Indigirka river basin), according to Equation (1), reach 0.19 km^3 and 0.23 km^3, respectively.

In total, in current climatic conditions, total aufeis resources of the North-East are estimated as the value not lower than 10.6 km^3 or 5 mm of water depth.

The calculations of the amount of water accumulated in aufeis can be used to approximately estimate groundwater resources. This is especially important since hydrogeological conditions of the region are poorly studied, and the hydrological gauges network is sparse and unevenly distributed [42,44–47].

4.3. Aufeis Runoff

We selected 58 hydrological gauges located within the study region (with basin area ranges from 523 to 526,000 km^2), which long-term (at least five continuous years in the period 1940–2017) streamflow observations are available. The mean annual streamflow at the studied basins ranges from 94 mm to 421 mm, with the winter flow (October–April) varying from 1.2 to 29 mm and spring freshet runoff (May–June) from 31 to 260 mm (Table S1). Some rivers completely freeze over in winter. Table 3 presents the data for the largest basins of the North-East, and Table S1 shows the data for all studied basins.

Table 3. Contribution of aufeis to water balance of large river of North-East of Russia.

Gauge ID	River Basin—Gauge	F [1]	H [2]	Hw [3]	Hs [4]	N [5]	S [6]	W [7]	Z [8]	H1 [9]	P1 [10]	P2 [11]	P3 [12]
1803	Kolyma—Kolymskoe [1]	526,000	199	20.2	85	2021	981	2,030,300	0.19	3.7	1.9	18	3.1
1801	Kolyma—Srednekolymsk	361,000	198	19.5	87	1322	658.4	1,379,000	0.18	3.6	1.8	19	2.9
3871	Indigirka—Vorontcovo	305,000	166	7.4	51	1220	1663.2	4,251,500	0.55	10.9	6.6	147	15
3489	Indigirka—Indigirskij	83,500	168	6.5	54	491	503.5	1,134,500	0.6	12.1	7.2	186	15.7
3861	Yana—Yubilejnaja	224,000	156	4.71	58	582	505.4	1,109,600	0.23	4.5	2.9	96	5.4
3414	Yana—Verhojansk	45,300	112	2.52	39	79	97	214,000	0.21	4.3	3.8	170	7.6
1501	Anadyr	156,000	258	13	116	755	398.1	838,400	0.26	5.1	2	39	3.1
1594	Amguema River—174 km	26,400	321	8.2	132	172	101.9	210,200	0.39	7.7	2.4	94	4.1
2219	Penzhina—Kamenskoe	71,600	324	23.7	194	538	189.0	400,000	0.26	5.6	1.7	23.5	2.0

[1] F—basin area (km^2), [2] H—long-term average annual runoff (mm), [3] Hw—winter runoff (October–April) (mm), [4] Hs—spring freshet runoff (May–June) (mm), [5] N—number of aufeis fields, [6] S—corrected aufeis area (km^2), [7] W—aufeis resource (thous., m^3), [8] Z—aufeis area share at the period of its maximum development (%), [9] H1—aufeis runoff (mm), [10] $P1 = \frac{H_1}{H}$, [11] $P2 = \frac{H_1}{H_w}$ and [12] $P3 = \frac{0.7 * H_1}{H_S}$—share of aufeis resources in the annual runoff, winter runoff and spring freshet runoff (%), respectively.

Aufeis has a different impact on river runoff depending on the time of year and aufeis field size. Figure 5 shows the seasonal transformation of an aufeis glade by the example of the giant aufeis in the Anmangynda River basin (the Magadan region, the upper Kolyma River basin): the aufeis thickness and active aufeis ablation in the summer period (July 2020, Figure 5a,b), when the aufeis provides a significant contribution to the streamflow; aufeis field without ice, when the aufeis has completely melted (October 2020, Figure 5c) and the beginning of the aufeis formation in November 2021 (Figure 5d).

Our estimates of annual aufeis flow for 58 hydrological gauges of the North-East range from 0.3 mm to 29 mm, with an average value 7.7 mm (or 3.8% of annual streamflow) (Table S1, Figure 6). For large rivers, the annual aufeis flow ranges from 3.7 mm to 11 mm (Table 2). The annual aufeis flow reaches 12.1 mm for the gauge Indigirskij (Indigirka River basin), where aufeis area coverage reaches 0.6%. The same values at the outlet of the Indigirka River (Vorontcovo) are 10.9 mm and 0.55%, respectively.

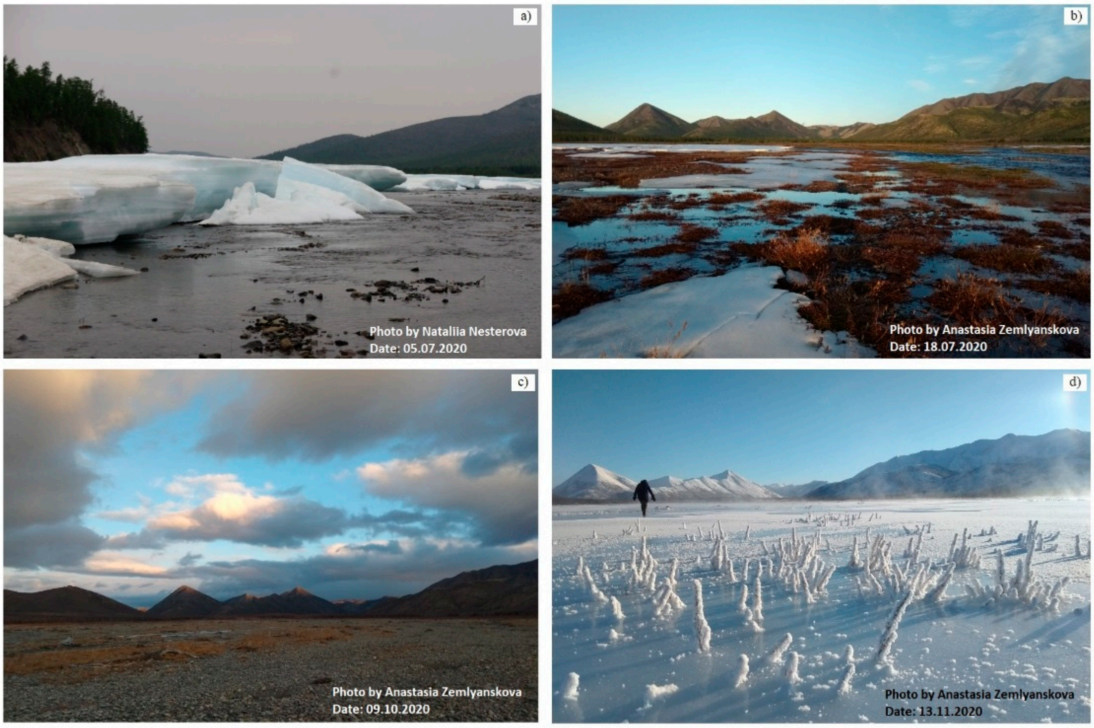

Figure 5. Seasonal transformation of the Anmangynda aufeis: (**a**) aufeis thickness—5 July 2020; (**b**) intense aufeis ablation—18 July 2020; (**c**) aufeis field without ice—9 October 2020; (**d**) beginning of aufeis formation—13 November 2020.

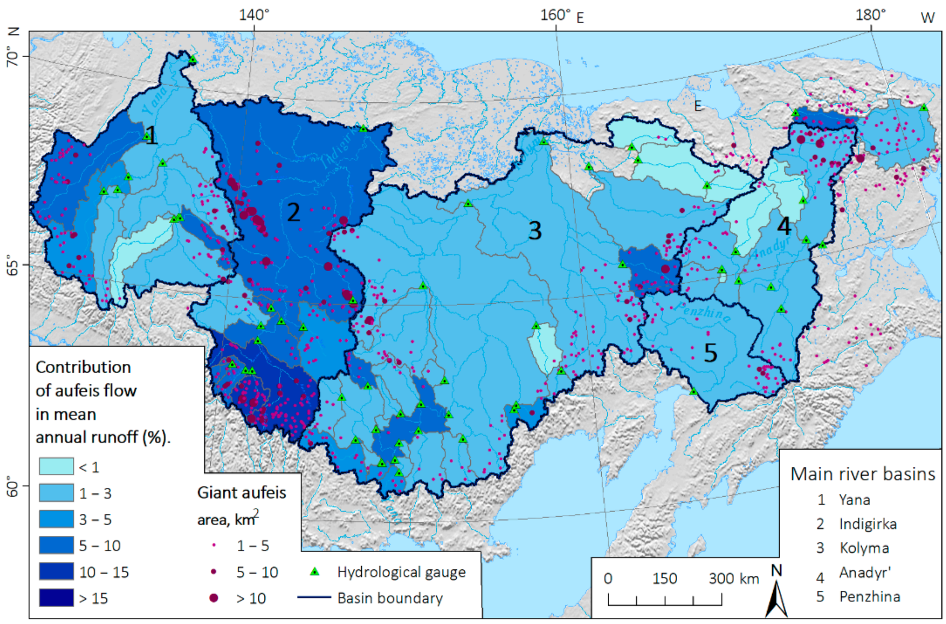

Figure 6. Contribution of aufeis flow in mean annual river runoff (%).

The Yana, Kolyma, Anadyr, and Amguema River basins have lower values of aufeis coverage (about 0.2–0.4%) and annual aufeis flow (3.6–7.7 mm). The greatest aufeis contribution to annual runoff is estimated for the Agayakan River (28.7 mm or 14.1% of annual value) and the Moma River (28.7 mm or 21.6% of annual value) in the Indigirka River basin.

In the winter season, the main part of river runoff is spent on the aufeis formation. The volume of aufeis-accumulated water ranges from 6% to 712 % (average 112%) of the winter runoff (Table S1; Figure 7) for the rivers of North-East. In the spring season, the aufeis meltwater gives from 0.2% to 43% (average 7.1%) of the spring freshet runoff (Table S1; Figure 8).

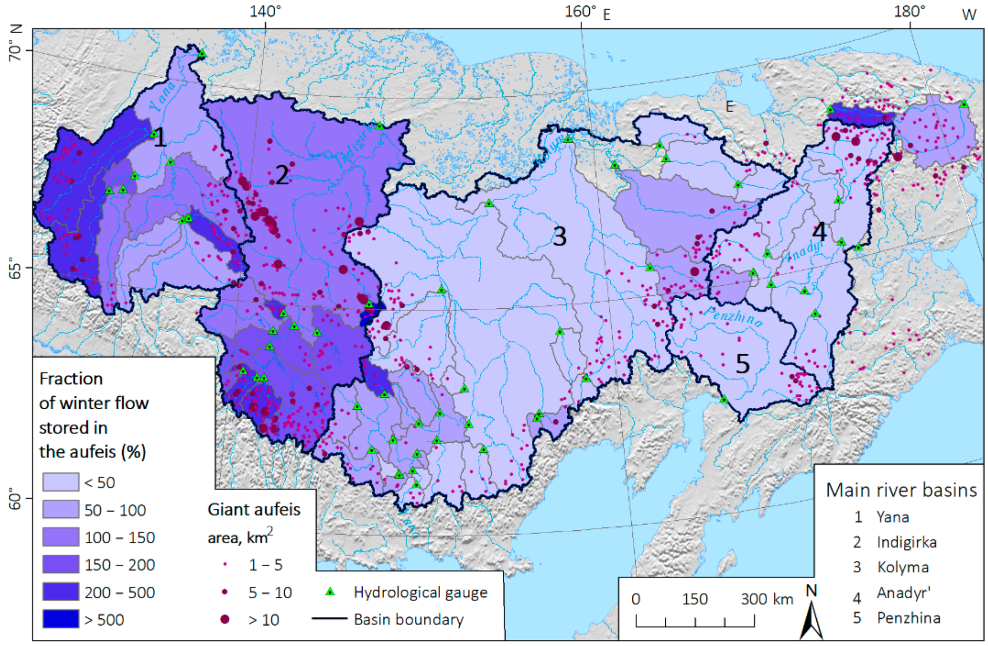

Figure 7. The fraction of winter flow stored in the aufeis (%).

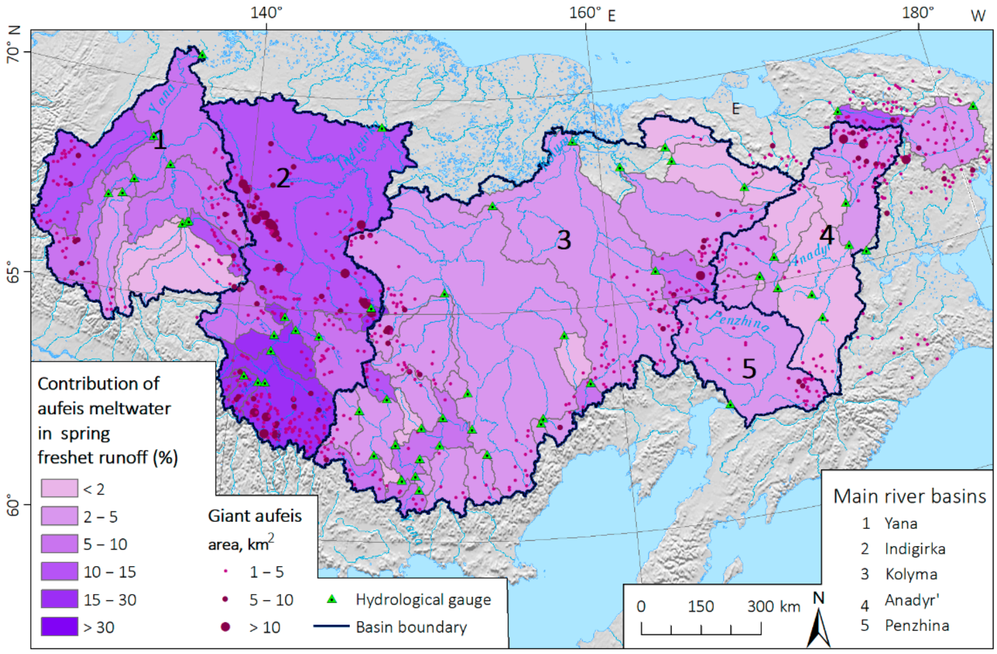

Figure 8. Contribution of aufeis meltwater in spring freshet runoff (%).

For large basins, the contribution of aufeis water accumulation in winter and their melting in spring does not exceed 190 and 20% of the winter and spring freshet runoff respectively. However, for smaller basins, the aufeis contribution can be very significant. So, the highest aufeis water accumulation is observed at the Moma River (712% of the mean winter runoff), while at the Agayakan River, 43.2% of the spring freshet runoff is associated with aufeis melt contribution.

5. Discussion

The hydrological role of aufeis substantially differs from that of glaciers. Water accumulation in glaciers is related to snowfalls, and snow transforms to ice only after a few years. The glacier's ablation process contributes to streamflow during the entire warm season, increasing in the second half of summer. In winter, glaciers do not affect either underground or surface flow. In their turn, the aufeis fields may be considered the indicator of the complex relationship between river and groundwater in permafrost conditions [48]. These water resources are excluded from the water balance in winter and contribute to streamflow in warm periods. Therefore, the fraction of winter flow stored in the aufeis ranges from 0.03 to 98%, with an average value of 18.2% in the Canadian territory [2]. The contribution of aufeis annual runoff in the Firth River basin (6000 km^2, Northern Yukon), which has the aufeis fields with a total area of 31 km^2, reaches 12–20% [2,49].

Aufeis cover 0.23% of the total area of the Yana River basin, which is 80 times more than the area covered by glaciers (0.003%) [10]. The glaciers are not common in the basins of the Kolyma and Penzhina rivers, and in the Anadyr River basin, they cover only 0.0004% of the basin area [10]. In the Indigirka River basin, the area of glaciers is only 0.06% of the total area [10], while the aufeis coverage is 0.55%.

In this paper, the analysis of modern aufeis resources in North-Eastern Eurasia has been carried out for the first time in the last 60–70 years. Previous estimates of the region's resources [19,50] were based on data of the aufeis Cadastre [43]. They, in turn, developed the Cadastre (1958) based on aerial photographs taken in the 1940–1950s.

A preliminary analysis of obtained data suggests that there has been a significant decrease in the aufeis resources of the Northeast. For example, total aufeis resources in the North-East of Russia are estimated at 26.2 km^3 in the study by Tostikhin (1974) [19]. It is worth noting that this estimate includes the aufeis from the Lena River basin, which are not included in the current study. However, in general, the estimate made by Tolstikhin (1974) [19] is about twice as high as our results. In the other study [46], the total aufeis resources of the Northeast are estimated at 16.9 km^3. However, the data of the analysis of the interannual dynamics of the aufeis area do not confirm the trend of a significant reduction in aufeis, performed in all major river basins of the region based on satellite images from 1973 to 2019 [51].

The aufeis dynamically react to climate change. Morse and Wolfe (2015) have shown that winter warming and autumn rainfall explain 28% of interannual aufeis variability in subarctic Canada. In the future, the increase in aufeis activity is predicted for this area with antecedent autumn rainfall, but, at the same time, the trend may be neutralized by less frequent winter warming intervals [52].

Another reason for aufeis variability may be the intensification of interaction between groundwater and surface flow [53]. The dynamics of aufeis formation are directly related to the winter runoff, whose changes are observed in different parts of the cryosphere [7,54,55]. The reasons for winter runoff increase have not yet been precisely identified. There is an increase in the amount of liquid precipitation in the autumn season, which is the significant factor affecting the increase of winter flow in Canada [54] and North-East of Russia [7]. Such transformation of the hydrological regime can lead to changes in the aufeis formation as winter runoff is the prerequisite for aufeis development.

The estimates of permafrost response, the impact of the dynamics of the active layer, and taliks on the interaction of surface and underground flow in the future remain uncertain due to the high heterogeneity of permafrost landscapes and their nonlinear interaction with the climate [56–59].

In general, the aufeis runoff values of the studied region are comparable to or exceed the estimates of glacial runoff in permafrost river basins of Canada and Alaska. For example, the average annual contribution of glacial runoff in Jarvis Creek was 15–28%, with the glacier coverage of about 3% [60]. According to Comeau et al. (2009) [61], the reduction in glacier volume contributed only an additional 3% to the total runoff of the

North Saskatchewan River at Edmonton (basin area 28 077 km^2) and the Bow River at Calgary (basin area 7 868 km^2) during 1975–1998 in Western Canada.

The estimation of glacial resources of the North-Eastern Eurasia region was also carried out according to Equation (1) with the coefficients $\alpha = 0.0451$ and $n = 1.139$ adopted from Nikitin (2009) [62]. The water resources of glaciers in the basins of large rivers are 0.02 km^3 for the Anadyr River and 0.27 km^3 for the Yana River, which in turn is 43 and 4 times less than the aufeis resources, respectively. In the Indigirka River basin, the glacier resources exceed aufeis resources almost twice and are estimated as 8.19 and 4.25 km^3, respectively (Table 2).

However, aufeis is a resource that contributes to the runoff in summer and accumulates its resources in winter. Glaciers do not ablate completely, giving only a part to the river flow. So, for example, there is the Agayakan River basin (7630 km^2), where both glaciers and aufeis are common. The area of glaciers in this basin is about 78 km^2, which is 1% of the basin area [10]. At the same time, the area of aufeis reaches 110 km^2 or 1.44% (Table S1). Koreisha (1972) [63,64] provides information about the contribution of aufeis and glaciers to the formation of river flow at this basin in 1957. Therefore, the glacial runoff was 3.8% of the annual flow and 6.1% for July and August, while the aufeis runoff was 18% of the annual and 40% for the summer period.

Climate warming affects the glaciers and aufeis [1,2,5,11,65]. There is a negative mass balance of glaciers in the permafrost zone of the Northern Hemisphere, which includes Canada, Alaska, Greenland, North-Western America, the Scandinavia countries, and the Arctic part of Russia. Every year, the glacier area and volume are reduced. So, the glacier losses amounted to 750 km^2 (30% of the initial area) in the western mountain range of Canada from 1919 to 2006 [66]. In Alaska, the loss of individual glaciers was 1.4% (5.63 km^2) from 2001–2010 [67]. In general, in the cryosphere, the length of glaciers, on average, decreases by 10–15 m per year [68]. The loss of the total glaciers volume on the Suntar-Khayata ridges in the Indigirka River basin is estimated as 1.4 km^3 for the period 1970–2003 [69], accounting for only 0.8 mm of additional runoff per year on average in the Indigirka River basin [11]. This value is an order of magnitude lower than the value of annual aufeis runoff in the Indigirka River basin (4.5 mm).

In the conditions of climate change, the continuation of research on the patterns, dynamics of aufeis formation and their resource potential, both in fundamental terms of studying the natural phenomena of the cryosphere and for practical purposes of ensuring sustainable and safe development of the region, is extremely relevant and timely.

With a strong relationship between aufeis and groundwater flow, the response of aufeis under degrading permafrost may be obtained by investigating aufeis distribution in the landscape and relations with terrain [2]. Such research can only be conducted by organizing special observations on the aufeis study sites [70]. The results of aufeis dynamic studies at individual representative aufeis, generalized for larger territories based on the analysis of satellite images, can help to understand the transformation processes of the hydrological cycle and the cryosphere. For example, the study of aufeis processes in the field may promote the understanding of the factors governing winter runoff changes [71]. Recently complex interdisciplinary studies of the giant Anmangynda aufeis have been initiated in the North-East of Russia (the Magadan region) to study the interaction of various components of water exchange in the cryosphere in a changing climate [70].

6. Conclusions

The general assessment of aufeis resources and their role in the water balance of the rivers in North-Eastern Eurasia was conducted based on a newly compiled aufeis dataset for the entire study area. Aufeis data were derived based on the interpretation of late-spring Landsat satellite images for the period 2013–2019. We corrected the maximum aufeis area using the method by Sokolov (1975) [38]. According to the calculation results, the maximum area of aufeis is 4529 km^2, which is 22% more than the initial satellite-derived estimate.

Based on recent data on aufeis fields dynamic, the error of area calculation for a single aufeis field may reach ±19%.

The aufeis resources of the North-East are at least 10.6 km^3 or 5 mm of aufeis runoff per year for the entire study area. The aufeis resources vary from 0.4 to 4.25 km^3 (or 3.7–11 mm) for individual basins of large rivers. The greatest aufeis resources in absolute values are located in the Indigirka River basin. The error of volume calculation for a single aufeis field is ±35%.

The contribution of aufeis runoff to water balance formation in different seasons is calculated for 58 hydrological gauges (basins area ranges from 523 to 526,000 km^2). Aufeis annual runoff ranges from 0.3 to 29 mm (0.1–22% with an average value of 3.8%), with the fraction of winter flow stored in the aufeis about 6–712% (average 112%) and the contribution of aufeis meltwater to spring freshet runoff is 0.2–43% (average 7.1%).

The influence of aufeis and glaciers on water balance is compared: aufeis runoff exceeds the glacial runoff, and aufeis water resources exceed the same of glaciers, except for the Indigirka River basin. Therefore, it is necessary to conduct field studies to observe the processes of aufeis transformation under changing climate.

In general, aufeis are important water resources that strongly impact the runoff formation in the permafrost zone. Under the warming climate conditions, the changes in the aufeis processes will play a significant role in the amount of river flow discharging to the Arctic Ocean. This will eventually lead to changes in the natural the ocean–climate system [72] and its various components, for example, sea ice formation [73], thermohaline circulation [74], and different environmental impacts [75].

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/rs14174248/s1, Table S1: Aufeis resources of river basins at North-East of Russia and aufeis impact to the hydrological cycle.

Author Contributions: Conceptualization, O.M., N.N., D.L. and V.A.; formal analysis, A.S., A.Z. and A.O.; data curation, A.S., A.Z. and A.O.; writing—original draft preparation, O.M., N.N. and A.Z.; writing—review and editing, O.M., D.L. and V.A.; visualization, A.S. and A.O. All authors have read and agreed to the published version of the manuscript.

Funding: The study was carried out with the support of St. Petersburg State University (project 75295776), Russian Foundation for Basic Research (projects 19-55-80028 and 20-05-00666), and the Kazan Federal University Strategic Academic Leadership Program ("PRIORITY-2030").

Data Availability Statement: All data is available by the request to corresponding author.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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