Earth Syst. Sci. Data Discuss., https://doi.org/10.5194/essd-2018-99
Manuscript under review for journal Earth Syst. Sci. Data
Discussion started: 31 August 2018

Aufeis of the Indigirka river basin (Russia): the database from historical data and recent Landsat images

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Abstract: Detailed spatial geodatabase of aufeis in the Indigirka River, the basin area 305 000 km^2, Russia was compiled from the Cadaster of aufeis of the North-East of the USSR published in 1958, topographic maps and Landsat images for 2013-2017. The aufeis area share varies from 0.26 to 1.15% in different river sub-basins within the studied area.

Digitized Cadaster (1958) contains the coordinates and characteristics of 897 aufeises with total area of 2064 km^2. The Landsat-based identification of aufeises for 2013-2017 allowed the description of 1213 aufeises on a total area of 1287 km^2. The combined digital database of the aufeis is available at https://doi.pangaea.de/10.1594/PANGAEA.891036. The satellite-derived total area of aufeis is 1.6 times less than in the Cadaster (1958). At the same time, more than 600 aufeis identified by Landsat images analyses are missing in the Cadaster (1958). It implies that the aufeis formation conditions may have been changed between the mid-20th century and the present.

About 60% of total area presents 10% of the largest aufeis. Most aufeis are located in the elevation band of 1 100 – 1 300 m.

The interannual variability of the aufeis area was estimated by the example of the Bolshaya Momskaya naled (aufeis) and the group of large aufeis in the basin of the Syuryuktyakh River for the period of 2001-2016. The results of analysis indicate a tendency towards a decrease in the area of the Bolshaya Momskaya naled in recent years, at the same time the reduction in the aufeis area in the basin of the Syuryuktyakh River has not occurred.

Keywords: aufies, the Indigirka river, the Map and Cadaster of aufeises, Landsat images, database, interannual variability, the Bolshaya Momskaya naled (aufeis)

1. Introduction

Aufeis (naled in Russian, icings in English) is one of the glaciation forms, standing on the same level with other types of snow-ice formations and affecting water exchange and economic activity (Alekseev, 1987). They are distributed in permafrost regions, for example, Alaska (Slaughter, 1982), Siberia (Alekseev, 1987), Canada (Pollard, 2005), Greenland (Yde and Knudsen, 2005) and other (Yoshikawa et al., 2007). Intensification of aufeis formation processes can result in significant economic expenses; they negatively affect engineering constructions' sustainability, as well as complicate exploitation of hydro-technical and industrial constructions (Aufeis of Siberia…, 1981). Moreover, springs, feeding aufeis, in some cases can be the only source of water supply for inhabited localities (Simakov, Shilnikovskaya, 1958).

In Russia aufeis are found in the North-East, Transbaikal region, Yakutia and West Siberia. Sokolov (1975) assessed water storage in aufeis of Russia to be not less than 50 km^3, which approximately equals the Indigirka River annual streamflow.

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The main hydrological role of aufeis is the redistribution of the underground component of river runoff from winter to spring-summer season (Surface water resources, 1972). In most cases, the share of the aufeis component in a river's annual streamflow accounts for 3-7 %, reaching 25-30 % in particular river basins with an extremely large proportion of aufeis (Reedyk et al., 1995; Kane & Slaughter, 1973; Sokolov, 1975). The most significant water inflow from aufeis melting takes place in May-June (Sokolov, 1975). For example, the share of the aufeis flow accounts for more than 11% from total annual streamflow at the Indigirka River (gauging station Yurty, basin area 51100 km^2). In May, it may be 50 % of monthly streamflow, but decreases in June to 35 % (Sokolov, 1975).

It is important to understand how aufeis formation may be impacted by climate change. Aufeis are formed by a complex interconnection between river and groundwater. Currently many studies report the increase of minimum flow in Arctic rivers (Rennermalm and Wood, 2010; Tananaev et al., 2016), including those where aufeis are observed in abundance Makarieva et al., 2018, in review). The widely accepted hypothesis is that a warming climate improves the connection between surface and groundwater in permafrost areas which leads to the increase of streamflow, both in cold seasons and in annual flow (Bense et al., 2012; Ge et al., 2011; Walvoord et al., 2012; Walvoord and Kurylyk., 2016). The dynamic of aufeis which can partly be assessed based on the analysis of remote sensing data can be viewed as one indicator of groundwater changes which are otherwise difficult to be observed naturally in remote arctic areas (Topchiev, 2008; Yoshikawa et al., 2007).

Projected assessments of change in aufeis in warming conditions vary. Alekseev (2016) points out that in long-term regime of aufeis in general there are 3, 7 and 11 year up and down cycles of maximum annual sizes, during which they vary by up to 25-30 % in comparison with average long-term values. However, for the last 50-60 years there is a decrease in the volumes of springs which feed aufeis, in agreement with other evidences of current cryosphere degradation (Alekseev, 2016). Some authors expect that degradation of permafrost in the discontinuous and island-like zones will lead to the decrease of the number of aufeis and in fact almost complete disappearance of them. Meanwhile, in the zone of continuous permafrost, a climate warming of 2-3°C being projected for North-East Siberia by the end of the 21th century, will not lead to the significant changes in permafrost regime, but will increase volumes of both through and open taliks (Pomortsev et al., 2010). This may result in dispersion of large aufeis and formation of new small ones (Pomortsev et al., 2010).

The projections of increasing dynamics of aufeis formation under climate change are confirmed by direct observations. Indeed, in the aufeis valleys of Ulakhan Taryn and Bulus (central Yakutia, Russia) only in 4 out of 10 aufeis seasons in this century aufeis didn't reach their maximum area, volume and depth (Pomortsev et al., 2007). In Alaska, according to Yoshikawa et. al (2007), on the contrary, there are no significant changes in the area and volume of aufeis over the past few decades or even a century. Yoshikawa et. al (2007) suggested that the formation and melting of ice is less dependent on climate change andmore so on the source spring water properties such as temperature and volume (discharge).

In 1958, Simakov and Shilnikovskaya (1958) compiled and published the Map (scale 1:2 000 000) and the Cadaster of aufeis of the North-East USSR. In the last 60 years, there has been no update of the information on aufeis in general in this region, apart from some specific studies. In 1980-1982, the Catalogue of aufeis of the zone of the Baikal-Amur Mainline was published (Catalog of Aufeis…, 1980, 1981, 1982). Markov et al. (2017) summarized the results of field studies of the aufeis in the southern mountain taiga of Eastern Siberia in the period from 1976 to 1983. Grosse and Jones (2011) compiled the spatial geodatabase of frost mounds (or pingos) for northern Asia from topographic maps. However, there does not exist an electronic catalogue of aufeis, similar to the one for glaciers, for instance (GLIMS and NSIDC, 2005, updated 2017).

The aim of this study is to update the Cadaster of aufeis in the North-East of Russia using Landsat images, as well as to develop a catalogue, which will contain data on historic and current location and characteristics of aufeis. As of now, the work has been completed for the Indigirka River basin (up to the Vorontsovo gauging station), 305 000 km^2.

Developed database and geographic information system (GIS) for the updated Cadaster of aufeis in the North-East for the Indigirka River basin are freely available for the public (Makarieva et al., 2018) and can be used both for scientific purpose and for solving practical problems, for example, engineering construction and water supply.

2. Research objective

The study region is the Indigirka River basin, covering the area of 305 000 km^2. The largest part of the basin is a highland with a number of mountain ranges, the Cherskiy and Suntar-Khayata being most significant, with the maximum height of up to 3 003 m. Lower reaches of the river are in a lowland with heights up to 350 m.

The climate of the study area is distinctly continental with annual average and lowest monthly air temperature varying from -16.1 and -47.1˚C at the Oymyakon meteorological station (726 m, 1930-2012) to -13.1 and -33.8˚C at the Vostochnaya station (1 288 m, 1942-2012) respectively. Most precipitation (over 60 %) occurs in the summer season. Average annual precipitation at the Oymyakon weather station is 180 mm, at the Vostochnaya station 278 mm.

The Indigirka River basin is located in the zone of continuous permafrost. Its depth can reach 450 m at watershed ranges and up to 180 m in river valleys and intermountain areas, being discontinued with taliks in river beds and fractured deposits. The hydrogeological regime is greatly influenced by the permafrost active layer, whose depth varies from 0.3 m to over 2 m (Explanatory note …, 1991).

The rivers regime is characterized by high snowmelt freshet and significant summer-autumn rainfall floods and low winter water level. In winter, small- and medium-sized rivers completely freeze. Freshet starts in May-June and lasts for approximately 1.5 months. In summer, melted waters from aufeis, glaciers and snow patches add to the rain feeding.

In total, in North-East Russia, about 10 000 aufeis with the total area of about 14 000 km^2 (Sokolov, 1975) are known. The basin share covered by aufeis in average varies from 0.4 to 1.3%, reaching 4 % in some river basins (Tolstikhin, 1974).

Most aufeis are of ground water origin; significantly less often they are formed out of river waters or are of a mixed type (Tolstikhin, 1974).

3. Materials and methods

3.1 The database of aufeis based on the Cadaster (1958) and topographic maps

The Map (scale 1:2 000 000) and the Cadaster of aufeis of the North-East of the USSR (Simakov, Shilnikovskaya, 1958), hereinafter referred to as the Map and the Cadaster, became the first historical generalizing work on quantitative accounting of aufeis and their features within the study territory. It was carried out in the framework of the Central complex thematic expedition of the North-East Geological Survey of the USSR.

The Cadaster contains data on 7 448 aufeis of different size and over 2 000 boolgunyakhs (frost mounds). Out of the total number of aufeis, 7 006 are plotted based on the air-photo interpretation data, and 442 – on the geological reports data. It is of importance that the parts of river valleys covered with aufeis were identified based on geomorphologic features, meaning that in some cases only the areas with aufeis were identified but not aufeis themselves.

In the Cadaster, the following characteristics of the aufeis are presented: their location (the name of the river, the distance from the mouth or source), sizes (maximum length, average width, area) and the dates of ice recording in aerial images (the earliest – 08.06.1944, the latest – 27.09.1945). Areas of the aufeis were evaluated via planimetering. The sizes of the aufeis, plotted on the Map according to the reported data and oral information, were not presented in the Cadaster.

Very large and gigantic aufeis areas were plotted on the Map (1958), all the rest are shown just as point locations. Each aufeis on the Map (1958) has its corresponding number, under

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which it can be found in the Cadaster (1958). As noted by Simakov and Shilnikovskaya (1958), some very small aufeis could have been missed due to their indecipherability on aerial images, as well as due to the fact that at the moment of air photography they might have already melted. For a sample of the Map's sheet (1958) for the Indigirka River upper reaches, see fig. 1.

In this study, the GIS database of aufeis in the Indigirka River basin up to the cross-section at the Vorontsovo gauging station was developed, based on the Cadaster of aufeis (1958) and topographic maps. It contains data on 896 aufeis. The aufeis are presented in as point objects in the compiled database. It includes areas of 808 aufeis. The total area of all the aufeis accounts for 2063.6 km^2, the area of individual aufeis varies from 0.01 to 82 km^2.

In the Cadaster, the dates of recording for 592 aufeis (66%) are presented, based on aerial images within the research area. The average date of ice recording is August, 2, the earliest – June, 8, and the latest – September, 27. The dates of ice recording for the remaining 34 % of the aufeis were not described, meaning that ice presence during deciphering of the aerial images was not recorded. Therefore, the Cadaster might as well contain data on old aufeis glades, where the aufeis themselves were absent.

Spatial positioning of the Map of aufeis was conducted using the location description by Russian topographic maps with the scale of 1:200 000. Grosse and Jones (2011) used the same set of maps for compiling the dataset of pingos (frost mounds) in northern Asia and described those maps in details therein. The maps used are based on more detailed maps of 1:50 000 and 1:100 000 scale, which were derived from aerial photography acquired in the 1970–1980's. The use of 1: 200 000 scale guarantees the position assessment precision within 100 m. Each map sheet was visually searched for aufeis, and identified aufeis were marked with an area polygon in a GIS layer. The locations of 330 aufeis (area 358 km^2) were determined based on topographic maps (when digitized, a point was plotted in the middle of an aufeis at a topographic map).

The locations of the remaining aufeis were determined with the positioned map of the Cadaster. Additionally, 11 aufeis were distinguished, which were absent in the Cadaster, but present in the topographic maps. Their areas were estimated by digitalization of these maps. Areas of the remaining aufeis were estimated with the Cadaster. For 88 aufeis it was impossible to estimate their area, as they are not present in topographic maps, and their areas are not stated in the Cadaster.

The GIS database contains the following characteristics of aufeis:

- Aufeis number according to the Cadaster (if an aufeis is only present in the topographic map it was set to «0»)
- Aufeis area
- The date of the aerial image when the aufeis was distinguished
- Presence in the topographic map («0» – absent, «1» – present)
- Presence in the Cadaster («0» – absent, «1» – present)
- The Cadaster map sheet number
- Topographic map sheet number
- Longitude, degrees
- Latitude, degrees
- Altitude above the sea level (estimated with DEM Aster GDEM), m
- Comments (mainly the misprints in the Cadaster Map were pointed out here).

3.2 Identification of aufeis based on Landsat data

Aufeis location and area are relatively easy to determine using Landsat and/or Sentinel-2 images, received immediately after snow cover melting. Snow and ice are known to be characterized with high relative reflectivity in visible and near infra-red range and a significant decrease in mid infra-red range. Normalized Differential Snow Index (NDSI) is based on this regularity and is calculated according to the formula (Hall et al., 1995):

$$NDSI = (GREEN - SWIR1)/(GREEN + SWIR1),$$

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where SWIR1 – reflection coefficient in mid infra-red range (1.56 – 1.66 μm for the Landsat-8 images), and GREEN – reflection coefficient in the green channel (0.525 – 0.6 μm for the Landsat-8 images). NDSI threshold value, based on which snow and ice surfaces are detected, is taken as 0.4 (Hall et al., 1995).

Apart from NDSI, to detect aufeis in Landsat images, other indices were also suggested: normalized difference glacier index (Normalized Difference Glacier Index, NDGI) and maximum difference ice index (Maximum Difference Ice Index, MDII). Their advantages and disadvantages are discussed by Morse and Wolfe (2015).

There is a significant complication in aufeis detection in satellite images as it is difficult to distinguish floodplain lakes from cryogenic ones, which in May-June are also covered with ice and have spectrum characteristics similar to aufeis. To tackle this problem it is recommended to mask water bodies in images taken in the middle of summer, when the ice cover on all water bodies is already breaking down (Morse and Wolfe, 2015).

Aufeis detection in the Indigirka River basin was carried out based on the Landsat-8 satellite images, 2013-2017, downloaded from the United States Geological Survey web-service (US Geological Survey Server). In total, 33 images completely covering the Indigirka basin were processed. Acquisition dates were specially chosen to detect the maximum possible number of aufeis, since in June they melt intensively. The earliest of the chosen acquisition dates is May 15, the latest – June 18. There were clouds in some images (covering from 1 to 20% of image area). Preprocessing of the images (transformation brightness into reflection coefficient) was performed with the use of Semi-Automatic Classification Plugin module in QGIS 2.18.

Aufeis detection algorithm was realized in ArcGIS with the help of the ModelBuilder application. Apart from the images, during calculation the digital terrain model (DTM) GMTED2010 (Danielson and Gesch, 2011) with the spatial resolution of 250 m was used. Based on this DTM, a network of thalwegs was created within the study basin. Using the thalwegs network is necessary, because almost all aufeis are located either at streams, or in immediate proximity to them. Preliminary visual analysis of the images allowed evaluating the optimal width of 1.5 km buffer zone around thalwegs, necessary to detect aufeis.

The process of aufeis detection in Landsat images consisted of the following steps:

- Detection of snow-ice bodies with the NDSI threshold of 0.4.
- Creation of a water mask with NDWI normalized difference water index thresholds (threshold is taken to be 0.3), and reflection coefficient in the near-infrared channel (threshold is taken to be 0.04).
- Cutting out the defined snow-ice bodies to buffer zone borders around thalwegs (1.5 km wide).
- Conversion to vector format, area calculation and removal of objects smaller than 5 Landsat pixels (0.45 ha).

The suggested algorithm allows successful aufeis detection in an image if they are not covered with snow. At the end of May – early June, many aufeis in mountain regions are still covered with snow. To detect them it was necessary to use later images (from mid-June).

Morse and Wolfe (2015) suggested a new spectral index MDII for automatically distinguishing snow bodies from ice ones. In the present work there was no chance to realize its advantages due to the fact that some of the aufeis were partially covered with snow at the acquisition time. When snow cover was present, aufeis outline detection was conducted manually, as well as removal of snow covered areas adjacent to aufeis.

While assessing the number of aufeis with satellite data, it is also necessary to take into account that during melt the aufeis often divide into several neighboring plots. Such plots were perceived to be the parts of a single aufeis if the distance between them did not exceed 150 m (5 Landsat pixels), and they were sequentially located within one valley (aufeis glade).

4. Results and verification

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Cross-verification of the historical and satellite data was carried out based on the Cadaster (1958). The verification is based on identification of closest objects between the point layer of aufeis, included in the Cadaster, and the polygonal layer, detected in the Landsat images. Besides, compared objects should be within a single thalweg or aufeis glade. Threshold distance between compared objects was not set, because since the mid-20th century, when the field studies were conducted, aufeis location within one valley could have changed significantly.

As a result of Landsat image automatic processing, an area of 1 253.9 km^2 of aufeis was detected. During the comparison with the Cadaster data, over 100 aufeis, with a total area of 33.5 km^2, were manually vectorized. The gaps were mainly due to the presence of snow cover and/or cloud coverage in the images. For the verification, 2-3 images of the same territory were used to reconstruct the missing objects. Total number of the aufeis, identified with the Landsat images in the Indigirka River basin accounted for 1 213, and their total area – 1 287.4 km^2. Therefore, the error of the second type (missed objects ratio) of automatic aufeis detection can be estimated as 2.7% of their total area.

The results of the comparison are presented in Table 1. In total, 634 aufeis from the Cadaster were detected in the Landsat images. They correspond to 611 aufeis identified with the images, meaning that in 23 cases one aufeis in an image corresponds to two aufeis in the Cadaster. But 262 aufeis from the Cadaster were not detected in the satellite images. Those are mainly small aufeis, which melt by the middle of June. However, among them there are also 43 large aufeis over 1 km^2 (fig. 2-a). It is likely that since the mid-20th century (when the field observations were conducted and the Cadaster of aufeis was compiled) some aufeis could have disappeared.

By comparison, less than half of the aufeis detected in images are included in the Cadaster: a total of 602 aufeis detected (the total area of 250,4 km^2) are not included in the Cadaster (fig. 2-b). Such a significant difference can be caused by the following reasons:

1. In some cases a single aufeis, according to the Cadaster, corresponds with two or more aufeis in a satellite image.
2. Aufeis are characterized by significant interannual variability of formation conditions, which results in possible formation of new aufeis in areas where they previously were not observed (Alekseev, 2015; Pomortsev et al., 2010; Atlas of snow…, 1997).

Total aufeis area evaluated based on satellite images, appeared to be 1.6 times smaller than stated in the Cadaster (1958). First and foremost, such difference can be explained by the fact that it was not the area of the aufeis themselves but the aufeis glades that was reported in the Cadaster (1958) (which correspond to the maximum aufeis area during one or several seasons). With the satellite data, the areas of the aufeis themselves were assessed, and in some cases (when the images of mid-June were used) this area was significantly smaller than maximum possible.

Aufeis area distribution according to the Cadaster and satellite data is illustrated by Lorenz curves (fig. 3). In both cases, the shape of the curves signifies a high degree of irregularity which is similar to both data sources: 10 % of the largest aufeis make up 61.1 and 57.4% of their total area according to the Landsat and the Cadaster data respectively.

The comparison of distribution of confirmed and not confirmed aufeis area during cross-verification of the Cadaster and satellite data has shown that almost 60% of aufeis presented in the Cadaster but not confirmed with the satellite data, have an area less than 0.25 km^2 (Fig. 4-a). Among the aufeis, confirmed with the images, these account for about 20% (area is stated according to the Cadaster). Thus, it was mainly small aufeis that were not confirmed by the images. In comparison, it can be seen in Fig. 4-b that almost 60 % of the aufeis, detected in the images and not confirmed by the Cadaster, have an area of less than 0.25 km^2 (area is stated according to the images).

4.1 Aufeis distribution by elevation

Relief is one of the most important factors defining the spatial distribution of aufeis. As a whole, aufeis distributions by elevation, assessed with the Cadaster and Landsat data, are quite

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similar (fig. 5). Most aufeis are located in the elevation band of 1 100 – 1 300 m. At lower elevations (up to 800 m) the number of aufeis, according to Landsat data, is higher than stated in the Cadaster. At the elevations of 1 400-2 000 m, more aufeis are identified according to the Cadaster data than by the satellite images. This can be explained by the fact that many aufeis located at high altitudes have small area, so they could have been missed during the analysis of the satellite data. They could have been covered with snow at the image acquisition time, which would increase the possibility of them being missed.

4.2 Aufeis distribution by river basins

In the Indigirka River basin, there are several zones with a high density of aufeis: in the southern part (in the Suntar and Kuidusun Rivers basins), as well as in the central part, at the Chersky Range slopes (fig. 6). The largest aufeis, identified with the satellite images, are located in the Syuryuktyakh River basin at the north-east slope of the Chersky Range. Meanwhile, aufeis are almost absent in the northernmost lowland part of the Indigirka basin.

The head reaches of the Indigirka River up to the Yurty village is the basin with the highest aufeis area cover (Table 2). Correlation between average elevation of basins and their aufeis percentage is statistically significant, but less noticeable than expected. Spearman rank correlation coefficients between the basin average elevation and aufeis percentage are 0.71 and 0.77, the aufeis percentage assessed with the Cadaster and satellite data respectfully.

4.3 Aufeis area interannual variability

The assessment of aufeis area interannual variability was conducted for two locations: the Bolshaya Momskaya aufeis (aufeis), located in the Moma River channel (according to the Cadaster its area is 82 km^2), and for the group of large aufeis in the Syuryuktyakh River basin – the left-bank tributary of the Indigirka (according to the Cadaster their total area reaches 287.8 km^2). Cloudless images from Landsat-5 (TM), Landsat 7 (ETM+) and Landsat-8 (OLI) were used with the acquisition dates between May 1 and June 30. In the USGS archives, there are no Landsat-5 images for the study territory for the 1984-2007 period. This limits the duration of satellite observations on aufeis to the period since 1999 (when the Landsat-7 satellite was launched). Also, the clouds complicate the acquisition of representative data. The list of the acquisition dates and assessed aufeis area values are presented in Table. 3.

When assessing interannual changes in areas of the examined aufeis, it is necessary to take into account that they are located at low elevations: Bolshaya Momskaya aufeis – 430 to 500 m, the aufeis in the Syuryuktyakh River basin – 200 to 500 m. This contributes to their relatively early and intensive melt in spring. The aufeis reach their maximum area by the beginning of May. Using the available satellite images it is impossible to make a firm conclusion on aufeis area growth or decline, because the acquisition dates vary significantly from year to year. However, it is possible to make some conclusions based on the available data:

1. In 2002-2017 the Bolshaya Momskaya aufeis did not reach the maximum area stated in the Cadaster (82 km^2), even according to the satellite image received in the first week of May 2005, when aufeis melting did not yet start. Comparing two images, taken in similar conditions (08.05.2005 and 15.05.2013), it was determined that aufeis area in 2013 was smaller by 18.1 km^2. All of the above might indicate the tendency of decrease in the area of the Bolshaya Momskaya aufeis.
2. The area of the largest aufeis in the Syuryuktyakh River basin in May 2014 was 78.0 km^2 – 8 km^2 larger than stated in the Cadaster. It can also be noticed that the maximum aufeis areas in the Syuryuktyakh River basin were detected in the images received at the end of the period in question (2014-2017), including mid-June (18.06.2015). Based on these data it can be suggested that the aufeis areas within this basin have not decreased since 2002.

5. Conclusion

The research conducted here is the first step of the study aimed at the development of a GIS database of the aufeis of North-East Russia. Historical data of the Cadaster (1958) data and topographic maps were used to create a geodatabase of aufeis in the Indigirka River basin (up to the Vorontsovo gauge, with the area of 305 000 km^2). It contains historical data on 896 aufeis with total area of 2063.6 km^2. Using the Landsat data, the aufeis detection was conducted for the 2013-2017 period. 1213 aufeis with the total area of 1287.4 km^2 were identified. The historical data from the Cadaster (1958) and the results of aufeis detection with satellite data were combined in the joint Catalogue of aufeis within the Indigirka River basin available at https://doi.pangaea.de/10.1594/PANGAEA.891036.

It can be seen that current aufeis area is 1.6 times smaller than stated in the Cadaster (1958). Meanwhile, the Cadaster is lacking data on over 600 aufeis, identified using satellite images. This suggests, on the one hand, that the data in the Cadaster was incomplete, while, on the other hand, that there was a significant change in aufeis formation conditions in the last half century. One of the further study goals will be to find out the extent to which these changes are climate-derived and to identify their impact on river streamflow.

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Table 1 Data correlation of aufeis based on the Cadaster (1958) and the Landsat images

Data source	Matching aufeis number (area km^2)	Not confirmed aufeis number (area km^2)
Cadaster (1958)	634 (1905,0)	262 (158,6)
Landsat	611 (1037,0)	602 (250,4)

Table 2 Assessment of aufeis area share (percentage) in the sub-basins within the Indigirka River basin by the Cadaster and Landsat

River – outlet	Area, km^2	Average elevation, m a.s.l.	% of aufeis by Cadaster	% of aufeis by Landsat
Suntar river – riv. Sakharinya mouth	7680	1460	0.97	0.78
Elgi – 5.0 km upstream of the river Artyk-Yuryakh mouth	17600	1104	0.49	0.23
Nera – Ala-Chubuk	22300	1174	0.32	0.26
Indigirka – Yurty	51100	1256	1.15	0.80
Indigirka – Indigirskiy	83500	1185	0.82	0.56
Indigirka – Vorontsovo	305000	803	0.68	0.41

Table 3 Aufeis areas changes, 2001-2016

Bolshaya Momskaya aufeis		The group of aufeis in the Syuryuktyakh River basin	
Imagery date	Aufeis area, km^2	Imagery date	Aufeis area, km^2
17.06.2002	29..2	26.06.2001	69.7
08.05.2005	66.2	29.06.2002	100.6
27.05.2006	57.9	04.06.2007	155.1
25.05.2011	61.7	17.06.2009	89.5
19.06.2009	39.5	22.06.2011	117.5
27.05.2012	49.6	21.05.2014	268
15.05.2013	48.1	18.06.2015	164.8
18.06.2017	21.9	04.06.2016	206.4

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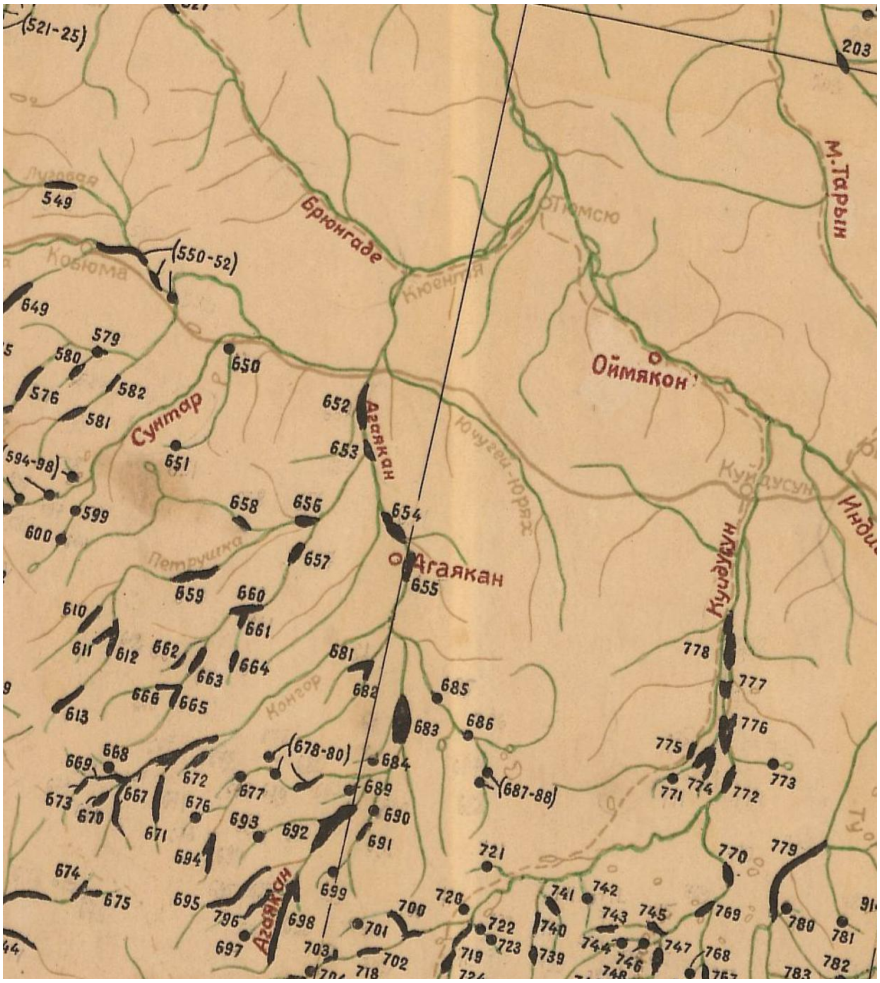

Fig. 1 Subset from the Map of aufeis of the North-East of the USSR (sheet 7, upper reaches of the Indigirka River – the basins of the rivers Suntar, Agayakan and Kuydusun)

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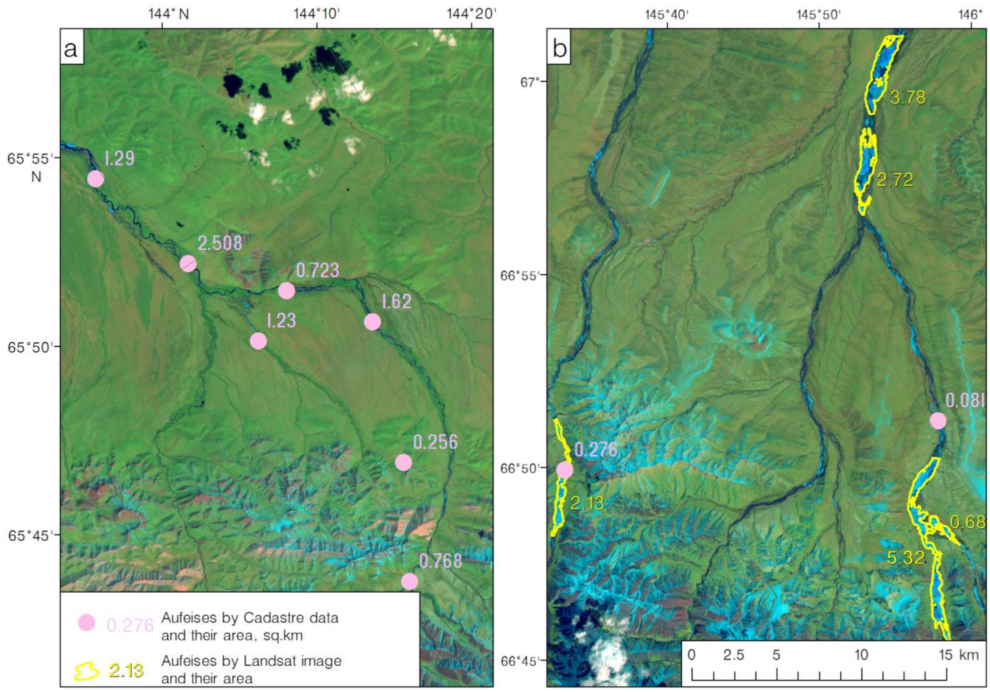

Fig. 2 Difference between aufeis location according to the Cadaster and satellite data: a) – aufeis are absent in the image but present in the Cadaster (Landsat-8 image of 18.06.2017); b) – aufeis are absent (or their area is understated) in the Cadaster but present in the image (Landsat-8 image of 30.05.2016)

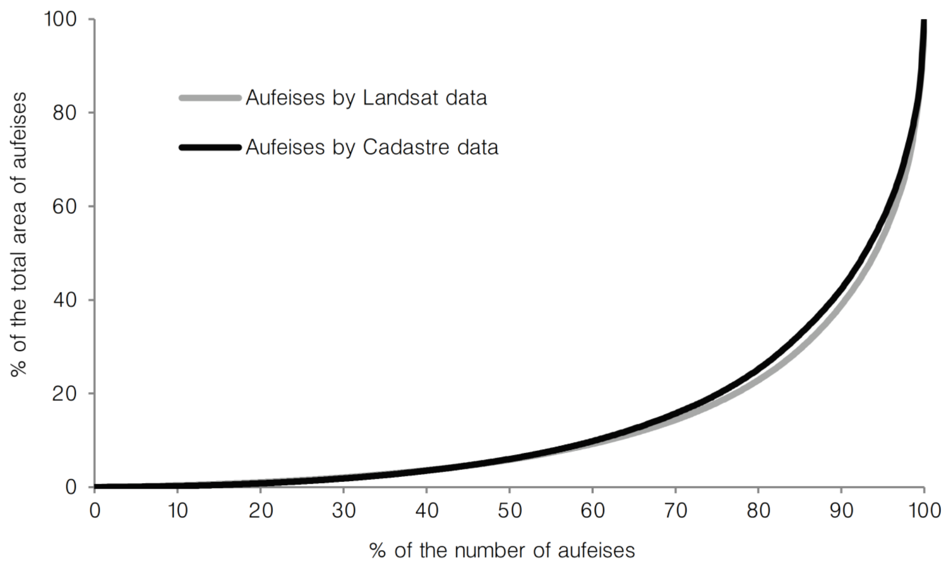

Fig. 3 Lorenz curves illustrating aufeis area distribution according to the Cadaster and Landsat data

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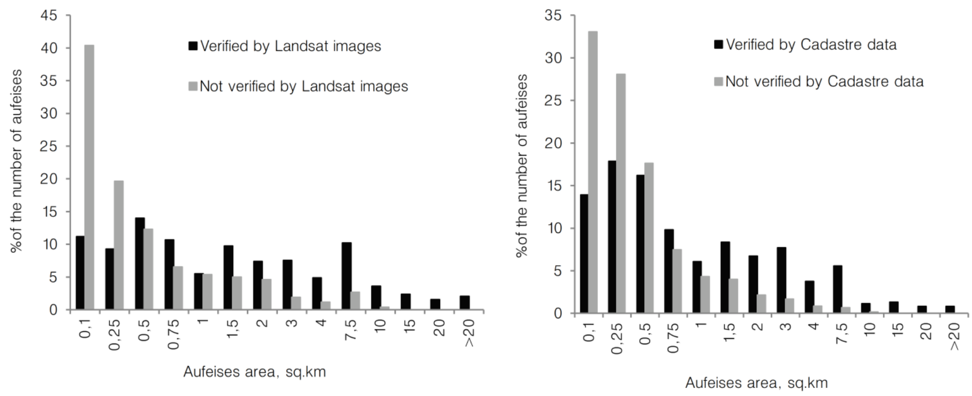

Fig. 4 Aufeis area distribution: a) – according to the Cadaster data, confirmed and not confirmed by Landsat images, b) – according to Landsat images, confirmed and not confirmed by the Cadaster

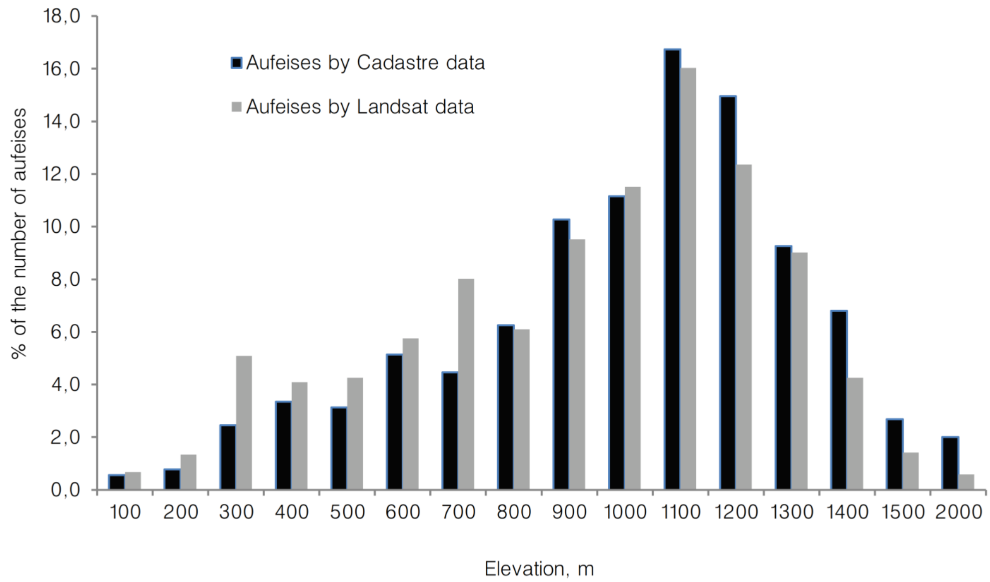

Fig. 5 Aufeis distribution by elevation within the Indigirka River basin

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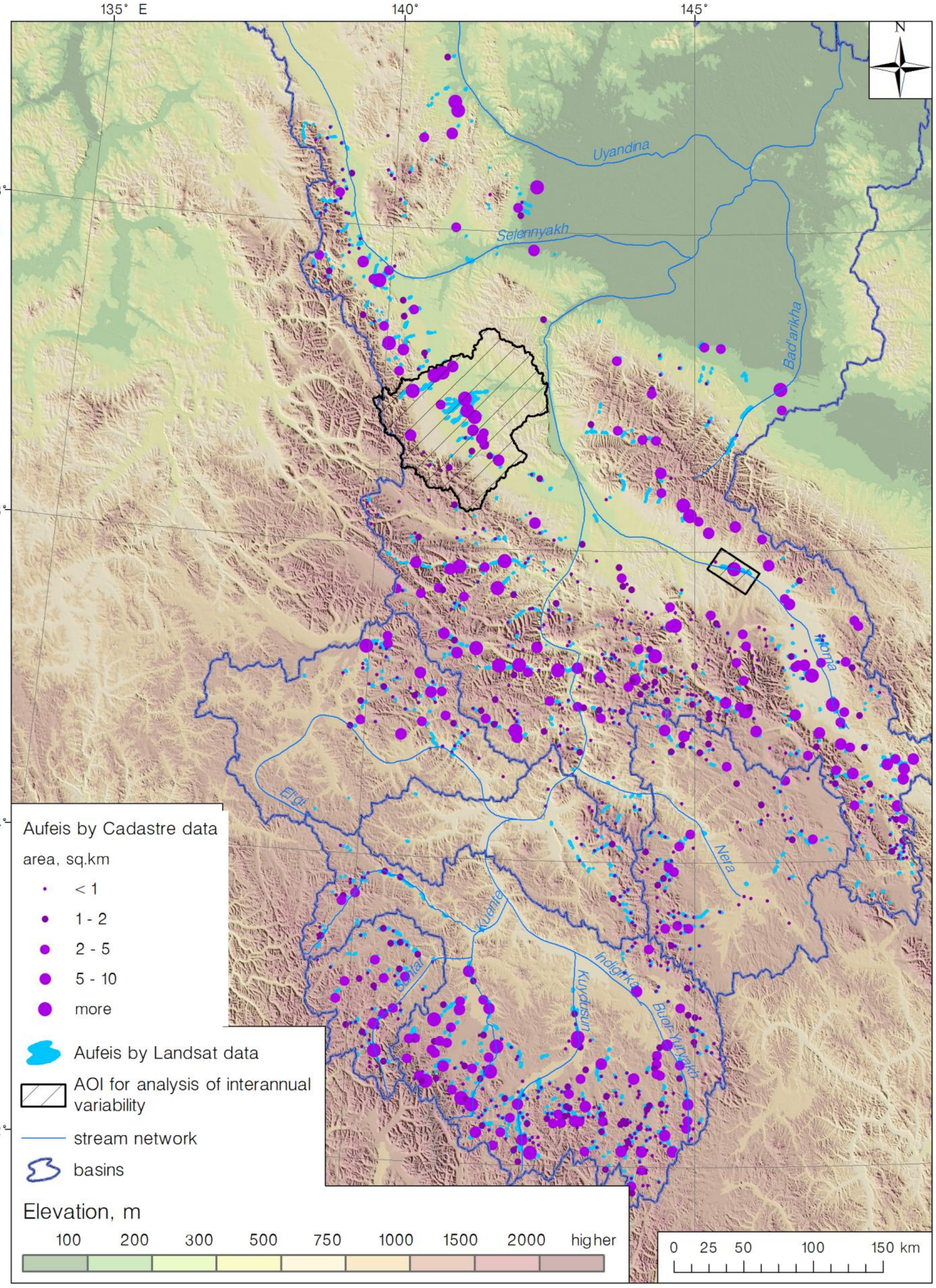

Fig. 6 Aufeis in the Indigirka River basin according to the Cadaster and Landsat images. Black outlines with section lining represent the zones where aufeis area interannual variability was assessed